Towards sail-shape optimization of a modern clipper ship

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1. Objective and motivation

Sail-shape optimization is challenging because of the complex coupling between the aerodynamic forces produced by a sailboat’s rig and the hydrodynamic forces produced by its hull and underwater appendages: see Marchaj (2000). Yacht designers generally assume a steady-state sailing condition, setting rig forces in equilibrium with hull forces to estimate performance: this assumption forms the basis of widely-used Velocity Prediction Programs or VPPs. Accurate numerical modeling of the complete boat (sails, hulls and appendages) is extremely expensive from a computational point of view, and not practical if many different configurations and flow conditions have to be investigated. In our sail-optimization research, we therefore rely on simplified models to handle the hull forces and the interaction between hull and sail forces. We use CFD to accurately compute the flow past the sails and the aerodynamic forces on the rig.

The typical goal of sail-shape optimization is to produce a configuration that optimizes the velocity made good, VMG (VMG refers to how fast a boat is traveling towards a certain target) for a given apparent wind speed and direction (the apparent wind is the vector sum of the boat velocity and the wind velocity). In many respects, a sail resembles an airplane wing and similarly it generates a lifting force, $L$, perpendicular to the free stream flow, and a drag force, $D$, in the direction of the free stream flow. At different apparent wind angles the optimal force configuration will be different. The essential requirement of a sail is to generate a large driving force $C_x$ along the centerline of the boat. Except when sailing dead down wind, this is not possible without producing a heeling force $C_y$ perpendicular to the centerline at the same time. The heeling force must be balanced by the the hull and a side force produced by the underwater appendages. The stability of the hull and the efficiency of the underwater appendages therefore limit the driving power that can be extracted from the wind. The relation between lift and drag, and driving and heeling force is determined by the sail sheeting angle relative to the centerline of the boat. In upwind conditions a sail is set at small sheeting angles meaning that most of the lift produced is directed perpendicular to the centerline, producing a large heeling force and a small driving force. The optimization criterion is therefore generally to maximize the ratio of driving force to heeling force. When a boat turns away from the wind the sheets are eased, which results in the lift contributing more to the driving force and less to the heeling force. Because the hull now needs to balance a smaller heeling force, more lift can be tolerated. When sailing on a beam reach (apparent wind angle of 90 degrees) most of the force produced by the rig acts along the centerline and thus a high lift coefficient is needed. On downwind courses, the only criterion for sail efficiency is maximum drag of the rig.

At present most sail-shape optimization is performed using parametric studies where

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design variables such as camber, draft and twist are adjusted in a trial-and-error fashion to maximize a certain performance measure. The performance of a given sail configuration can be evaluated using full-scale testing, wind tunnel testing or numerical simulation. Full-scale testing is accurate, but expensive and time-consuming. Wind-tunnel measurements are also expensive and, in addition, it is difficult to scale real-world performance to model size. Computational Fluid Dynamics (CFD) has the potential to evaluate the performance of a given sail shape accurately. CFD calculations also provide a more detailed description of the flow field than either wind-tunnel testing and full-scale testing, and can therefore contribute to a better understanding of the optimization problem. CFD techniques have been successfully applied to shape-optimization problems in the aerospace industry for a number of years: see Reuther et al. (1996), Mohammadi & Pironneau (2001) and Kim et al. (2002). A major advantage of using CFD to evaluate the forces produced by a sail is that CFD solvers can be easily integrated with optimization procedures to automatically search for optimized sail shapes.

The goal of our current work is to explore the possibility of using automated optimization algorithms coupled to CFD for sail shape optimization: see Shankaran et al. (2002) and Doyle et al. (2002). There are two major categories of shape-optimization techniques; adjoint and iterative methods. Adjoint methods calculate the optimal shape via the solution of an adjoint problem obtained from the governing equations describing the fluid flow. This is effective because the cost of an adjoint solution is typically equivalent to that of the original problem and, most importantly, independent of the number of design variables (Kim et al. (2002)). The adjoint method has become a popular choice for design problems involving inviscid fluid flow, and has been successfully used for the aerodynamic design of aircraft configurations (Reuther et al. (1996)). The major difficulty in using this approach is the definition of the appropriate adjoint equations for viscous flows.

In this work we explore the use of iterative methods. We have chosen two approaches: a classical-gradient based cost-function minimization algorithm and an evolutionary strategy (ES). Both have been successfully applied to shape-optimization problems at the Center for Turbulence Research at Stanford. In the first approach, a cost function characteristic of the performance of the sail is minimized with respect to one or more control parameters. The iterative procedure requires the calculation of the derivatives of the cost function with respect to each of the control parameters at every iteration step. The second optimization approach uses evolutionary algorithms (EAs). EAs are biologically inspired optimization algorithms, imitating the process of natural evolution. EAs do not require gradient evaluations, but use a set of solutions (population) to find the optimal designs. The population-based search allows parallelization, and may avoid premature convergence to local minima. However, the population normally must be large, thus requiring many flow calculations.

Coupling optimization algorithms to CFD calculations requires the integration of various subsystems, such as the grid generation tool, the flow solver, and the optimization algorithm. Initially, we consider a simplified two-dimensional model to facilitate the development of the optimization procedure. We design the procedure so that it can be directly extended to the three-dimensional case. In addition, it is possible that the two-dimensional model will be able to guide the three-dimensional optimization. Once both models have been implemented we will compare the 2D optimization results to the 3D results to evaluate the need for the more expensive 3D calculations.
2. Optimization Approach

2.1. The problem

Because of the complexities involved in developing a general optimization method for sail shapes we start with a relatively simple application: we optimize the yard, camber and sheeting angles of the rig of a modern clipper ship, the Maltese Falcon (figure 1), for upwind performance in moderate winds. The boat has three masts constructed of yards with circular-arc cross-section. The Maltese Falcon will be 87 meters in overall length, with a mast height of 53 meters off the water and a maximum yard length of 22 meters. The rig is based on an original design by W. Proeells, which was further developed at Hamburg University in the early 1960’s (Wagner (1976)) and is currently being developed by designers from Gerard Dijkstra & Partners and Doyle Sailmakers (Dijkstra (2002)). Wind-tunnel data are available, and eventually real-world measurements will be produced. This will allow a direct assessment of the numerical code.

From a modeling point of view this rig is attractive because the flying shape of the sails will be very close to the shape of the yards. This is due to the construction of the rig, which consists of yards with sails stretched between them. Although the sails will slightly deflect in reality, it is believed that the deformation will not significantly influence the forces on the rig. In addition, the spanwise (vertical) variation of the sail cross section is very limited, and wind-tunnel tests conducted with a model of the rig showed streamlines (visualized using smoke) that were mainly two-dimensional except near the top and bottom of the rig.

2.2. Evolutionary strategies and gradient-based shape optimization

The general objective is the minimization of a properly-constructed cost function, $J$. The function is characteristic of the performance, and depends on a set of control variables, $\theta_i$. Two optimization algorithms are being developed: a classical gradient-based optimization algorithm and an Evolutionary Strategy.

2.2.1. Gradient-based optimization

The gradient-based optimization procedure requires the evaluation of the derivatives of the cost function with respect to the control parameters in each iteration step. A finite-difference formula is used to calculate the derivatives as:
These derivatives determine the direction of improvement. For the following iteration, a step is taken in this direction and the procedure is repeated until convergence (Mohammadi & Pironneau (2001)):

$$\theta_i^{\text{new}} = \theta_i^{\text{old}} - \gamma \frac{\partial J}{\partial \theta_i}$$

(2.2)

The weighting parameter $\gamma$ is used to weight the gradient information and changes with cost function and control variables.

It is important to note that during each iteration the number of flow calculations needed is equal to $1 + N$ where $N$ is the number of control variables. Present simulations include 6 control variables and an entire iteration only take a few minutes; three-dimensional simulations, or an increase in the number of control parameters, will make the current procedure computationally expensive.

In our studies, we determined an appropriate $\gamma$ by trial and error. A comprehensive sensitivity study will be performed in the future.

2.2.2. **Optimization using evolutionary strategies**

An evolutionary algorithm tries to mimic natural selection to determine the optimal shape. At each step random mutations (changes) to the control variables are attempted and only those solutions that are better than their predecessors are selected in a method that resembles the survival-of-the-fittest natural process. Again a cost function representing performance is defined to compare one solution to another. Our initial implementation is based on a very simple evolutionary strategy called a One + One ES (Sbalzarini et al. (2000)). In this scheme an initial solution is calculated $J_{\text{parent}}$; then each control variable is perturbed (using a random Gaussian distribution with standard deviation $\sigma$), and a new solution $J_{\text{child}}$ is evaluated. The new solution is compared with the old solution, and if $J_{\text{child}} < J_{\text{parent}}$ the child becomes the new parent for the next iteration. The standard deviation is adjusted using Rechenberg’s 1/5 rule: every $N * L$ iterations (where $N$ is again the number of control variables and $L$ is a constant) the standard deviation is increased (decreased) if the success rate is higher (lower) than 1/5. As the iterations proceed and the optimal solution is approached, the standard deviation continues to drop. In this work, we use $L = 10$. Again, further analysis is necessary to determine the optimal choice.

2.2.3. **Sail-shape optimization**

When applied to sail-shape optimization the control variables are the parameters that define the sail geometry and configuration with respect to the boat. In our case the relevant control parameters are the camber of the yards and the sheeting angle. Initially we will apply the optimization method to a 2D model of a horizontal cross-section of the rig (taken at mid-mast).

In this study we are interested in optimizing the upwind performance of the Maltese Falcon in moderate winds. As mentioned earlier, defining the cost function is a difficult task in upwind conditions. Ideally the cost function would be the VMG predicted with the use of a VPP, to take into account the hull/sail interaction. At present we do not have access to hull-performance data, so in order to develop our procedure we consider...
simplified cost functions. Possible simplified cost functions are driving force, ratio of
driving force to heeling force, lift produced or ratio of lift to drag.

Our simplified model has nine control parameters: the three sheeting angles ($\theta_i$, $i = 1,2,3$), the three cambers ($C_i$, $i = 1,2,3$), and the three chord lengths ($CH_i$, $i = 1,2,3$) as shown in Figure 2. The total force on the rig can be decomposed into lift ($C_l$) and
drag ($C_d$) or alternatively heeling force ($C_y$) and driving force ($C_x$). The other variables
in our two-dimensional model are the apparent wind direction and velocity. Initially we
consider the chords to be defined by the chord lengths approximately half way up the
mast taken from the profile of the original design, but eventually the chord lengths may
also be optimized. Because the chord lengths vary in the span-wise direction the spacing
between sections at different heights also changes. To date the effect of the spacing (the
distance between the 2D sections) has not been investigated but is believed to be an
important parameter, and will be the subject of further study.

2.2.4. Flow solution and grid generation

The flow past the sails is calculated using FLUENT 6.0. We use FLUENT’s incom-
pressible Reynolds Averaged Navier-Stokes (RANS) solver on non-conformal unstruc-
tured grids. In general, unstructured grids (as opposed to structured grids) are more
flexible in terms of being able to handle complex and dynamic geometry. Because of the
high Reynolds number of the sail flows (of the order of one million), turbulence modeling
is required. The turbulence model used in the present calculations is the Spalart-Allmaras
turbulence model, which is sufficiently accurate for upwind and close-reaching conditions,
and also computationally efficient (Collie et al. (2001)). More-sophisticated turbulence
models must be used for larger angles of incidence, because of flow separation.

In order to couple FLUENT with our optimization procedure it is necessary to auto-
mate the solution process. The automation is accomplished using FLUENT’s scripting
capability. A central program serves as the interface between the flow solution and the
optimization algorithms. The flow-solution interface takes as input the sheeting angles,
cambers and chord lengths of each of the sections, together with a description of where
each section is placed relative to the center of each mast. A grid is automatically created
from the input geometry and then the flow solution is calculated. The entire process takes
around 1 minute to produce a solution on a computer with an Athlon 1.2 GHz processor
using a relatively coarse grid of around 7500 elements. Figure 3 shows a system diagram of the automated solution procedure.

The most challenging aspect of automating the flow solution procedure is the robust and efficient generation of grids to discretize the domain of interest. Here, ‘robust’ refers to the ability to successfully generate meshes for any possible value of the control parameters. The mesh generation is efficient if it clusters grid points in areas where large gradients of flow variables are expected (such as in the boundary layers) so that a minimal number of grid elements is required to obtain accurate predictions.

The grid-generation process starts with defining the three sectional shapes. Once the sections have been defined, the region immediately surrounding the sail is clustered densely with grid points in order to properly resolve the boundary layer. Because the gradients are smaller in the streamwise direction than the direction normal to the sail surface (‘wall-normal direction’), we use quadrilateral elements with large aspect ratio. The Spalart-Allmaras turbulence model requires the distance between the first grid point away from the wall to be placed at a non-dimensional distance, known as $y^+$, on the order of 1. After meshing the region immediately adjacent to the sail, the remaining domain is discretized using triangular elements. The use of non-conformal grids allows a mismatch between the grid points on the boundary of the inner and outer regions. FLUENT uses interpolation to communicate the flow variables from the inner to outer regions.

Triangular elements are used because the algorithm used by FLUENT’s grid generator Gambit to produce triangular elements is robust, and can handle the varying geometry created by adjusting the camber and sheeting angle of the sections. Quadrilateral elements require fewer elements to discretize the same volume but the current algorithm available in Gambit is not reliable in handling this geometry. We extended the far-field
region to roughly 20 chord lengths in all directions, and discretized it with quadrilateral elements. The entire process is shown in figure 4.

3. Results

Initial tests were performed on isolated circular arc cross sections to verify our numerical solution method and to gain a better understanding of the aerodynamic properties of such foils. The results were compared to classical theoretical studies. In this section we will focus on two optimization studies.

3.1. Sheeting-angle optimization

The first step in developing an automated sail-shape optimization procedure is to ensure that, for a given apparent wind angle, the sails are set in the optimal configuration. This is straightforward for a single section. Once lift and drag are determined as functions of the angle of attack, the sheeting angle can be set to produce an incidence that optimizes the performance for the given apparent wind direction. With three interacting sections, however, the flow field is dependent on all three sheeting angles and it is not possible to set the optimal sheeting angles \textit{a priori}.

Initially, we consider two simple cost functions \( J_1 \) (max \( C_x \)) and \( J_2 \) (max \( C_x/C_y \)): \( J_1 \) and \( J_2 \) are reasonable choices in upwind and downwind conditions respectively. Optimization runs are performed for both cost functions for apparent wind angles ranging from 30 to 90 degrees. Both optimization strategies were used and lead to identical results with comparable runtime. We present results for apparent wind angles of 30, 60 and 80 degrees in table 1 and figure 5. Table 1 displays the driving force and heeling force coefficients for each apparent wind angle for both cost functions. The optimal sheeting angles are also given. Figure 5 shows plots of static pressure around the sail as well as the pressure distribution on each section.

For all apparent wind angles tested, the cost function \( J_2 \) results in more open (larger
Table 1: Force coefficients and sheeting angles for the optimal sail configuration (the number in parentheses corresponds to the apparent wind angle).

<table>
<thead>
<tr>
<th>Cost Function</th>
<th>Force Coefficient</th>
<th>Sheetling Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driving ($C_d$)</td>
<td>Healing ($C_h$)</td>
</tr>
<tr>
<td>$J_1(30)$</td>
<td>0.9304</td>
<td>1.9038</td>
</tr>
<tr>
<td>$J_2(30)$</td>
<td>0.7988</td>
<td>1.4754</td>
</tr>
<tr>
<td>$J_1(60)$</td>
<td>1.4943</td>
<td>1.0116</td>
</tr>
<tr>
<td>$J_2(60)$</td>
<td>1.1327</td>
<td>0.6888</td>
</tr>
<tr>
<td>$J_1(90)$</td>
<td>1.6193</td>
<td>0.3893</td>
</tr>
<tr>
<td>$J_2(90)$</td>
<td>1.2571</td>
<td>0.2499</td>
</tr>
</tbody>
</table>

Figure 6. Telltales, imagined to be on the leading edge of the aft sail, are shown to lift for the optimal condition predicted using the cost function $J_1$, indicating an over-trimmed sail. They stream back for the configuration corresponding to the $J_2$ optimum, indicating a properly-trimmed sail.

3.2. Sheetling angle and camber optimization

Initial camber-optimization runs have been performed to investigate the influence of section camber on rig performance. All runs started with sections of 12% camber and the optimal sheeting angles presented in the previous section. In these runs six control parameters are considered: the sheeting angles and the section camber. A summary of the results is presented in table 2. Results are presented only for maximizing the driving force, as problems with convergence of the CFD code prevented conclusive results for optimizing the ratio of driving force to heeling force from being obtained.

Streamlines are shown in figure 7 for the optimal configurations calculated for maximum driving force. The cambers selected to optimize the driving force are seen to be...
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Figure 7. Streamlines for maximum driving force for three apparent wind angles: (a) 30 degrees, (b) 60 degrees and (c) 90 degrees.

<table>
<thead>
<tr>
<th>Cost Function</th>
<th>Force Coefficient</th>
<th>Sheeting Angle</th>
<th>Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driving ($C_x$)</td>
<td>Aft ($θ_1$)</td>
<td>Mid ($θ_2$)</td>
</tr>
<tr>
<td>$J_1(30)$</td>
<td>1.14</td>
<td>-0.5</td>
<td>-15.3</td>
</tr>
<tr>
<td>$J_1(60)$</td>
<td>1.96</td>
<td>-42.0</td>
<td>-48.6</td>
</tr>
<tr>
<td>$J_1(90)$</td>
<td>2.39</td>
<td>-68.2</td>
<td>-71.9</td>
</tr>
</tbody>
</table>

Table 2: Table 2: Force coefficients, sheeting angles and cambers for the optimal sail configuration (the number in parenthesis corresponds to the apparent wind angle).

greater than the original 12% sections in all cases. For apparent wind angles of 60 degrees and 80 degrees maximizing the driving force can be considered a reasonable cost function but for an apparent wind angle of 30 degrees the heeling force needs to be accounted for. The results for maximizing driving force at 30 degrees are presented as a reference with which to compare the results found in the previous subsection for optimizing the driving force at 30 degrees with only the sheeting angles as control parameters. It is interesting that the optimal sheeting angles are essentially the same as the ones presented before even if the cambers are consistently higher than 12%. Finally, it is interesting to mention that the increase in the performance (as measured by the cost function $J_1$) ranges from 18% to 32%.

4. Discussion and future work

A CFD-based optimization procedure for sail configuration has been developed and applied to two-dimensional sections of a three-mast clipper ship, the Maltese Falcon.

Optimization runs were conducted using both the gradient-based optimization technique and a scheme based on evolutionary strategies. Both methods converge to the same solution in about the same amount of time, but further studies are required to optimize their performance. The major burden in the gradient-based methods is the calculation of the derivative of the cost functions with respect to the parameters. It is possible that an approximate evaluation of the gradients would be sufficient to drive the optimization process (Mohammadi & Pironneau (2001)).
The value of the parameter $\gamma$ greatly influences the convergence rate of the gradient-based algorithm. The value we used in this work was found by trial and error. A more thorough sensitivity analysis is required. Within the One + One ES the selection of the initial standard deviation and the constant $L$ should also be investigated. In addition, the One + One ES is the simplest possible ES and there are other strategies that use larger sets of populations to arrive at the optimal configuration.

In this paper we presented the design of our optimization method, and the development of the basic optimization tools. We are currently working on:

- Further validation of the various components of the two-dimensional optimization strategy;
- Development of more realistic cost functions that account for hull forces (and the global force balance) using experimental correlations;
- Refinement of the CFD model to reflect more accurately the aerodynamic characteristics of the rig (three-dimensional effects).

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REFERENCES


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