Lift Optimization of Airfoils using the Adjoint Approach

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Introduction

Optimization of aerodynamic profiles is often done using methods based on coupling potential flow theory and boundary layer corrections [1, 2, 3, 4]. In order to have a higher accuracy in the prediction of loads, computational fluid dynamics (CFD) are used in this work, based on the Reynolds-Averaged Navier-Stokes equations (RANS). CFD simulations are computationally more expensive than other methods and thus a cheap optimization method is needed. In this context, a gradient-based optimization using the adjoint approach is often used [5, 6], because the adjoint method is independent from the number of design parameters. For the computation of the flow field, the open-source library OpenFOAM [7] is used and extended by the authors. The focus of this work is to show a proof of concept of the optimization method and its future potential.

Approach

In this work the adjoint approach is used for a gradient-based optimization using steepest-descent. It is a simple optimization technique considered to be more suitable for a high number of design parameters, because it is not necessary to compute or approximate second order derivatives. The adjoint method in CFD has been widely used in aeronautics [5, 6], but to the authors knowledge it is not commonly used for wind energy applications.
To test the efficiency of the adjoint approach, a simple test case is set up with a NACA 0012 in laminar flow at low Reynolds number $Re=50$ and at zero angle of attack $\alpha=0°$. The objective I is to reach an aimed lift coefficient c_l of the airfoil, following a least-squares approach:

$$I = ½\cdot(c_l - c_{l,0})^2,$$

where the index 0 is used to indicate the aim lift coefficient. For comparison, the shape of the test case is optimized by two different methods:
1.) Using the above described method, which is a steepest-descent gradient-based optimization using the adjoint approach.
2.) Using a differential evolution implemented in a package of the SciPy module of the programming language Python [8].
The airfoil itself is parametrized by four Bézier curves: Two for the suction, two for the pressure side, each going from the leading edge to the point of maximum thickness or, respectively, from there to the trailing edge. Due to a fixed leading and trailing edge and some limitations of the point motion similar as in [1] this yields to 14 independent design parameters. Although the Bézier curves do not exactly represent the shape of a NACA 0012, they deliver a good approximation.
A detailed view of the resulting shapes of both approaches for a lift coefficient aimed at $c_{l,0} =0.01$ is shown in figure 1 and a clear difference can be seen in the shapes. Where the first approach deforms mostly the leading edge, the second approach increase mainly the thickness. The drag is stronger increased using the differential evolution. Still, both approaches fulfil the requirements of the objective function as both shapes have a lift coefficient of $c_{l,0} =0.01$ and drag is not mentioned in the objective. Comparing the computational effort, the differential evolution needs more than 1,500,000 CFD iterations, whereas the adjoint approach in combination with steepest-descent needs approx. 85,000 CFD iterations only.

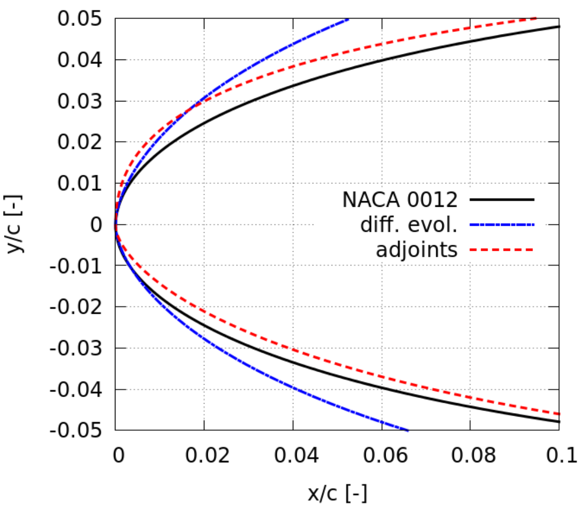

Figure 1

The speed of both approaches may be improved by a better calibration of the optimization parameters, such as number of iterations, step size, convergence rate or the population size in case of differential evolution. However, optimization using the adjoint method will be much faster than evolutionary algorithms in cases which have many design parameters and are expected to be close to a local optimum. This is why in the further work only optimization with the adjoint approach is used.

Main body of abstract

In order to show a proof of principle for a more realistic airfoil geometry, the NACA 63-415 is simulated and compared against experiments [9]. A structured, hexahedral O-mesh is generated, where the boundary layer is resolved (dimensionless wall distance $y^+ < 1$) and due to a higher Reynolds number of $Re = 1{,}600{,}000$ turbulence is modelled using the k-ω-SST model. The angle of attack is at $\alpha = 8°$ and the difference to the experimental lift coefficient is approx. *0.5 %*, whereas the drag coefficient differs in *5 %*. Although different settings or turbulence models could improve the results, the focus in this work does not lay on validation, but on optimization.
Instead of Bézier curves, the NACA 63-415 is parametrized using a spline via 60 design points, resulting into 120 individual design parameters due to a movement into x- and y-direction. By this way of parametrization, it is possible to have much more degrees of freedom compared to the Bézier curves of the previous test case. This can also result into completely new shapes, which might not be found using only few parameters.

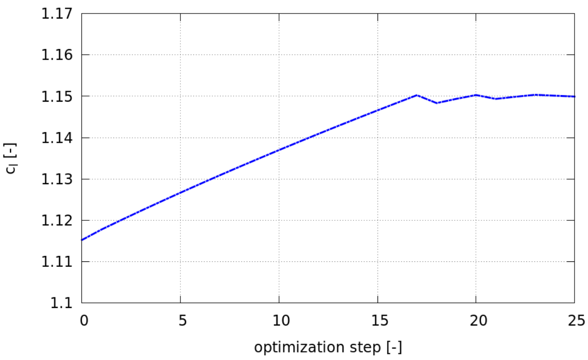

Figure 2

Figure 2 shows the lift coefficient plotted over the optimization steps of the airfoil, where the initial lift is at $c_l = 1.115$. The objective function is defined as in the previous section with a lift aiming at $c_{l,0} = 1.15$, which leads to an improvement of approx. 3 %. This seems to be a rather small increase, but the authors interest in this work is the proof of principle and a much higher goal lift could require a finer mesh or a coarser parametrization. The optimization needs 25 iterations and for the computation in total approx. 100,000 CFD iterations are needed, which takes about 4 hours on 2 CPUs used for this work.

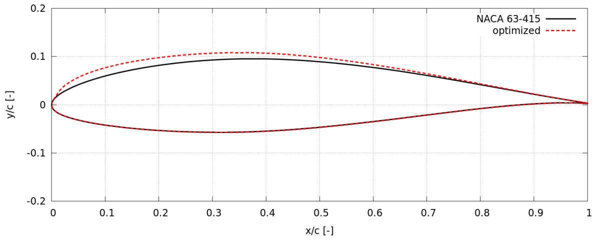

Figure 3

The resulting shape is shown in figure 3 and the lift increase is mostly realized by an increase in the thickness on the suction side, around the position where the suction peak occurs. This changes the maximum thickness, but as it is an unconstrained optimization, the objective is fulfilled. A thickness-constraint is in the current phase of development, because of its high importance for any future industrial application, but the principle of the optimization using the adjoint approach is proofed.

Conclusion

It was shown that a gradient-based optimization using the adjoint approach can be much faster than an optimization using evolutionary strategies. In case of accurate load predictions by CFD, which are computationally expensive, it is very important to use a fast optimization technique. An initial comparison of the methods was done for a simple test case and it was shown that the resulting shape depends not only on the parametrization, but also on the used algorithm. For the shown case, the drag increase was smaller when using the adjoint approach.
More realistic conditions were used for a NACA 63-415, which was parametrized by a spline using 120 design parameters. Such an amount of design parameters can lead to shapes, which may not be discovered by simpler parametrizations such as a few Bézier curves. It was shown that the aimed lift coefficient could be reached and although the maximum thickness was increased, the concept was proofed as the thickness was not included in the objectives.
However, it is possible to include thickness-constraints in the optimization. And a further inclusion of drag into the objectives will reduce the necessity for those constraints and lead to an improvement of the aerodynamic efficiency, which might be a major design goal for wind turbines. This is under current development as well as a multi-point optimization for a range of angle of attacks. By these future developments, the adjoint approach will become a powerful tool for airfoil optimization using

a high fidelity load prediction.

Learning objectives

A lift optimization of airfoils is done using computational fluid dynamics (CFD), where an optimization using the adjoint approach is compared with differential evolution. The efficiency of the adjoint method is much higher and the approach is used for a realistic airfoil. It is represented by a spline with 120 individual design parameters and this can lead to completely new shapes, which cannot be discovered by simpler parametrizations.

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