Mitteilung

Fachgruppe: Multidisziplinäre Optimierung

Adjoint-based aerodynamic shape optimization with free laminar-turbulent transition

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Introduction:
Aerodynamic shape optimization plays a critical role in aircraft design in order to achieve the desired operational performance. In this context, adjoint methods are already a common practice to efficiently compute the gradients of the predefined figure of merit, subjected to geometrical and physical constraints, that indicate the direction of the required shape modification to attain the optimal design. Laminar-turbulent transition is usually neglected during these processes to avoid the complications of adding the external modules that are usually needed to compute the transition prediction. However, the increased demand for cost-efficient aircraft designs and the growing awareness for global warming effects have shifted the attention towards natural laminar flow (NLF) aircraft designs [1], where transition becomes relevant. Optimization processes based on fully turbulent solvers may lead to very underoptimized NLF configurations. In addition, transition may also have a noteworthy impact on configurations with shock or flow separation, where its location affects the strength and location of both flow phenomena. The current availability of transition transport models (TTM) for predicting transition without the need of external modules, could enable considering this effect also in inverse design processes. Therefore, the design capabilities of the discrete adjoint solver of the DLR TAU code was extended to account for free transition effects by integrating the DLR γ TTM which was successfully coupled to the negative S-A turbulence model in [2].

Numerical Method:
The optimization problem consists in finding the design variables that minimize the figure of merit. This is,

$$\min_D I(W, X, D)$$

under the constraint

$$R(W, X, D) = 0,$$

where *I* is the cost function such as lift (L) or drag (D), *W* is the vector of flow variables, *X* is the mesh node coordinates, *D* is the vector of design variables, and *R* is the discretization of the flow governing equations. Since $R(W, X, D)$ and its derivative with respect to D are zero for all D, the derivative dI/dD, which indicate the minimization direction, can be found from the derivative of the Lagrangian, dL/dD, where

$$L = I + \Lambda^T R.$$

The adjoint vector Λ^T is computed by the adjoint solver by solving the linear adjoint equation,

$$\left(\frac{\partial R}{\partial W}\right)^T \Lambda = -\left(\frac{\partial I}{\partial W}\right)^T.$$

To consider free transition predicted by the DLR γ TTM coupled to the negative S-A turbulence model, the flow variables vector is extended to include the transition controlling variable γ, $W = [\rho\ u\ v\ w\ p\ \tilde{\nu}\ \gamma]^T$, and the same for *R* to include its transport equation R^γ, $R = \left[R^\rho\ R^u\ R^v\ R^w\ R^p\ R^{\tilde{\nu}}\ R^\gamma\right]^T$, where $R^{\tilde{\nu}}$ was also corrected according to the modifications of the coupling strategy. For further details on the implementation of the adjoint method and the DLR γ TTM the authors refer to [2,3].

Results:

The first validation results of the implementation of the DLR γ TTM into the adjoint solver of the DLR TAU code for shape design considering free transition was performed on the RAE2822 airfoil at M = 0.72, $Re_c = 23 \cdot 10^6$, and Tu = 0.1%. Three design points, based on the lift coefficient ($C_L = 0.27$, $C_L = 0.98$, $C_L = 0.33$), were arbitrarily selected for the optimization. The optimization meant to minimize drag at constant lift by minimizing *I* = *-L/D*, while C_L is kept constant throughout the optimization process by adjusting the angle of attack, then $\alpha = \alpha(D)$. The shape parametrization is performed by a Hicks-Henne function with 9 design points on the upper and the lower surface of the airfoil, and the geometry volume reduction was constrained to avoid an excessive reduction of the airfoil thickness during the optimization. The optimization was performed for each design point independently and for a multi-point design by applying a weighted sum of the three design points. Figure 1 shows that the outcomes of the optimization processes result in configurations that actually improved their performance in accordance to the design conditions. The single-point optimized geometries return the larger reduction in drag at their design condition, although their performance may worsen for the off-design points (e.g. Opt. pt. 3 at the design points 1 and 2). On the other hand, the multi-point optimized geometry produces an overall better performance at expense of a slightly reduction of the drag drop compared to the single point design at the specific design points. In the final paper, it will be presented a full description of the optimization processes and mechanisms, as well as a detailed investigation of the benefits of considering transition during the optimization.

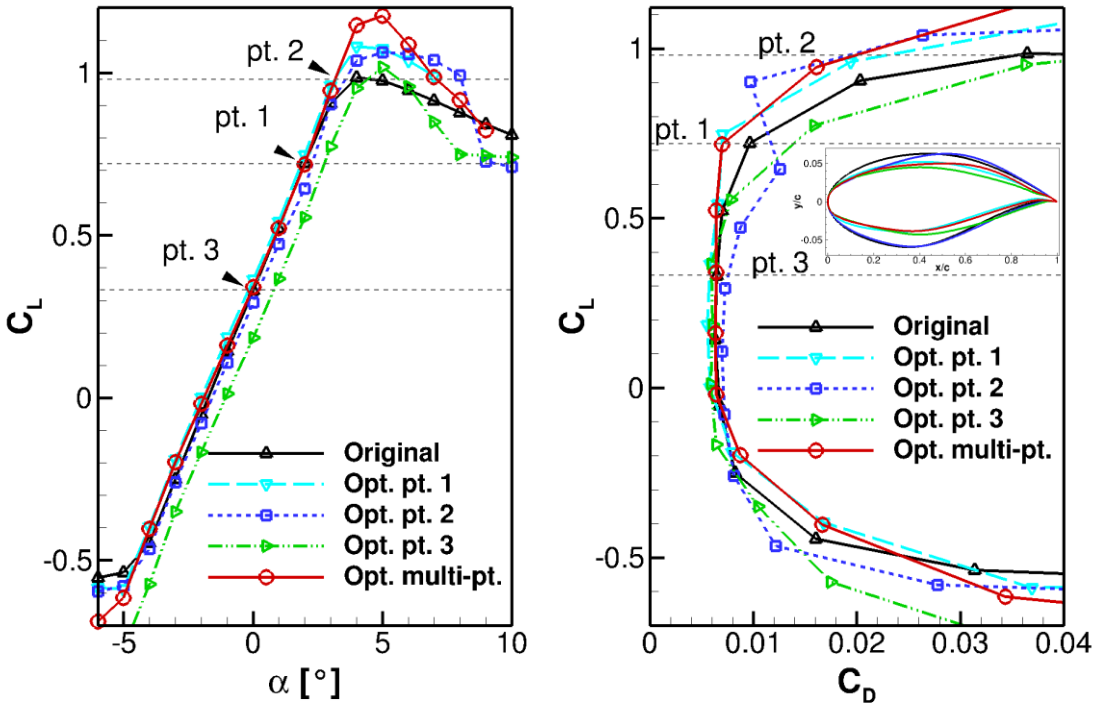

Figure 1: Comparison of Aerodynamic polars between the initial geometry (original), the single point optimized geometries (Opt. pt. 1,2, and 3), and the multi-point optimized geometry (Opt. multi-pt.).

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