Aerodynamic Optimization of the TurboLab Stator: A Comparative Study between Conventional and Adjoint-based Approaches

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The goal of this work is to develop a CAD-based aerodynamic optimization workflow for the application on the TurboLab Stator benchmark. Two different approaches are examined and compared: (i) A conventional gradient-free optimization procedure which makes use of 2D and 3D CFD results and constructs a response surface to obtain the optimum solution and (ii) an adjoint gradient-based optimization process, where the adjoint derivatives w.r.t. the design parameters are calculated by linking the adjoint surface sensitivity map with the model's design parameter sensitivities. The latter are computed using finite-differences between discrete representations of the CAD geometries. Both methods are applied to the turbomachinery test case, where two objective functions and three operating points are considered. Moreover, manufacturing constraints have to be incorporated in the process chain, which makes the case even more challenging. Since the optimization output is already in CAD format, there is no requirement for a back-to-CAD step and the optimum blade can be straightforwardly manufactured.

I. Introduction

For turbomachinery design, adjoint-driven CFD design offers an efficient approach to improve the aerodynamic performance of the engine gas path and its containing components, like rotor and stator blades [1]. Especially for high ratios between number of design parameters such as blade chord length or blade's thicknesses and number of aerodynamic design criteria such as efficiency, surge margin or capacity, adjoint-based numerical optimization shows clear benefits against classical search strategies in terms of computational effort. This has been demonstrated by a number of publications, such as Ref. 2-4. However, large challenges related to the industrial applicability of adjoint-based methods are not sufficiently resolved yet.

Especially for a CAD-centric approach it is of great importance to have universal and robust methods in place to link the adjoint-based CFD results directly to existing and approved design parameterizations [5,6]. This enables both error-free mapping of the adjoint gradient results to CAD and fast and explicit assessment of design parameter sensitivities by the design engineers. Furthermore, the adjoint method has to be robust and stable for realistic flow characteristics, such as flow separation or instabilities in wakes and vortices [7].

For these reasons, this paper summarizes activities which have been conducted in an industrial environment for the third test case from the "About Flow Adjoint Optimization Benchmark". Aim of the test case is to optimize the 3D shape of the TurboLab Stator from the Technical University of Berlin with respect to aerodynamic criteria. Specifically, the TurboLab Stator is a compressor stator in a one row rig with subsonic flow but high degree of turning [8].

II. TurboLab Stator Optimization

To perform optimization in an automated manner, a proper design parameterization is required. In general, different design parameterizations exist for a compressor blade. However, for the present investigation the approved and powerful classical aerofoil build-up in conjunction with a 3D profile stacking approach is used [9]. More specifically, this parameterization utilizes a non-dimensional camber-line angle distribution, from which

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the camber line is derived, and a non-dimensional thickness distribution. The 2D profile contour for different radial blade heights is obtained by adding thickness values perpendicular to the camber line. A 3D blade shape is generated by a proper stacking definition using axial and circumferential shifts along a defined line in the radial direction [10].

An automated process has been developed and validated to (i) compute the adjoint derivatives w.r.t. each design parameter which is part of the classical aerofoil build-up and (ii) perform gradient-based optimization according to the test case description. In parallel to this purely adjoint-based shape optimization, a conventional direct optimization has been performed, followed by another adjoint-based optimization which uses as a starting point the optimized blade from the conventional search. The results of the three different strategies are compared regarding the aerodynamic performance and required computational cost.

The conventional direct optimization procedure consists of two main steps. Firstly, extensive purely aerodynamic 2D section optimizations are performed for different radial blade heights, where Mises [11] is used to predict the blade-to-blade flow characteristics. Subsequent to this, an optimal stacking line is determined using 3D CFD and emulation-based optimization, where the Rolls-Royce in-house solver HYDRA [12] is used to predict the 3D flow.

III. Results

Preliminary results of the classical 2D-based optimization clearly show performance improvements compared to the reference design, Fig. 1. Especially the turning requirement has been improved by a huge amount. For the adjoint-based optimization, all required derivatives w.r.t. the 176 design parameters have been computed and validated against finite differences for the baseline design. Fig. 2 compares the adjoint sensitivity maps for the baseline, a preliminary unstacked 2D-optimized blade and a preliminary adjoint-based blade after the first optimization step.

From the stacking point of view, the manufacturing constraints from the test case need to be considered carefully. During preliminary studies, it turned out that the blade fixture holes break the blade surface even for small sweep and lean stacking definitions in the vicinity of the hub and tip regions. Therefore, an automated process has been implemented to maximize the stacking parameter bounds before the actual optimization. Using this approach, the aforementioned manufacturing constraint can be guaranteed a priori.

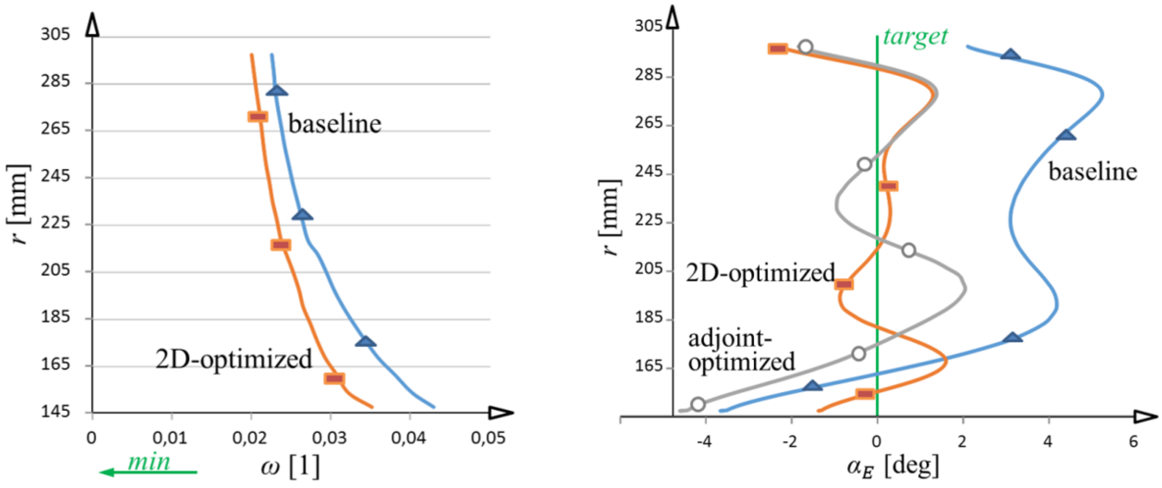

Figure 1: Mises-based 2D CFD losses for baseline and 2D-optimized blade (left) and circumferentially averaged Hydra-based 3D CFD exit whirl angles for baseline, unstacked 2D-optimized blade and preliminary adjoint-optimized blade (right)

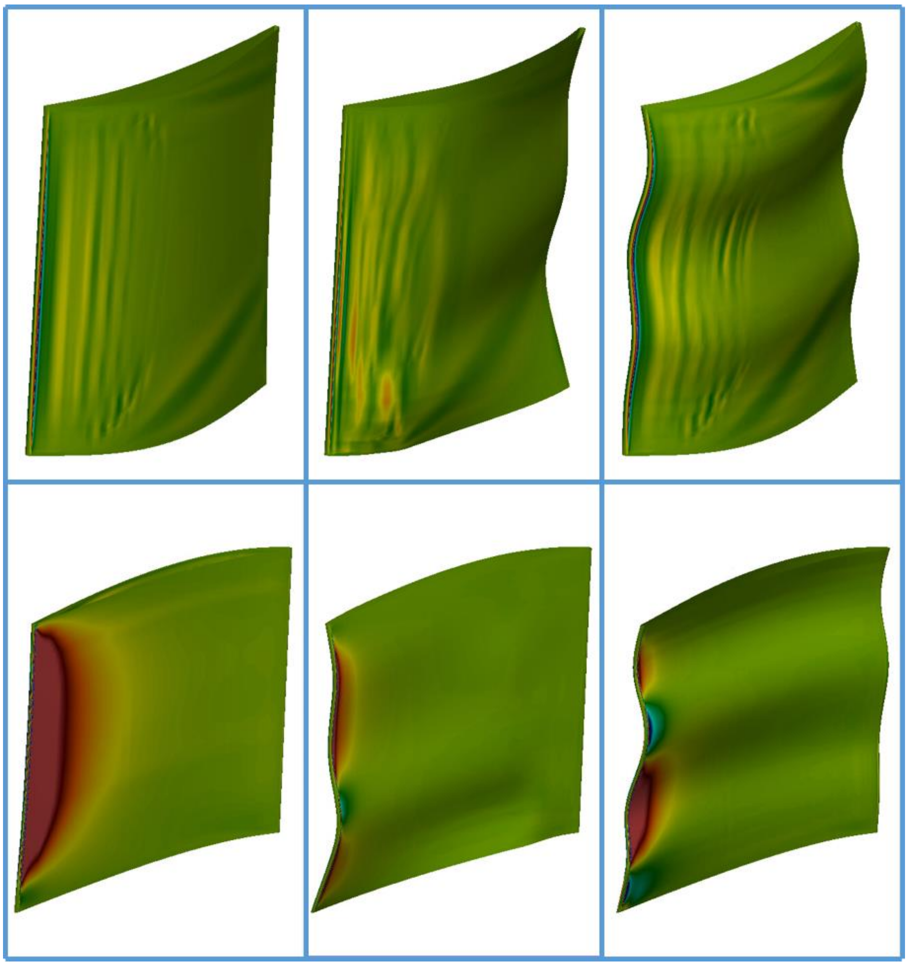

Figure 2: Adjoint sensitivity maps for baseline design (left), 2D-optimum design (middle) and 1st adjoint-based design (right) w.r.t. pressure loss objective (top) and whirl angle objective (bottom)

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