Aerodynamic Shape Optimization with the Adjoint Method

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Abstract

The biggest cost for airlines is due to fuel consumption. Therefore, it is of the interest of airlines that fuel consumption be minimized. This task is done by aircraft manufacturers, including Airbus, for example, by reducing drag. Currently, this work is done by experienced engineers with years of experience, making use of their extensive knowledge in aircraft aerodynamics. Nevertheless, this work is done manually and by trial and error, which becomes particularly challenging for complex shapes and complex aerodynamics. The subject of automatic aerodynamic optimization responds to this problem. It is a recent subject and promises good results where human insight fails. Namely, aerodynamic shape optimization with the adjoint method offers many advantages with respect to other techniques. This technique, in conjunction with others will be studied and applied to the optimization of a transonic airfoil and of a winglet for a long range airplane of Airbus.
Keywords: aerodynamic optimization, adjoint method, airfoil shape, winglet

1. Introduction

In 2014, the airline industry was estimated to spend 212 billion (US) dollars in jet fuel, corresponding to 29.7% of the total operating costs [1]. In order to better respond to the highly competitive air transport industry, airlines look for the best fuel efficient aircraft. Furthermore, as fuel consumption is reduced, carbon emissions are also reduced, which is essential to comply with new environmental regulations. Fuel consumption reduction can be achieved by drag reduction. As an example, a reduction of 1% in total drag corresponds to about 900kg of fuel savings for a 11000km flight. To reduce drag, aircraft components such as: lifting surfaces, pylon, nacelles, fuselage, etc. are aerodynamically optimized. Currently, this work is done by experienced engineers who make use of their extensive knowledge in aircraft aerodynamics. However, this is done by trial and error, which becomes challenging for complex shapes. Due to its reduced need of human insight, a solution is the use of a fully automatic aerodynamic optimization chain.

2. Background

Automatic aerodynamic optimization means that the user doesn't interact with the optimization process. He is responsible for setting up the design space and optimization and CFD parameters, but the whole optimization is carried out automatically. The optimizer evaluates many designs, attempting to minimize a given objective function. The way these designs are generated highly depends on the chosen algorithm(s) and even the same algorithm may produce different results, depending on how aerodynamic and optimization information, such as lift, drag or their gradients, are computed. Since these metrics are obtained with a CFD solver, which has a high computational cost, the selection of the optimization optimization strategy is of crucial importance to keep a low turnaround time. A class of algorithms that are commonly used when dealing with many parameters are gradient-based algorithms [2]. These determine the successive designs based on the gradient of the objective function with respect to the design variables. Yet, conventional methods of gradient computation such as finite differences are usually computationally expensive, since they require many CFD evaluations. Moreover, they present issues such as the value step size. The adjoint method presents itself as an answer to this problem, having several advantages over such conventional gradient computation methods [3, 4, 5, 6]. An optimization of a transonic airfoil and of a long range aircraft winglet with a gradient-based algorithm, aided by the adjoint method for gradient computation are studied.

3. Work Outline

This work is divided into four parts:

- Aerodynamic Shape Optimization Theory
- Analysis and Optimization Tools at Airbus

- 2D optimization: RAE2822 transonic airfoil
- 3D optimization: LR aircraft winglet redesign

In the first part, a detailed analysis on the theory of aerodynamic shape optimization is given. The second part presents and explains each individual tool of the optimization toolchain. The third part deals with a two-dimensional optimization problem, which also serves as a first example of a complete optimization process. Finally, the fourth part is dedicated to a three-dimensional real case of the winglet of a long range aircraft designed by Airbus.

4. Results

We start with the two-dimensional case of the RAE2822 transonic airfoil. This study begins with the definition of the optimization problem. It is argued that it is of interest to optimize $\frac{C_{lp}}{C_d}$ at its maximum value, since this is the point at which aircraft usually fly (cruise). For the baseline design, this occurs at $C_{lp} = 0.63$. An unconstrained optimization was run to solve this problem, which resulted in a significant improvement of 4.95% in $\frac{C_{lp}}{C_d}$. However, the optimization design presented an undesired global behavior, since it shifted the maximum of $\frac{C_{lp}}{C_d}$ to a higher value of C_{lp}. Attempts to fix this issue were previously tried at Airbus. In this work, a new strategy was developed by adding a constraint to the optimization problem $\frac{d}{dC_{lp}}\frac{C_{lp}}{C_d} = 0$. This constrained optimization improved the objective function by 3.60%, slightly worst than the unconstrained optimization. Nevertheless, as desired, it kept the maximum of $\frac{C_{lp}}{C_d}$ at the baseline's maximum location of $C_{lp} = 0.63$. Finally, it was shown that the location of the maximum of $\frac{C_{lp}}{C_d}$ could willingly be changed to a desired value of $C_{lp} = C^*_{lp} < 0.63$ at the expense $\frac{C_{lp}}{C_d}$, a behavior which hadn't been previously studied at Airbus. Based on the knowledge acquired from the 2D case, focus was shifted to the 3D case. There is an increase of complexity in shape and aerodynamics, especially highlighted by the difficulty of predicting the performance behavior with respect to the design variables, apart from particular cases. In order to address this problem, the DOE technique was introduced and executed. It rendered possible an analysis of sensitivity and dependency. This analysis allowed the determination of design variables that don't have correlation with any of the outputs and supplied a ranking of the remaining variables according to their individual importance with respect to the objective function and constraint. Multiple strategies were employed, all resulting in very close final values, demonstrating the effectiveness of the adjoint optimization alone as a sufficient optimization process against hybrid strategies. Finally, a strategy where the DOE modifies the planform, while the adjoint optimization modifies the twist and camber parameters only, was employed. This strategy didn't produce the best design, although it did generate designs whose performances are close to that of the previous optimized designs.

5. Conclusions

All objectives set at the beginning, as well as along the internship were achieved to great extent. Regarding the RAE2822 case, the shifting behavior of adaptation C_{lp} of the unconstrained optimization was previously known. However, the attempt at solving this issue by adding an equality constraint hadn't previously been tried nor studied at Airbus. Moreover, the study on changing the adaptation C_{lp} of an airfoil is also new. The winglet case demonstrated the robustness and flexibility of the optimization chain by allowing multiple strategies to be employed. Furthermore, a sensitivity and dependency analysis was realized for the first time at Airbus within the framework of aerodynamic optimization. Aerodynamic optimization methods, within an industrial framework such as Airbus, were employed with success to the optimization of real-life cases. Moreover, results which are not trivial were found and important conclusions drawn upon.

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