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A new efficient technology of aerodynamic design based on CFD driven optimization

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Abstract

This paper describes a new technology of aerodynamic design based on CFD driven constrained optimization to minimum drag. Within an aircraft development project we focus on the aerodynamic design of wings and show how the design process has been advanced with the new capabilities achieved through the use of the recently developed in-house optimization tool OPTIMAS. The optimization method of the present work is based on the use of Genetic Algorithms and accurate full Navier–Stokes drag prediction. The results include a variety of optimization cases for aerodynamic design of transport-type aircrafts.

Keywords: Aerodynamic design; Constrained optimization; Genetic algorithms; High-performance computing; Navier–Stokes computations

1. Introduction

The process of aerodynamic design has been based on the following primary tools: wind tunnel, flight test and computational flow simulation. Due to the tremendous cost involved, the development through the wind tunnel and (especially) flight tests must be minimized. Since CFD provides an ability to rapidly and cheaply carry out aerodynamic simulations, it is preferable (from the cost reduction viewpoint) to increase its relative contribution to the overall design.

CFD, by its nature, can provide detailed information everywhere in the flowfield, but its applicability is, of course, limited by the accuracy which depends on the assumptions of mathematical model, numerical algorithm and computer resources.

Alongside with the improvement in CFD accuracy, its contribution to the aerodynamic design steadily grows. In fact, the past three decades brought a revolution in the entire process of aerodynamic design due to the increasing role of computational simulation.

The first attempts to introduce optimization tools to aerodynamic design are associated with Lighthill [5]. More complicated CFD driven optimization methods appeared over the years [1–4,7]. However, prior to the last few years, these methods had a very limited impact on the design practice especially in the case of 3D aerodynamic shapes.

The reason why the optimization tools are still not being exploited as one would like in the design process is partially due to the following three reasons. First, only recently computational simulation has been allowed for relatively accurate drag prediction. Second, the industrial optimization of aerodynamic shapes necessitates high-dimensional search spaces, and a large number of non-linear constraints are placed upon a desired optimum.

Last but not least, the huge computational volume needed for optimization (and the corresponding huge computational resources) presents a major obstacle to the incorporation of CFD based optimization into the core of the industrial aerodynamic design.

The aircraft design process is generally divided into three stages: conceptual design, preliminary design, and final detailed design (see [14] for the resources required). In the development of commercial aircraft, aerodynamic design plays a leading role during the preliminary design stage where the external aerodynamic shape is typically finalized. This phase is estimated by a cost of 60–120 million dollars [3]. The final design would

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be normally carried out only upon the commercially promising completion of the preliminary stage which makes the preliminary design stage crucial for the overall success of the project.

Due to the importance of this stage (where, according to [3], a staff of 100–300 people is generally employed for up to 2 years) let us go into detail. The aerodynamic design process is embedded in the overall preliminary design with the starting point coming from the conceptual design. The inner loop of aerodynamic analysis is included into an outer (multidisciplinary) loop which is a part of a major design cycle. Due to the limitations of the overall design technology, this cycle is usually repeated a number of times. For example, in recent Boeing practice, three major design cycles, each requiring 4–6 months, have been used to finalize the wing design [3]. Thus the introduction of a CFD driven robust automatic aerodynamic optimization which will allow the reduction of the design cycles amount would significantly shorten the overall design process and considerably increase the probability that the following final design will result in a real aircraft.

To additionally underline the importance of drag minimization, consider the task of delivering a payload between distant destinations. Based on the Breguet range equation [13], which applies to long-range missions of jet-aircraft, the operator would have to reduce the pay-load (and thus to reduce the revenue) by 7.6%, to recover the 1.0% increase in drag. Since most airlines operate on small margins this service most likely will no longer be a profit-generating venture. This illustrates that a 1% delta in total drag is a significant change.

In this context, the main objective of this paper is to present a new efficient technology of aerodynamic design which successfully incorporates a CFD based tool (the code OPTIMAS) into the core of the preliminary design stage. Our goal is also to demonstrate that this technology opens up new possibilities for applied aerodynamic design and allows to reduce the design cost while improving the quality of design.

The power of the method is illustrated by design of a number of 2D and 3D aerodynamic wings typical of a transport-type aircraft. The results cover a wide range of wing planforms and flight conditions. It was demonstrated that the proposed technology allows to design feasible aerodynamic shapes which possess a low drag at cruise conditions, satisfy a large number of geometrical and aerodynamic constraints (15–20 per design) and offer a good off-design performance in markedly different flight conditions such as take-off and high Mach zone.

2. Problem formulation

The starting point of the aerodynamic wing design cycle is an initial CAD geometry definition. In the first design cycle, this definition results from the conceptual design stage. An additional information which also originates from the stage of the conceptual design provides the aerodynamic performance data. This includes the prescribed cruise lift, Mach, altitude and minimum allowed drag values which should be achieved in order to ensure the aerodynamic goals of the aircraft mission (such as range, payload, fuel volume etc). The desired geometry is sought in the class of solutions which satisfy different geometrical, aerodynamic and multidisciplinary constraints which also originate from the stage of conceptual design. Specifically the constraints are usually placed upon airfoils' thickness, maximum allowed pitching moment, minimum C_L^{max} at the take-off conditions etc.

The objective of this cycle is to develop a wing geometry with as low a drag at cruise conditions as possible which, at the same time, satisfies the above constraints.

The conventional approach to achieving this goal is by the trial and error method. It greatly depends on the aerodynamic intuition of designers and the previous engineering experience.

The main idea behind the proposed approach is to accomplish this objective through a CFD-based solution of the properly formulated multipoint constrained optimization problem.

It is worthwhile to stress that in view of the above described objective of the preliminary design cycle, the present task is focused onto the simultaneous taking into account numerous constraints of different nature and thus radically differs from classical conventional optimization problems.

In order to correctly state the present optimization problem, it is important to clarify the nature of different constraints, their structure and the interaction in the framework of this structure.

The set of constraints may be divided into the following two classes: the class of geometrical constraints and the class of aerodynamic constraints. The geometrical constraints are mostly independent of flight conditions and are easily verified (that is, the verification of the tested geometry is computationally cheap) while aerodynamic constraints naturally depend on flight conditions, and necessitate heavy CFD runs for their verification.

The aerodynamic constraints are subclassified into the following two subsets of constraints: constraints at the main design point (which usually coincides with the cruise conditions), and the constraints at off-design conditions.

The second important issue is the choice of the objective function. We assume that the drag coefficient C_D of a tested configuration is a sensitive and reliable indicator of its aerodynamic performance and thus we employ C_D as the objective function of the considered optimization problem.

The next basic principle is related to the implementation of constraints in the optimization algorithm. Where possible, the constraints should be satisfied exactly in the direct way while the remaining constraints should be converted into alternative constraints which can be expressed in terms of drag. For example, we managed to satisfy the geometrical constraints and such aerodynamic constraints as the prescribed lift coefficient exactly while the requirement of a sufficiently high C_L^{max} at the take-off conditions is reformulated in terms of drag at the corresponding flight conditions.

Finally in order to ensure the accuracy of optimization we require that for any geometry feasible from the constraints' viewpoint, the value of the objective (cost) function remains exactly equal to the value of the drag coefficient without any penalization. Note that this requirement is not easily satisfied.

Based on the above principles, the mathematical formulation of the optimization problem whose solution allows to achieve