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Jaime A. Escobar Gomez *Editors*

Numerical Simulation of the Aerodynamics of High-Lift Configurations

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To REM

Preface

Wing loading has been increased as a result of a combination of higher cruise speeds and aerodynamic efficiency but with adverse effects on stall speeds. At the same time, the length of the airports' runaways cannot be increased due to economic reasons, in addition to the fact that the speeds of takeoff and landing are limited to satisfy safety standards. It is in this context in which the importance of high-lift devices for commercial aerodynamic applications comes into play.

The design of high-lift devices is focused on simpler systems to maximize the lift and reduce maintenance costs. The aerodynamic design of these devices is restricted by takeoff and landing distances, safe speeds during landing and takeoff and climb rates. All these operational parameters impose restrictions on aerodynamic properties such as the lift coefficient (C_L), lift-to-drag ratio (L/D) and stall angle of attack. In recent years, numerical simulations have played an important role in the prediction of these aerodynamics properties. As an example, NASA and the American Institute of Aeronautics and Astronautics (AIAA) have organized three events related to the application of numerical simulations in the prediction of the aerodynamic properties of high-lift configurations since 2010. I have personally participated in these events, called High-Lift Prediction Workshop (HiLiftPW), and in general the conclusion is that the problem of correctly estimating the turbulent and separated flow near C_{Lmax} is still an important challenge for modern computational codes and software. Also, there is still a need to develop reliable turbulence models for this application, and the computational cost of these simulations is considerable, given the fact that finer meshes (around 200-M cells) are needed to reduce the deviation of the numerical solution between the various different codes and softwares. Numerical results consistently show that C_L is typically under-predicted, as well as are the drag and the magnitude of the pitching moment. In this context, this book is devoted to gathering some of the results of the most recent version of the HiLiftPW that was held in June 2017.

This book has six chapters dedicated to the numerical simulations of high-lift configurations and specifically all of them that are related to full Navier–Stokes (NS) solvers. This means that the numerical and computational techniques used for these contributions are based on Computational Fluid Dynamics (CFD). All the chapters discuss numerical solutions of the high-lift system proposed for the third HiLiftPW held in Denver in June 2017. All the chapters show numerical solutions for the aerodynamic properties of the models studied and comparisons (validation) with experimental data when available.

The first chapter is a review of high-lift configurations in order to provide a context for the book. This chapter also shows some results of the simulation of the flow around the High-Lift Common Research Model (HLCRM), which was one of the models introduced in the last HiLiftPW. These results are briefly introduced only to give some insight to the reader about the physics of the turbulent flow around these devices. The second chapter is dedicated to the topic of grid generation of high-lift configurations for CFD simulations. Typically, this is not a topic deeply discussed in textbooks or technical articles, so I personally consider that this contribution helps to give a better idea of the challenges and main features that need to be considered when facing such a complex problem. One of the interesting topics in this chapter is the discussion of the guidelines given by the AIAA on grid generation for high-lift systems. The third, fourth and fifth chapters are all dedicated to numerical computations of the Japanese Aerospace Exploration Agency (JAXA) Standard Model (JSM), using three different CFD solvers and simplifications of the governing equations. For example, Chapter "Incompressible Solutions About High-Lift Wing Configurations" is devoted to the use of an incompressible flow solver. The conclusions reached and observations made in this chapter are quite interesting since one of the main requirements of the HiLiftPW is to use fully compressible NS solvers for the simulations. Chapter "Numerical Investigations of the Jaxa High-Lift Configuration Standard Model with MFlow Solver" deals with the numerical solution of the JSM using a fully compressible NS solver; a very interesting topic discussed in this chapter is the High-Performance Computing (HPC) resources needed and the estimation of efficiency for performance in parallel computation for this kind of simulation. In Chapters "Incompressible Solutions About High-Lift Wing Configurations" and "Numerical Investigations of the Jaxa High-Lift Configuration Standard Model with MFlow Solver", computations are performed using the Finite Volume (FV) method which is the standard way to discretize the governing equations. Nevertheless, in Chapter "Time-Resolved Adaptive Direct FEM Simulation of High-Lift Aircraft Configurations", the numerical method used for computing the solution of the flow is the Finite Element Method (FEM). Since I read the book "Computational Turbulent Incompressible Flow" by Professor Hoffman in 2007, I have been intrigued by the capabilities of the FEM proposed in that book. In Chapter "Time-Resolved Adaptive Direct FEM Simulation of High-Lift Aircraft Configurations", this question is solved by showing the efficiency of the solver based on this methodology and its advantages in comparison with other numerical techniques typically used in CFD. Finally, Chapter "RANS Simulations of the High Lift Common Research Model with Open-Source Code SU2" deals with the numerical solution of the flow around the HLCRM using an open-source code called SU2. This final chapter also uses an FV method for solving the fully compressible NS equations.

It is expected that this book can serve as a reference for graduate students, as well as researchers in the field of CFD applied to the aerodynamics of high-lift configurations. Designers and engineers from the aeronautical industry may also benefit from the content of the book as it provides the state-of-the-art in CFD computations applied to the prediction of aerodynamic properties of high-lift configurations, as well as flow characteristics. We hope that the way the book is organized helps the reader to find a specific topic of interest and to engage the reader as he/she goes from one section to the next one. Finally, I would like to acknowledge the help of Dr. Rumsey and Dr. Slotnick during the 3rd HiLiftPW for helping me in the realization of this project.

Bogotá, Colombia
August 2017

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Review on High-Lift Systems for Aerodynamic Applications

A. Matiz-Chicacausa and C. A. Sedano

Abstract One of the main focal points in aircraft aerodynamics has been the study and development of high-lift devices and systems. These are designed in order to enable manipulation of the lifting force at various moments during flight (takeoff, cruising and landing) in such a way that the aircraft can increase or decrease the lift-to-drag ratio accordingly. High-lift systems are classified into trailing-edge and leading-edge devices. The first consists mainly of various types of flaps such as the plain flap, Fowler flap or the Krueger flap which act to increase the lifting force by reducing minimum speed, delaying flow separation or increasing the effective camber or the wing area. On the other hand, leading-edge devices consist mainly of fixed slots, movable slats, leading edge flaps or cuffs. The main idea of these devices is to sustain the lifting force even when the aircraft's speed decreases. Nowadays, there has been increasing interest in the study of high-lift systems using Computational Fluid Dynamics (CFD), instead of the experimental techniques traditionally used. Nevertheless, CFD techniques still face some major challenges that in some cases can only be solved through experimentation.

1 Introduction

The importance of the high-lift systems in modern transport aircraft is the significant payoff in the aircraft's performance during take-off and landing stages. To design efficient high-lift systems, several methods have been employed; most recently, Computational Fluid Dynamics (CFD) simulations, with the rapid growth of computational capabilities, have achieved increased accuracy and reliability of their results making it a more suitable tool and complementing wind-tunnel tests. The use of

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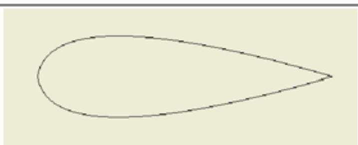
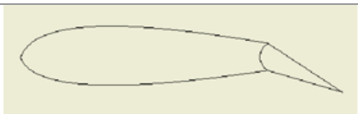
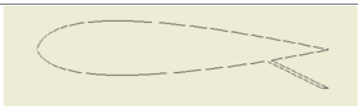
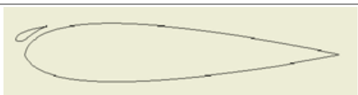
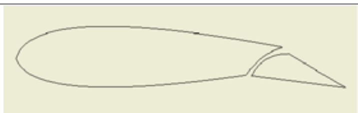
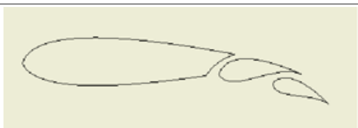
numerical simulations has resulted in wing designs that enable the bearing of higher loads without reducing cruise performance.

Although, high-lift studies trace back to the late 1920s, most of those works were empirical and the experimental databases were not widely published. As a historical note, after the end of the Cold War, nations worldwide(especially NATO countries) required that military forces react quickly anywhere in the world; thus, military transport aircraft needed to be able to operate on short landing/take-off strips [1]. This demanded better designs of high-lift systems. It was not until Smith's work in 1975 that a theoretical work published the explanations for those systems, establishing a baseline for future developments [2].

High lift-systems surfaced as a solution to reduce the extra baggage that the wing area constituted at cruising conditions, but was necessary for take-off and landing; namely flaps, slats, slots etc. Nowadays, high-lift systems are classified into two groups: leading-edge and trailing-edge devices. Trailing edge devices were the first

Table 1 Standard high lift devices

High-lift device	Schematic	Maximum C_L
Plain airfoil		1.3–1.5
Plain flap		2.4–2.5
Split flap		2.6–2.8
Leading-edge slat		2.3–2.5
Single-slotted flap		2.9–3.1
Double-slotted flap		3.1–3.3

to be developed, starting in the 1920s and 1930s. By far, the choice of wing area was established according to the speed at takeoff or landing [3]. However, the appearance of such devices provided sufficient lift while having a small wing area. The reduction in the wing area enabled designers to reduce structural weight; hence, skin- friction drag was decreased. The creation of this kind of devices had consequences in wing design and aircraft structure, therefore, also in fuel consumption, manufacturing and operational costs. Some of the standard devices employed since 1920 can be seen in Table 1, along with the respective increase in lift provided by each device.

2 Trailing Edge Devices

The first and most common high-lift system was the plain flap. Henri Farman first used this in 1908, however, engineers at the time were not interested in such devices. It was not until 1914 that they were installed in the SE-4 biplane and became standard on airplanes, built by Fairey beginning in 1916 [3]. The flaps are a movable part attached to the trailing edge of the wing. These are used to lower the minimum speed to produce sufficient lift force, such that the aircraft can fly, and also to increase the angle of deployment for takeoff and landing configurations. The plain flap is limited to a 20 degree angle of deployment that limits its capability to produce lift [4].

Three different innovators later developed the single-slotted flap independently: a German pilot G.V. Lanchman (1917), Sir Frederick Handley Page in England and an engineer working for Junkers in Germany. The principle of operation is that the high-pressure air below the wing is forced through the gap between flap and wing, delaying flow separation, while the airflow remains attached to the flap to increase lift. In the beginning, the patent was rejected with the argument that such a device could destroy the wing's lift. However, after Prandtl at Gottingen University were convinced to perform wind-tunnel tests, it was found that lift increased by 63%, hence Lanchman got his patent and shared rights with Page. After a two-year, wind-tunnel testing program, the single-slotted flap's viability was established beyond a doubt.

At the same time, in the US, the split flap was developed, which increased both lift and drag. The increase in drag was found beneficial during landing, resulting in a reduction of the lift-to-drag ratio, thus reducing the landing distance. This type of slat was the first type used on an airplane designed in the US, although it does not produce a significant increase in lift. The next development was the Fowler flap (see Fig. 1) by an engineer who worked with the Army Air Corps in 1924, Harlan D. Fowler. It combined two effects: The deflection of the flap was able to increase the effective camber of the wing to increasing lift. Additionally, the flap could be deployed increasing the lift by increasing the wing area. Up until 1932, the National Advisory Committee for Aeronautics (NACA) tested it, proving the value of this kind of flap. Later on, some variations of the Fowler flap were developed, such as the double-slotted Fowler flap. The single-slotted is rarely used in industry; however, the double or multiple-slotted Fowler flap are still used on modern aircraft. For instance,