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Prediction and delay of 2D laminar boundary layer separation near leading edges

Anna Dostovalova

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Department of Applied Mathematics

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This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Abstract

Boundary-layer flows near leading edges of generally curved obstacles have been studied for a long time. Apart from having many practical applications, the theory and approaches prevailing in this area stimulate development of a variety of computational tools and form a ground for testing them.

The specific aim of this work is to study two-dimensional laminar boundary layer flows near the leading edges of airfoils and other elongated bodies, and to explore geometries for which boundary layer separation can be avoided. This class of problems is relevant to optimal design of wings, aircraft and projectile noses, laminar flow control methods and adaptive wing technology. One of the findings of this work suggests that local modifications to parabolic wing noses can yield up to 11% increase in the unseparated angle of attack. Another result obtained here is the set of shortest possible generalised elliptic noses of long symmetric bodies which allow unseparated flow.

Methods adopted in this work are based on the combined use of numerically solved Prandtl equations written in Görtler variables, and inviscid solutions obtained semi-analytically by the conformal mapping method. The resulting technique being reliable, fast and computationally inexpensive, can complement or test the results obtained using a comprehensive CFD approach.

Contents

Introduction

Boundary-layer flows near leading edges of generally curved obstacles have been studied for some time [36, 25, 33, 30]. Apart from having many practical applications, the theory and approaches prevailing in this area stimulate development of a variety of computational tools and form a ground for testing them.

Computational Fluid Dynamics is now perceived by many as a separate branch of applied mathematics. The idea to reduce solution of complex fluid mechanics problems to operating solvers has created a new field of specialisation. The resulting technology successfully employs the effort of programmers and engineers at different stages of computation: from grid and input data generation, and model description, to postprocessing and visualisation. Flows thus computed and their parameters are subsequently used in the design of actual aircrafts and vessels.

The comprehensive CFD approach, in which the full viscous flow is computed for an exact, or very similar, aircraft/vessel geometry does not eliminate the need for approximate semi-analytic techniques, which, though allowing us to consider only simplified geometries, can yield an alternative solution and yet be less computationally demanding (e.g. see the review [2] where the set-up and grid generation costs for CFD routines are discussed).

Local behaviour of the stream near some elements of aircrafts and vessels can often be approximated with a boundary layer flow past a leading edge. Prandtl's equations [24, 26, 23] have been used for description of laminar boundary layers since 1905 [12]. In particular, they provided an explanation for the phenomenon known as *separation* of flow from the surface of the obstacle.

Being a cause of flow instability and strong drag, separation of boundary layers is usually considered as something which should be avoided [9]. One of the techniques used for avoiding boundary layer separation called *laminar flow control* [13] is based on a *steady suction* (slot, porous and perforated suction), *thermal control* and *wave management* [29].

Resulting savings in fuel consumption due to drag reduction (up to 14 % for some models [13]) can outweigh increased design costs associated with the laminar flow control. In addition, the suction and thermal control requirements can be reduced by using wing geometry considerations. The corresponding technique is referred to as the *hybrid laminar flow control*. Naturally, such a technique requires understanding of laminar boundary flow behaviour and its dependence on the wing geometry. Our primary goal here is to study laminar boundary layer flows near the leading edges of airfoils and similar bodies and to explore geometries for which boundary layer separation can be avoided. This class of problems is also of a direct relevance to the adaptive wing technology [29].

The work is organised in three chapters, and each of them considers a specific body geometry.

In Chapter 1 we study local laminar boundary layer flows past near-parabolic noses of thin airfoils, modelling such noses by semi-infinite bodies. We suggest nose modifications which delay separation of the boundary layer to greater values of the angle of attack, thus permitting greater lift before stall is reached. Here we also provide details of the numerical procedure we use for computation of the laminar boundary layer. Our approach is based on the technique developed by Werle and Davis [36]. This is one of a family of methods for obtaining exact solutions of the full Prandtl boundary layer equations using finite differences (see [37] and other papers referenced in [37]). Alternative methods for the approximate calculation of boundary layers which use momentum integral relations and *a priori* velocity profiles [37, 11, 7, 8] may reduce computational cost, but are also likely to give different results for separation characteristics due to strong sensitivity of the solution to the shape of the boundary.

In Chapter 2 we consider finite-length general airfoils. We revisit here the Theodorsen–Naiman method for computation of the potential flow about a complete airfoil, incorporating it into a convenient graphical user interface, which allows one to perform visual manipulations needed for improvement of convergence of the iterative procedure. We also discuss the limits of the method's applicability to computation of laminar boundary layers for very long thin airfoils. The resulting program thus allows solution for flows about arbitrary user-defined airfoils. In that sense, it has similar objectives to packages such as XFOIL by M. Drela [8], MELFOIL by M. S. Garelik, PROFIL by R. Eppler and other packages, noting that XFOIL [7, 8] also couples the potential flow with an approximate boundary layer solution.

In Chapter 3 we show how the technique considered in Chapter 2 can be modified to make it applicable to the study of boundary layers in flows past long objects. We then consider a particular family of smoothly curving front faces or noses of length L and width H attached to a semi-infinite plate of finite width, and use the developed procedure to determine the front face profile, allowing an unseparated flow, for which the aspect ratio L/H of the nose is minimal.

Results of Chapters 1 and 2 have been previously published by the author in papers and reports [6, 34, 28, 27].