Shock–Boundary Layer Interaction Control, Predictions Using a Viscous–Inviscid Interaction Procedure and a Navier–Stokes Solver

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The present contribution describes two prediction methods for flows around transonic airfoils, including shock control devices. The whole work was done in the frame of the European Shock Control Investigation Project EUROSHOCK–AER–2, and the global objective was the improvement of the flight performance, in transonic speed, in terms of cruise speed, fuel consumption and exhaust emissions for both laminar and turbulent wings. More specifically the "passive" control of shock/boundary layer interaction, whereby part of the solid surface of the airfoil is replaced by a porous surface over a shallow cavity, has been shown to be a means of improving the aerodynamic characteristics of supercritical airfoils.

Keywords: shock/boundary layer interaction, passive control, transonic airfoils.

INTRODUCTION

Two methods are presented here for the calculation of transonic flows around airfoils including shock control devices. The use of blowing and suction, through a perforated plate below the shock–boundary layer interaction zone, is present in order to minimize the wave drag, due to the presence of the shock, to prevent the shock–induced separation and in order to alleviate the occurrence of the annoying buffet phenomenon. The aim of this paper is to investigate ways of predicting the complicated phenomena present in the shock–boundary layer interaction region, when control of the shock wave is implemented, as well as to provide numerical solutions and comparisons with existing experiments.

In the first place, an integral semi–inverse boundary layer calculation method is combined with a time marching Euler solver, resulting in a viscous–inviscid interaction computational tool, which could handle the flow around airfoils when shock waves are present. A substantial amount of work was performed subsequently in order to modify the relevant equations and procedure in order to account for shock control. The resulting calculation procedure is an iterative one, utilizing successfully the inviscid and the viscous computational tools until convergence is reached.

The integral momentum and kinetic energy equations, written for compressible flow are used for the viscous computation. All normal fluctuation terms, important for the calculation of separated flows, are retained. The calculation method is operated in the direct mode until separation is approached or strong adverse pressure gradients are encountered. Then, the equations are solved in the "inverse" mode, in order to avoid the well known singularity of boundary layer equations at separation or break down of the boundary layer calculation procedure, because of unrealistic values of the streamwise pressure gradient imposed by the inviscid calculation. This resulting calculation method copes successfully with separated flows, using a small number of iterations.

A second computational method is presented, subsequently, which resolves the Navier–Stokes equations.
The corresponding solver[^1^—^3] is an explicit, time-marching, fractional step one, which utilises multigrid acceleration.

This solver has been tested extensively and found both fast and accurate. Turbulence is modelled through either the Baldwin Lomax or the two equation \( k - \varepsilon \) model (Jones and Launder) Both low-Reynolds and wall functions techniques can be employed. This solver was appropriately modified in order to incorporate it in a passive control mechanism. Both suction and blowing are possible in the shock–boundary layer interaction zone, where the flow is fully turbulent.

the validity of several passive shock–control laws was tested. Firstly, as in most of the methods, the normal velocity component \( v_w \) was expressed as a given function of the pressure difference across the perforated surface above the cavity in the shock–boundary layer region (Darcy law expressions). In the second place the calibration formula proposed by Poll[^4] was used. Finally, the isentropic relations proposed by Abramson and Brower were used.

The main influence of the mass injections through the porous surface in the passive control region, is restricted inside the portion of the boundary layer close to the wall. As it is more preferable to treat this zone with a robust turbulence model, it was decided to use the algebraic Baldwin–Lomax one near the wall and leave open the choice for the outer region, where either the same model or the more elaborate \( k - \varepsilon \) model may be used.

Transpiration effects were taken into account by modifying van Driest’s wall dumping function. From the numerous modifications proposed in the literature, that of Cebeçi[^5] was selected and incorporated.

Numerous numerical tests were performed in order to compare the two methods with one another and both to available experimental results first without and then with shock control.

NUMERICAL PROCEDURES

Part I. Viscous–Inviscid Interaction Procedure

An integral semi–inverse boundary layer code was combined with the time marching Euler solver for the calculation of shock shear layer interaction. The calculation procedure is an iterative one, utilizing successively the inviscid and the viscous computations until convergence is reached.

Governing Equations

In this section a brief description of the development of the integral equations will be presented. Details for the development of the method may be found in Ref.[10],[19],[20].

The basic equations are considered in a rotating frame of reference since it is easy to deduce from them those valid for a stationary frame.

An axially symmetric orthogonal curvilinear system of coordinates is used. The continuity, the two momentum and the energy equations are expressed in this system. In addition, the turbulent kinetic energy equation is used for turbulent flow.

The above mentioned equations are simplified in the following way: (a) The stress terms containing the coordinate system curvatures, as well as the terms containing the derivatives of stresses in the \( s \)-direction (parabolization) are neglected. However, all normal fluctuation terms are conserved. (b) Some simplifications are applied, concerning the inertia terms of the normal momentum equation. However, the main effect of these terms which contributes to the variation of the static pressure in the normal to the flow direction is retained. (c) Following Lock and Firmain[^21], a representative wall curvature is taken into account for each position \( (s) \). It is partly due to this curvature that the variation of the static pressure along a normal to the flow direction is accounted for. (d) The pressure term in the turbulent kinetic energy equation is neglected. At this level, the production term in the streamwise momentum equation for turbulent flow is substituted by the corresponding terms appearing in the turbulent kinetic energy equation.

With the above mentioned simplifications, the equations are written for the external inviscid and the real flow. Then, they are subtracted from each other, forming the corresponding deficit equations. These equations are then integrated along the normal to the streamwise direction resulting in this way the corresponding integral equation of momentum and kinetic energy.

The working equations of momentum and energy are further manipulated by introducing the non dimensional quantities \( L_k \) and \( X \). \( L_k \) is a form factor, while \( X \) is the logarithm of a Reynolds number based on energy thickness. We have to note that the two new variables \( L_k \) and \( X \) allow the representation of the state of the boundary layer at every step of the streamwise calculation, on an image plane with \( L_k \) and \( X \) as ordinate and abscissa. This proves to be very helpful, as the basic characteristics of the boundary layer (whether laminar or turbulent, attached or separated, losses etc.) can be easily assessed.

In order to close the problem, a semi–empirical frame is necessary in order to relate all variables with the working variables \( L_k \) and \( X \). Thus, for laminar