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Numerical Solution of Incompressible Turbulent Flow over Airfoils near Stall

Harwood A. Hegna*
Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio

Abstract

NUMERICAL solutions are obtained for two-dimensional incompressible turbulent viscous flow over airfoils of arbitrary geometry. A body-fitted coordinate system is numerically transformed to a rectangular grid in the computational plane. The unsteady Reynolds-averaged Navier-Stokes equations in the primitive variables of velocity and pressure are used. Turbulence is modeled with an algebraic eddy viscosity technique modified for separated adverse pressure gradient flows. The set of transformed partial differential equations is solved with an implicit finite-difference method. Numerical solutions for a NACA 0012 airfoil near stall at a chord Reynolds number of 170,000 are favorably compared with surface pressure and velocity field measurements. A small laminar separation bubble near the leading edge is observed. Computed lift and drag coefficients agree well with experimental values.

Contents

Much effort has been expended in determining the aerodynamic characteristics of airfoils. Experimental investigations are used to determine the characteristics near stall where separation phenomena become important. Recent developments in numerical techniques have stimulated research on numerically solving the Navier-Stokes equations. These equations model the viscous effects which contribute to airfoil stall. A review presented in Ref. 1 of existing numerical solutions of these equations for two-dimensional flow over airfoils reveals Reynolds number and angle-of-attack restrictions which prevent the accurate computation of the flowfield and resulting aerodynamic characteristics for an airfoil near stall. The purpose of this investigation is to develop a numerical Navier-Stokes method that will accurately determine the aerodynamic characteristics for incompressible turbulent viscous flow over two-dimensional airfoils near stall.

The unsteady, Reynolds-averaged, two-dimensional, incompressible Navier-Stokes equations are used with the convective velocity divergence term D retained. The pressure field is computed using a simplified Poisson equation for pressure given by

$$D_t + (u_x^2 + 2v_x u_y + v_y^2) = -(p_{xx} + p_{yy}) \tag{1}$$

where u and v are the Cartesian components of velocity, p is the static pressure, and the subscripts denote differentiation. The airfoil surface pressure is calculated using Chorin's[2] iteration technique.

Turbulence is modeled with a Cebeci et al.[3] two-layer algebraic eddy viscosity approach modified for adverse pressure gradient separated flows. The upper airfoil surface has a pressure distribution composed of a low-pressure region near the leading edge followed by an adverse pressure gradient which decreases as the flow recovers toward the trailing edge. The inner eddy viscosity parameter values of $k_I = 0.65$ and $A^+ = 52$, reported by Jobe[4] for constant adverse pressure gradient flows, are used where k_I is the von Kármán constant and A^+ is the laminar sublayer relaxation length. The parameter k_I is relaxed[1] back toward the equilibrium value of 0.41 in the trailing-edge separated region. Measurements[5] indicate a lower but finite turbulent intensity in this region compared with the turbulent separated shear layer. This phenomenon is modeled with a limiting technique that prevents the inner eddy viscosity from decreasing in either the local outward normal or downstream flow directions. Turbulent structure in the wake is described with an outer eddy viscosity expression similar to the model previously introduced.

A computational grid with 79×44 grid points is numerically generated using a modified Thompson's[6] transformation as discussed in Ref. 1. The system of partial differential equations is transformed to a computational rectangular grid plane and solved using an implicit finite-difference procedure. Second-order-accurate upwind and central spatial differences are used together with first-order backward time differences. The system of linearized simultaneous difference equations is solved using successive-over-relaxation iteration at each time step. A steady-state numerical solution is assumed when changes in the computed values of the lift and drag coefficients are less than 1% over one characteristic time period.

Numerical solutions for the flow over a NACA 0012 airfoil at angles of attack of 5, 7.5, 9.5, and 11.5 deg with a chord Reynolds number of 170,000 are presented. This Reynolds number case is selected for comparison with experimental data.[7,8] The mean flow streamline contours for the solution at 11.5 deg are shown in Fig. 1. The large separated region typical of trailing-edge stall is evident. For a moderately thick airfoil with a smooth surface in a flow with a low freestream turbulent intensity, the laminar boundary layer near the leading edge may separate upon encountering an adverse

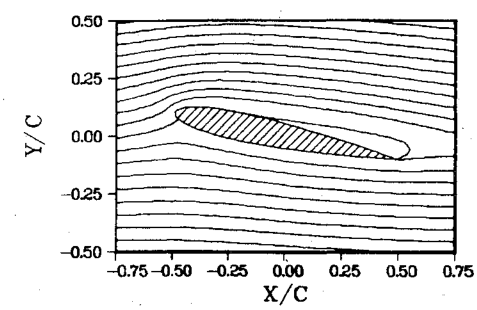

Fig. 1 Computed mean flow streamline contours for NACA 0012 airfoil at 11.5 deg and $Re = 1.7 \times 10^5$.

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*Captain, U.S. Air Force, Computational Aerodynamics Engineer. Member AIAA.

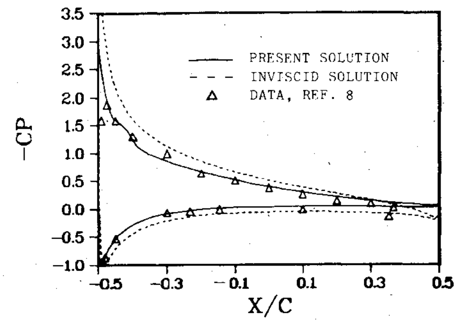

Fig. 2 Surface mean pressure coefficients for NACA 0012 airfoil at 7.5 deg and $Re = 1.7 \times 10^5$.

Table 1 Computed laminar separation parameters

α, deg	M	H_{12}	Re	$10^2\delta^*$	L_b
5.0	0.124	3.1	220	0.25	0.27
7.5	0.091	3.2	168	0.13	0.09

pressure gradient. Subsequently, shear-layer instabilities can cause transition to turbulence which may reattach the shear layer and form a separation bubble. A review of experimental studies involving airfoil separation bubbles is given in Ref. 1. The surface mean pressure coefficients for a 7.5 deg angle of attack are presented in Fig. 2. The bubble constant pressure region followed by a rapid pressure recovery is observed downstream of the suction peak. The suction peak and the lower surface pressure peak are well defined and compare favorably with the experimental data which have an estimated error of 5-8%. An inviscid finite-difference solution with Kutta condition was also computed and is shown in Fig. 2.

In this study, the beginning of turbulent transition along the upper surface and the transition length are based on the closure of the laminar separating shear layer. Computed values of several parameters at the separation point are given in Table 1 and compared with empirical results. The computed nondimensional pressure gradient $M = -\theta^2\, Re\, du_e/ds$ and shape factor $H_{12} = \delta^*/\theta$ (where θ is the momentum thickness, δ^* the displacement thickness, Re the freestream Reynolds number, and s the arc length) agree with Curle and Skan's[9] laminar separation criteria given by $M \geq 0.09$ and $H_{12} \sim 3.5$. The assumption that laminar separation precedes turbulent transition agrees with Crabtree's[10] transition criteria since the computed momentum thickness Reynolds number is less than 780 at separation. Transition in the solution occurs near the downstream side of the bubble where the steep pressure recovery begins. The short bubble length L_b is of the order $10^2\delta^*$ at separation and decreases rapidly with angle of attack.

The computed lift and drag coefficients are compared with both an inviscid calculation and experimental data in Fig. 3. The lift curve correctly predicts trailing-edge stall at this Reynolds number and agrees with the data within 5% near

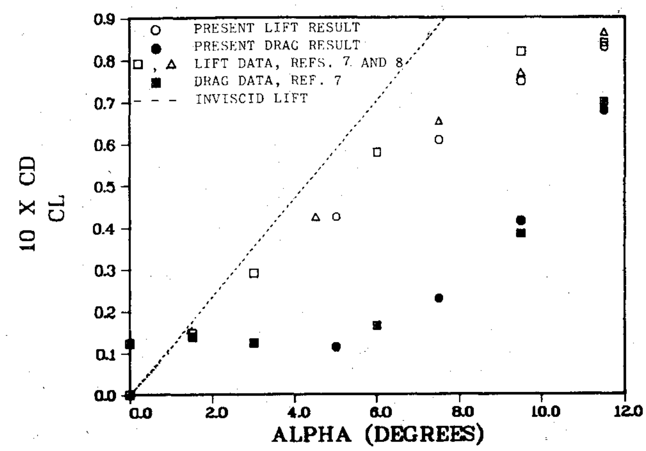

Fig. 3 Lift and drag coefficients for NACA 0012 airfoil at $Re = 1.7 \times 10^5$.

stall. The computed drag coefficients and experimental results agree within 10 drag counts in the region of maximum lift to drag ratio.

Acknowledgment

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