Numerical Prediction of Dynamic Forces on Arbitrarily Pitched Airfoils

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Abstract

NUMERICAL solutions for an NACA 0012 airfoil undergoing various pitching motions are compared with both previous static and new dynamic experimental data. The unsteady incompressible Reynolds-average Navier-Stokes equations for a rotating coordinate system are used. A body-fitted grid is mapped into a rectangular coordinate system using a time-independent transformation. The set of transformed partial differential equations is solved with an implicit finite difference method.

Contents

The prediction of dynamic forces and moments caused by the motion of airfoil surfaces is of significant interest in aircraft performance and maneuver analyses. Pitching motions can produce unsteady, viscous-inviscid, interacting flowfields with regions of separation. Pressure distributions and resulting dynamic aerodynamic characteristics can differ substantially from static fixed angle of attack results. Instantaneous flowfields can be modeled with the unsteady Navier-Stokes equations. The numerical prediction of time-dependent aerodynamic characteristics has primarily been restricted to laminar flows over airfoils with sinusoidal motions as reviewed in Ref. 1. The purpose of this investigation is to use the Navier-Stokes equations to numerically predict the aerodynamic characteristics for incompressible turbulent flow over arbitrarily pitched airfoils.

The time-dependent, incompressible, two-dimensional, Reynolds-averaged Navier-Stokes equations formulated in a body-fixed or pitching (x,y) coordinate system are used. These equations include centrifugal, Coriolis, and angular acceleration terms. The pressure field is computed using a simplified Poisson equation for pressure derived for the pitching coordinate system and given by

$$D_t + (u_x)^2 + 2v_x u_y + (v_y)^2 + 2\dot{\theta}(u_y - v_x - \dot{\theta}) = (-1/\rho)\nabla 2_p \tag{1}$$

where u and v are the Cartesian components of mean velocity, p is the mean static pressure, ρ is the density, and the subscripts denote differentiation. The pitch angle $\theta(t)$ (defined positive counterclockwise) describes the angular motion of the airfoil relative to an inertial reference frame. The pitch axis is located a positive distance L along the airfoil chord from the origin or midchord toward the airfoil leading edge.

An algebraic two-layer eddy viscosity method[2] modified for separated adverse pressure gradient flows[3] is used to model turbulence. The starting location and length of transition are based on closure of the separating shear layer. This approach was previously used[3] to compute static airfoil stall. The model is implemented for pitching motion by using static values for the initial angle of attack α_0 until movement of the separation bubble is detected after a rotation $\Delta\theta$. The transition location and length are then allowed to vary with respect to an effective angle of attack defined by $\alpha_0 - \theta + \Delta\theta$ in a manner analogous to the static results. The effect which a transient body motion has on the structure of turbulence near the surface is not well understood. A recent study by Marvin et al.[4] did indicate, however, that an algebraic eddy viscosity approach can predict the mean features for unsteady flows when compared with experimental data.

The body-fitted grid, consisting of 83 surface points and 44 contours, is numerically generated with a modified Thompson's[5] transformation as discussed in Ref. 1. Approximately eight contours are located within the boundary layer with one

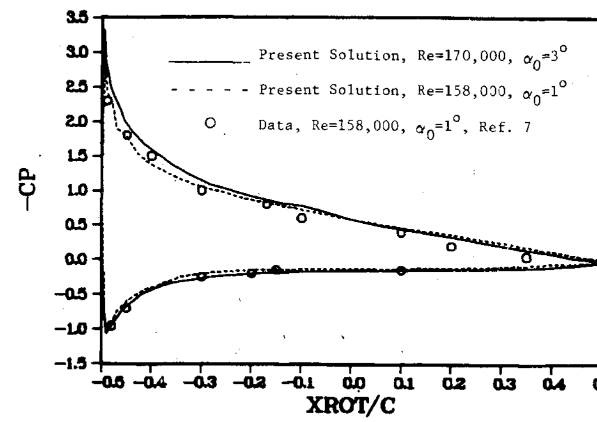

Fig. 1 Dynamic surface mean pressure coefficients for NACA 0012 airfoil at 10.5 deg with $k = 0.041$.

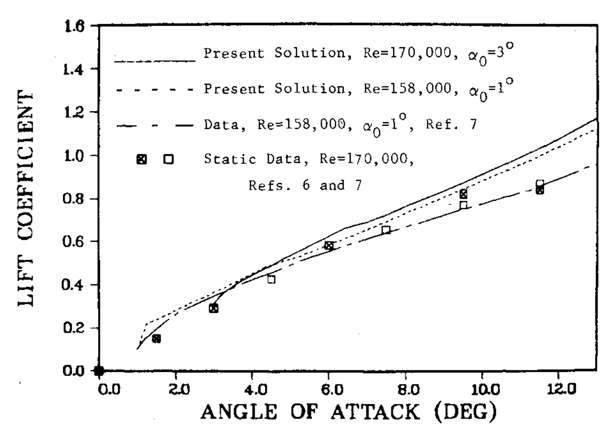

Fig. 2 Dynamic lift coefficient curves for NACA 0012 airfoil with $k = 0.041$.

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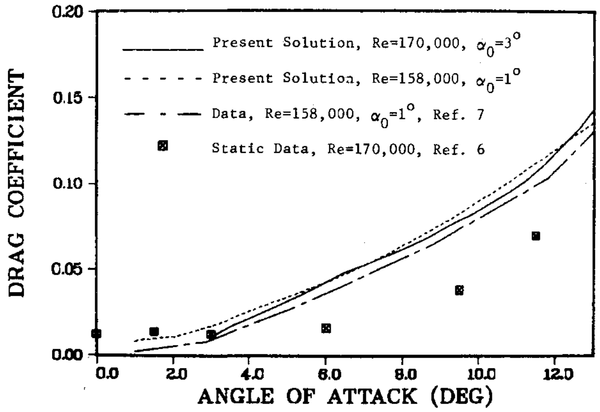

Fig. 3 Dynamic drag coefficient curves for NACA 0012 airfoil with $k = 0.041$.

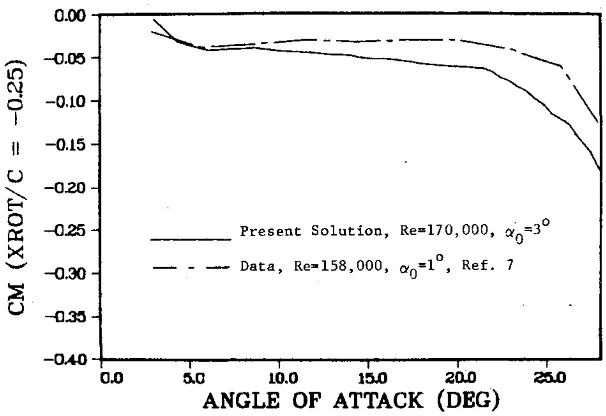

Fig. 4 Dynamic quarter-chord pitching moment coefficient curves for NACA 0012 airfoil with $k = 0.041$ and $L = 0$.

contour within $y^+ = 5$. Second-order-accurate upwind and central spatial differences and first-order backward time differences are applied to the transformed partial differential equations. The linearized simultaneous difference equations are solved using successive-over-relaxation (SOR) iteration at each time step. The convergence criterion used for the SOR iteration requires that the maximum change in the relative magnitudes of u, v, and p be less than 0.5%. This criterion was met with a nondimensional time step $U_\infty \Delta t/c = 0.0002$ and a maximum of three iterations per time step where U_∞ is the freestream velocity and c is the airfoil chord.

Numerical solutions for the flow over an NACA 0012 airfoil with various pitching motions at chord Reynolds numbers of 158,000 and 170,000 are presented. These Reynolds numbers are chosen for comparison with experimental data.[3,6,7] The airfoil is accelerated from rest at either 1 or 3 deg angle of attack to a constant angular velocity Ω with a reduced frequency of either 0.004 or 0.041. The reduced frequency k is defined by $\Omega c/2U_\infty$. A sinusoidal motion at a corresponding reduced frequency of 0.41 is also presented in Ref. 1.

The constant angular velocity pitching motion case with reduced frequency of 0.041 was chosen for comparison with recent dynamic experimental data.[7] The initial spin-up motion is modeled with a constant angular acceleration acting over an experimentally determined nondimensional time of 1.36. The prescribed constant angular velocity is reached after approximately 3 deg of pitch from the initial angle of attack. The solution through a 13 deg angle of attack required about 3 CPU h on a CDC 750 computer. The mean surface pressure coefficients for both Reynolds number solutions at an instantaneous angle of attack equal to 10.5 deg are shown compared with an ensemble-averaged set of data in Fig. 1. The ensemble average consists of 20 experimental runs for the given motion. The angular delay in the turbulence model is 4 deg compared with 0.8 deg for the smaller $k = 0.004$ case. A comparison given in Ref. 1 with previous static results shows that the motion delays both the forward movement of the separation bubble and the formation of trailing edge separation. The pressure distributions on both surfaces are in excellent agreement with the experimental results.

The computed dynamic lift coefficients are presented in Fig. 2, along with the previous static results and a smoothed ensemble-averaged experimental result.[7] Fluctuations in the original ensemble-averaged curve are approximately 10% of the smoothed curve. The effect of a difference in the small initial starting angles of attack is observed to be small after the constant angular velocity is reached. The pitching motion is seen to sustain the lift through the static stall region. The numerical dynamic drag coefficients are compared with smoothed, ensemble-averaged, dynamic pressure drag experimental data in Fig. 3. The small difference is probably attributed to the computed skin friction contribution which dominates the drag at small angles of attack. The computed quarter-chord pitching moment coefficients agree within the 10% scatter of the dynamic data at a value of about -0.04 through static stall as shown in Fig. 4. For larger angles of attack, a vortex appears to form and move down the airfoil surface as indicated by the increase in negative pitching moment.

Future numerical work is planned for high angle of attack cases which will parallel an experimental research effort[7] using laser velocimetry to measure mean flow and turbulence properties.

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