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SOME ASPECTS OF VORTEX FLOWS DETERMINED FROM THE THIN-LAYER NAVIER-STOKES EQUATIONS

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ABSTRACT Vortex flows caused by a swept wing are described in some detail. The thin-shear-layer Navier-Stokes equations with an algebraic eddy-viscosity turbulence model are solved. An implicit, factored numerical scheme is used. On the upper surface of the wing, flow is primarily along the free-stream and spanwise direction, respectively, at small and large angles of attack.

1. Introduction

Various kinds of three-dimensional regions of separation exist in laminar and turbulent boundary layers on lifting aerodynamic configurations in flows from subsonic to hypersonic speeds. When a three-dimensional boundary layer detaches from a surface along a swept separation line adjacent to which the skin-friction lines converge rapidly, a vortical flow develops. Usually well formed vortical flows are observed, for example, on a helicopter rotor blade, on a delta wing, at wingtips, and on a highly swept wing. For computational convenience, this paper investigates the vortical flow phenomena caused by a wing with two tips. This wing is almost like a helicopter rotor blade. This investigation is accomplished by solving the thin-layer Navier-Stokes equations.

2. Computational Grid System

For a fixed number of node points, the O-O grid topology resolves the flow field better than any other (H-H, C-H, C-O, or O-H) grid topology. The O-O grid topology offers the maximum resolution of the flow field in the neighborhood of the wing, particularly near the leading and trailing edges and near the wingtips. Further, it possesses singularities that are regular.

When a boundary of a flow field can be mapped with an analytical function, when the resulting distribution of boundary points is nearly satisfactory, and when the interior grid distribution is less of a concern, conformal transformations provide better flow-field resolutions. They give rise to simple geometrical mapping quantities, and it is easier and more computationally efficient to assemble a grid system with them than by using a differential method.

An algebraic generation method is developed here to generate the O-O grid topology for the study of an aircraft wing. The region exterior to the wing is mapped inside a unit sphere with a series of conformal transformations. This mapping is achieved in three steps. First, the line joining the mid-chord locations of the unswept wing at different spanwise locations is sheared so that it aligns with the Cartesian coordinate in the same general direction. The airfoil sections are sheared in the same manner.

Second, the region exterior to each spanwise station is mapped into a near circle using the Kármán-Treffez transformation. These near circles are transformed into exact circles following a procedure given by Ives [1]. As a result of these steps, the wing is mapped into an axisymmetric body. Third, the region exterior to the two-dimensional body formed in a spanwise plane of symmetry is transformed into the interior region of a unit circle. These three steps map the wing into a unit sphere with a spherical (r, θ, ϕ) grid topology.

3. Thin-Layer Navier-Stokes Equations and Turbulence Model

Limited computer resources motivate the thin-shear-layer approximation and a simple turbulence model for the present investigation. This approximation and the turbulence model are described below.

A set of equations that falls between the boundary-layer equations and the full Navier-Stokes equations is used to represent the flow past the wing. This intermediate set of equations is obtained by neglecting all streamwise and spanwise derivatives of the viscous and turbulence stress, conductive heat-flux terms, and any term involving mixed derivatives. These equations are generally referred to in the literature as the thin-layer Navier-Stokes (TLNS) equations. Advantages and limitations of using these equations are discussed by Mehta and Lomax [2].

A zero-equation turbulence model patterned after that of Baldwin and Lomax [3] is used. The Baldwin-Lomax model does not require the location of the outer edge of a thin-shear layer. It uses the distribution of vorticity to determine the length scale in the outer region of the shear layer. Consequently, it also uses vorticity in the inner region. The Baldwin-Lomax model is extended for present three-dimensional application.

4. Computational Procedure

An implicit, approximate factorization method is used to solve the Reynolds-averaged TLNS equations in the spherical coordinate system. The numerical method is formulated in Δ-form [4]; and some parts of it are the same as those given in reference [5]. Because of limited computer resources only steady-state computations are attempted using the diagonalization procedure for the implicit operators [6] and space-varying time increments.

A useful three-dimensional computation of the flow past the wing requires a large number of node points that create huge data sets for a solution of the Navier-Stokes equations. These data sets cannot be stored in the main memory of the Cray X-MP/48 class of computers. Therefore, external storage devices and an efficient data-management procedure are required for an efficient computation.

There are two aspects of efficient data management. First, the computer programming language should be such that programming logic is relatively simple. This is achieved by coding the computer program in VECTORAL, a computer language developed at NASA Ames Research Center. This language simplifies the data management between the computer and the external storage device. Second, the organization of the data structure should be relatively simple to use. This is achieved by using the pencil data structure concept [7], which enables the code to run a huge number of node points with a relatively small computer (main) memory. Data sets are divided into cubes of node points. A stack of cubes, which are of same size, extends from one computation boundary to the other boundary, parallel to a coordinate direction. This stack is referred to as a pencil. Only one pencil of data on which computations are performed, resides in the computer memory at any time and results are stored back on the external storage device. There may be different number of pencils in each coordinate direction. Further details are given by Pan and Pulliam [8].

5. Discussion of Results

We study the flow phenomena generated by the wing in a supersonic flow for the following conditions: The free-stream Reynolds number and Mach number are 4.0×10^6 per foot and 1.4, respectively. The wing is swept to an angle of 65°; and the angle of attack (α) is varied from 2 to 14°. Under these conditions, solutions were determined on a CRAY X-MP/48 computer. Calculations are made on a relative coarse grid system utilizing a spherical (r, θ, ϕ) grid topology with $42\times85\times41$ node points. Some representative solutions are briefly discussed for $\alpha = 2$ and 10°.

There is a significant difference between the upper-surface flow fields of a swept aerodynamic surface at low angles of attack and those at high angles of attack. The combination of the angle of attack and the sweep angle determine whether there would be a vortical flow along the surface. Particle paths (Fig. 1) initiated away from the surface within the boundary layer and free to move with local velocity, and those initiated next to the surface and restricted to remain next to surface provide essential insight into the nature and formation of vortex patterns. Although at low angles of attack a vortex pattern along the wingspan is not observed, there is spanwise flow next to the surface near the trailing edge of the wing. At moderate and high angles of attack, vortex patterns along the wingspan are observed, and oil-flow patterns show regions of flow separation and reattachment. Such vortex flow patterns are observed on delta wings and on swept wings at incidence. Computations also capture the tip vortices that are caused by a helicopter rotor blade and a wingtip.

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SWEEP 65^o, $Re = 4.0 \times 10^6$, $M_\infty = 1.4$

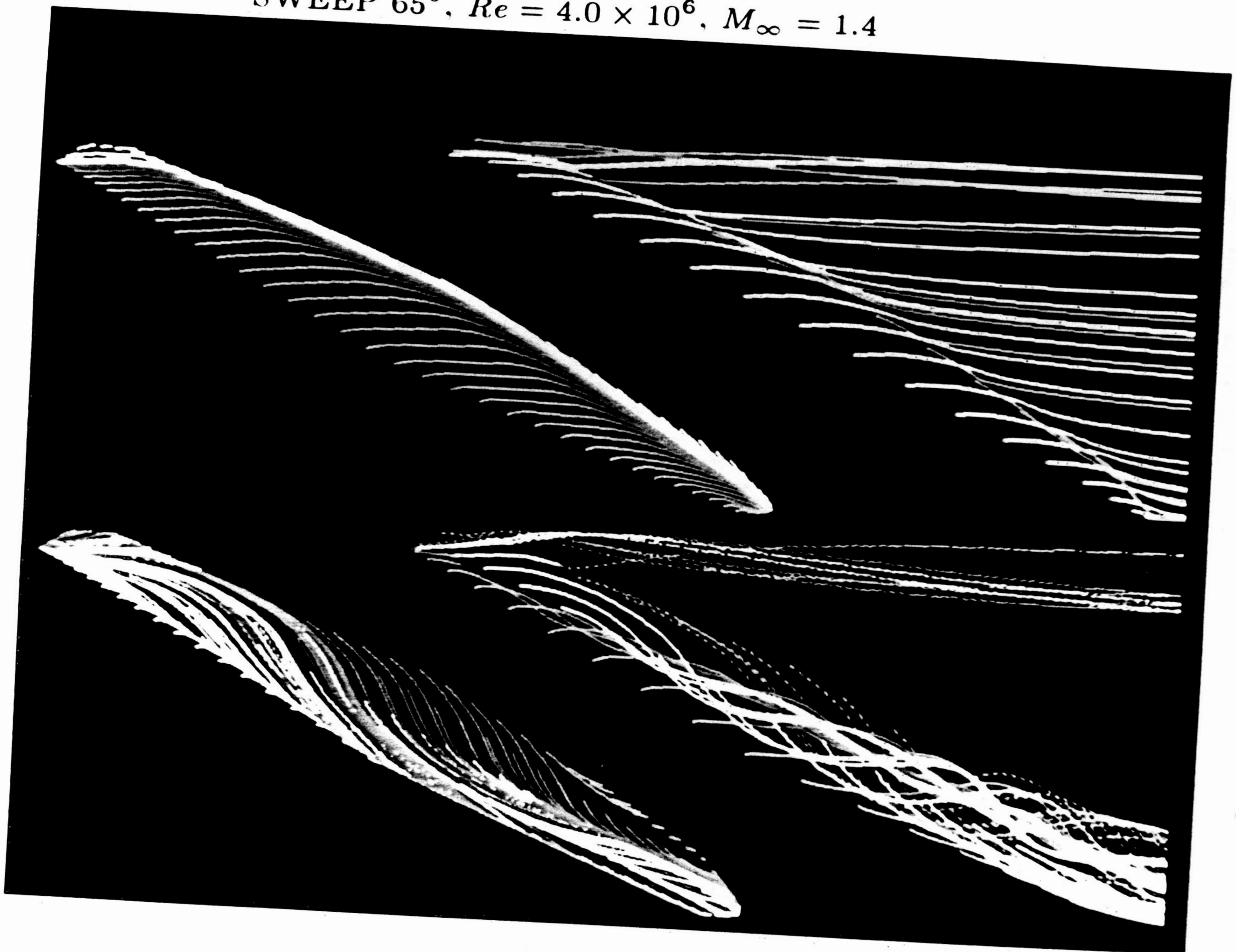

Fig. 1. Simulated oil-flow patterns (left) and particle traces (right) on the upper surface for $\alpha = 2^o$ (top) and 10^o (bottom).

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16. Abstract

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