rather than nosing down into a dive at too low an altitude to complete the recovery.[1,2]

In a canard, it is awkward to mount a vertical stabilizer far enough aft to produce adequate weathercock stability. However, if inherent stability is dispensed with in yaw as well as in pitch, the weathercock effect is no longer needed and the necessary control moment in yaw can be generated by a contjrol surface at the front.

Summary

Automatic, as opposed to inherent, stability permits the center of gravity of an aircraft to be shifted aft, thus improving the vehicle's lift/drag ratio and maneuverability. However, the increased loading on the rear surface, if carried far enough to optimize the apportioning of load between front and rear, will make the rear surface prone to stall and can lead to pitching moments which may be difficult or impossible to control. This danger can be avoided by controlling the aircraft in pitch by varying the lift of the front surface rather than the rear surface, i.e., by using a canard layout. A pitching divergence can then be checked, or a stall recovery made by reducing the lift of the canard surface, which is always possible, rather than by increasing the lift of a tail surface, which may be impossible.

Acknowledgment

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Simulation of Flat-Plate Turbulent Boundary Layers in Cryogenic Tunnels

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TRANSONIC wind tunnels which use cryogenic nitrogen as the test gas are being designed and built in this country[1] and in Europe[2] in order to obtain a higher test Reynolds number capability. The higher Reynolds number capability, generally achieved by operating at increased pressure as well as at reduced temperature, should provide better simulation of the viscous flow effects that occur in flight. However, if appreciable real-gas effects on viscous flow simulation are encountered in the high pressure cryogenic environment, certain limitations on the test conditions would be required with a corresponding reduction in Reynolds number capability. Various studies have examined the real-gas effects on inviscid[3-6] and viscous[6-8] flows that will be simulated in cryogenic nitrogen-gas wind tunnels. Of these studies, only Inger,[8] who has examined real-gas effects on turbulent boundary-layer shock interactions, has indicated very large real-gas effects. The gas model which Inger has used is strictly that for an ideal gas. Constant values of the ratio of specific heats (up to 1.8), which cover the range for cryogenic nitrogen at pressures to 9 atm, were substituted into the ideal-gas boundary-layer equations and the results used to infer the magnitude of real-gas effects. For inviscid flows this procedure has been shown to be entirely inadequate for estimating the magnitude of real-gas effects.[3,4]

This Note will examine the validity of the method used by Inger and present sample results of a real-gas analysis to determine the effects on the characteristics of a flat-plate turbulent boundary layer due to testing in cryogenic nitrogen.

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Theoretical Model

The turbulent boundary-layer model for this study is that of Anderson and Lewis.[9] The program based on this model will obtain boundary-layer solutions for both ideal gases and real gases in chemical equilibrium. The thermodynamic properties of cryogenic nitrogen[10] were table interfaced with this program.

Sample Case

A case was chosen for study that should represent a "worst case" in terms of simulating flat-plate turbulent boundary layers in transonic cryogenic wind tunnels. For cryogenic tunnels such as the National Transonic Facility, it is anticipated that the worst case would occur at conditions of maximum stagnation pressure (9 atm) and the corresponding minimum stagnation temperature. The freestream Mach number was arbitrarily set at 1.2. For this Mach number and stagnation pressure, the minimum stagnation temperature to avoid liquefaction at freestream conditions is approximately 120 K. The specific heat ratio γ for these stagnation conditions is approximately 1.6. In addition to real-gas boundary layer solutions, ideal-gas solutions with $\gamma = 1.6$ were obtained. Both of these solutions were compared to ideal diatomic gas ($\gamma = 1.4$) solutions, since air at the temperature and pressures of transonic flight behaves for all practical purposes like an ideal diatomic gas.

Results and Conclusions

Since the purpose of this study is to determine to what degree the real-gas solutions deviate from the ideal diatomic gas solutions, the results are presented relative to the ideal solutions. The relative values of local skin friction coefficient are shown in Fig. 1. The real-gas coefficients deviate from the ideal-gas $\gamma = 1.4$ values by only 0.5%. This deviation is essentially independent of Reynolds number (streamwise plate location, X/L). The friction coefficients calculated for the $\gamma = 1.6$ ideal gas deviate from the $\gamma = 1.4$ values by 4 to 4.5%. The deviations calculated in this way are roughly an order of magnitude higher than those calculated using real-gas equations and the actual properties of nitrogen.

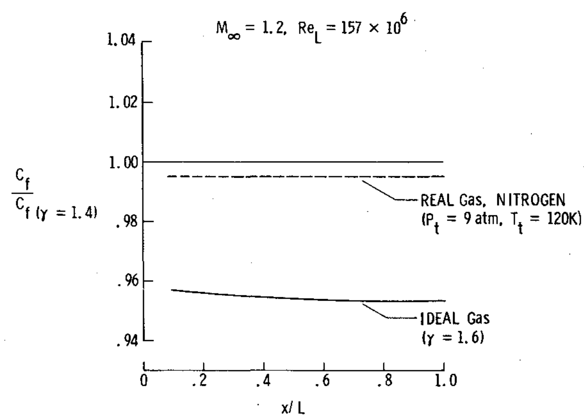

Fig. 1 Relative values of local skin-friction coefficient for a turbulent boundary layer on a flat plate.

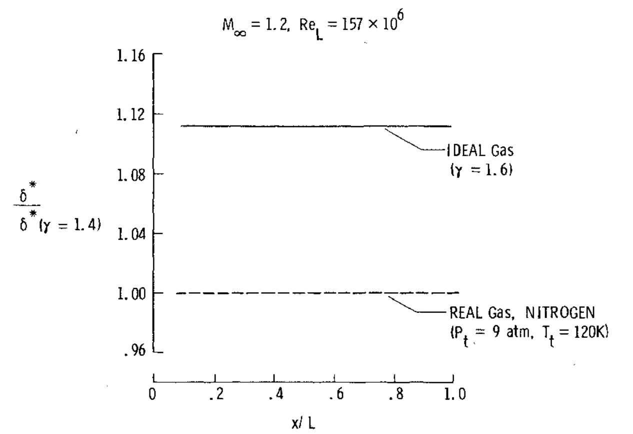

Fig. 2 Relative values of displacement thickness for a turbulent boundary on a flat plate.

The values of relative displacement thickness for the two methods of calculation are shown in Fig. 2. The deviation of the real-gas values is only about 0.1% while the ideal gas $\gamma = 1.6$ values differ by about 11% in the opposite direction. Other boundary-layer parameters, such as momentum and velocity thickness, have deviations for the two methods of calculation which are similar to those for friction coefficient and displacement thickness.

The results indicate that the real-gas effects on a flat-plate turbulent boundary-layer simulation due to testing in a cryogenic nitrogen tunnel are very small and presumably insignificant. Also, these results show that for flat-plate turbulent boundary layers, the use of ideal gas equations in combination with the γ values of cryogenic nitrogen, which in reality are non-constant, gives erroneously high indications of the magnitudes of real-gas effects. Since it has been shown that erroneous results are given for both viscous (this Note) and inviscid flows[3,4] when ideal-gas equations are used in conjunction with real-gas properties, it is extremely doubtful that the large real-gas effects reported by Inger[8,11] for turbulent boundary-layer shock interactions are an accurate prediction of the actual situation that will exist in cryogenic nitrogen gas wind tunnels during the simulation of such flows.

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Application of Unsteady Airfoil Theory to Rotary Wings

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An examination of the mathematical models reveals that unsteady airfoil theory is being used incorrectly in almost all major helicopter loads analyses, and also in some aeroelastic stability analyses. The difficulty lies in the identification of the airfoil pitch and heave motions in terms of the variables describing the motion of a rotor blade.

Theodorsen theory for a thin, two-dimensional airfoil undergoing unsteady motion in an incompressible flow gives the following result for the lift and pitch moment:

$$L = \pi\rho b^2(\ddot h + U\dot\alpha - ba\ddot\alpha) + 2\pi\rho UbC(\dot h + U\alpha + b(\tfrac{1}{2} - a)\dot\alpha)$$

$$M = \pi\rho b^2[ba\ddot h - Ub(\tfrac{1}{2} - a)\dot\alpha - b^2(\tfrac{1}{8} + a^2)\ddot\alpha]$$
$$+ 2\pi\rho Ub^2(a + \tfrac{1}{2})C[\dot h + U\alpha + b(\tfrac{1}{2} - a)\dot\alpha]$$

[Eqs. (5-311) and (5-312) of Ref. 1]. Here U is the freestream velocity, b is the airfoil semichord, and ρ is the air density. The airfoil has heave motion h, and α is the pitch angle about the axis a distance ab aft of the midchord. C is the Theodorsen lift deficiency function, which depends on the reduced frequency k. The use of this theory in a helicopter analysis requires that expressions be obtained for $\dot h$ and α in terms of the rotor blade degrees of freedom. To this end, examine the boundary condition of the unsteady airfoil theory, which involves the normal velocity due to the airfoil motion:

$$w_a = -(\dot h + U\alpha) - \dot\alpha(x - ba)$$

[Eq. (5-268) of Ref. 1]. It is only through this boundary condition that the airfoil motion enters the problem. Since the boundary condition depends upon the quantities $(\dot h + U\alpha)$ and $\dot\alpha$, it follows that the solution of this linear problem must depend only upon the same two quantities. Therefore, rewrite the lift and moment as follows:

$$L = \pi\rho b^2[(\dot h + U\alpha)^{\cdot} - ba\ddot\alpha]$$
$$+ 2\pi\rho UbC[(\dot h + U\alpha) + b(\tfrac{1}{2} - a)\dot\alpha]$$

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