Engineering Notes

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Avoiding Divergent Stall in Control Configured Aircraft by Using a Canard Arrangement

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Discussion

INHERENT stability in an aircraft is achieved at a cost in lift/drag ratio. The rear surface, i.e., the tail of a conventional aircraft or the wing of a canard configuration, carries less load than does the front per unit area. As the reliability of servomechanisms increases, it becomes tempting to move the center of gravity aft to increase the load on the rear surface, and to rely for stability on automatic operation of the aircraft's controls. As well as increasing the lift/drag ratio of the aircraft, this can increase its maneuverability. However, in a tail-aft aircraft such a center of gravity shift brings a danger of divergent tailplane stall. In a stable airplane, tailplane stall is unlikely and not ordinarily catastrophic. In some aircraft the tail's lift is negative, while in others it is positive with a lift coefficient much less than that of the wing. In either case the wing ordinarily stalls first. Even if the tail stalls as well, the net pitching moment of most aircraft is nose down, initiating recovery.

Now consider an aircraft whose wing and tail operate at the same lift coefficient to maximize efficiency. (To minimize induced drag the spanwise lift distributions of wing and tail should add up to an ellipse.) Assume neither surface is cambered, so neither generates a pitching moment about its aerodynamic center. In the absence of downwash, neutral static stability is insured by this apportioning of load, i.e., by locating the center of gravity so that the ratio between the distances from it to the aerodynamic centers of wing and tail is the inverse of the ratio between their areas. Downwash, however, renders this aerodynamically efficient configuration statically unstable. Automatic operation of the elevator or tailplane can provide stability in this situation so long as the tail can generate the force that the servo system demands. At low lift coefficients this assumption is safe, but at high lift coefficients the tail, like the wing, will be near to stalling. It may stall before the wing as the lift coefficient is slowly increased with the aircraft in trim, but even if it does not, a sudden control input, either intentional or in response to turbulence, may stall it. Once the tail has stalled it can no longer balance the destabilizing pitching moment of the wing, so the aircraft will pitch up, or pitch down if the stall is inverted.

Control movements will have small effect, and the magnitude of the pitching moment will increase rapidly until the wing also stalls. Once this happens the divergent pitching moment will probably decrease sharply in magnitude or even change sign if the tail is unblanketed and has a higher lift coefficient than the wing when stalled. Even if the latter occurs, the aircraft will probably reach a very high angle of attack before its pitching motion reverses, and may well spin.

Shifting the c.g. forward reduces the likelihood of tailplane stall and the difficulty of recovery, but also reduces the efficiency. Shifting it aft makes tailplane stall more likely and recovery more difficult. It also reduces the efficiency, but may, nevertheless, occur through fuel mismanagement or bad cargo loading or simply because the designer is seeking the greatest maneuverability.

If the wing of a statically unstable airplane has positive camber, the wing's nose-down pitching moment statically about its aerodynamic center will make tailplane stall more likely in negative g maneuvers than in normal flight. If the c.g. is shifted farther back so as to allow the wing's lift in normal flight to balance the pitching moment about the c.g. caused by the positive camber, the load on the tail will be larger still in negative g maneuvers, and inverted tailplane stall even more probable.

A half measure against tailplane stall is to shape the tail so it resists stalling and loses little lift if it stalls. Typically this calls for a low aspect ratio, with its penalty in increased induced drag. A sure cure is to control the aircraft in pitch by varying the lift of the front surface rather than the rear surface so that stabilizing pitching moments are created by reducing the lift of the controlled surface rather than increasing it. Though not theoretically necessary, it is then practical to make the front surface smaller than the rear, i.e., to use a canard arrangement. Whereas an aft-mounted tail on the point of stall can provide only a negligible increase in its lift coefficient, the canard surface can have its lift coefficient reduced to zero and then increased to stalling value in the opposite sense, a change of two units or more. Even if the wing stalls, initiating a pitch up, the canard surface can apply the necessary nose-down corrective moment to halt the divergence, provided it can reach a low or negative angle of attack with respect to the airstream. This may require an "all-flying" surface. It is not forbidden to have a tail at the rear in addition to the canard surface, as long as the canard surface is big enough and can be deflected far enough to make the net pitching moment stabilizing when the tail and wing are stalled.

Conventional canard aircraft, which have their centers of gravity located far enough forward to make them stable, can pitch down sharply after canard stall. The nose-down rotation following partial stall of the front surface increases its angle of attack, which makes the stall more complete and increases the nose-down pitching moment, further accelerating the pitch down, and so on. This should not be a problem with the unstable canard, because the inherent stability-induced pitch down does not happen. The nose-down rotation for stall recovery which has been described previously is a consequence of nose-down deflection of the canard surface and occurs at a rate set by the automatic control system. Without the operation of this system the recovery does not occur. The Wright brothers exploited this freedom from unavoidable recovery. Apparently they understood inherent stability, having flown their 1900 glider in a stable, tail-aft configuration by flying it backward. They persisted with their unstable canard configuration, stabilized by the pilot's reactions to avoid the incomplete stall recovery that had killed Lilienthal.[1] Their aircraft would mush to the ground, stalled,

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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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References

[1] Hooven, F.J., "The Wright Brothers Flight-Control System," *Scientific American*, Vol. 239, Nov. 1978, pp. 166-184.

[2] Culick, F.E.C., "The Origins of the First Man-Carrying Airplane," *Scientific American*, Vol. 241, July 1979, pp. 86-100.

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.

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.

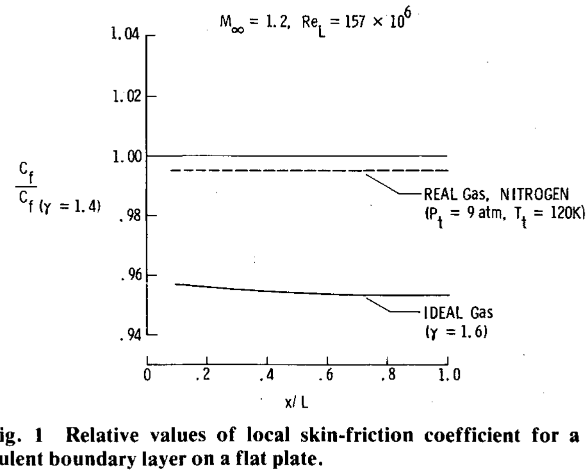

Fig. 1 Relative values of local skin-friction coefficient for a turbulent boundary layer on a flat plate.

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Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Transonic Flow; Testing, Flight and Ground.

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