Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Separation Jump and Sudden Stall over an Ellipsoidal Wing at Incidence

K. C. Wang*
San Diego State University, San Diego, California

Introduction

THIS Note reports some calculated results of an incompressible laminar boundary layer along the leeside symmetry plane of a wing-like flat ellipsoid. This is a follow-up of earlier investigations[1,2] for an ellipsoid of revolution or a prolate spheroid. The latter problem was also repeated in Ref. 3.

The emphasis here is on the "separation jump" phenomenon, which was first reported for the case of a body of revolution.[1,2] Accompanying such a discontinuous change of the separation point on the leeside symmetry plane, there is a corresponding change of the overall separation pattern on the whole body from an open-type separation to a closed-type separation.[4-6]

The present work also found a similar separation jump phenomenon. This was somewhat unexpected because of the wide differences between a body flow and a wing-like flow. Although it has long been known that when a short separation bubble on a two-dimensional airfoil bursts into a long bubble, there results a sudden change of separation point. However, the physical processes involved in the separation bubbles are absent in our present problem. A short bubble appears first near the leading edge and then extends rearward during the changeover to a long bubble; the separation jump reported here, on the contrary, results from a sudden movement of the separation point from the rear to the front. Whereas the separation bubble phenomenon involves turbulent reattachment, the present finding follows from straightforward laminar boundary-layer calculations. Thus, even though the phenomenon of stalling has been known for a long time, the triggering mechanism could still be subject to different interpretations.

Equations

We use the coordinates μ, θ, and z (Fig. 1) where μ is normal to the symmetry plane, θ is the angular coordinate, z is normal to the body surface, and u, v, and w are the corresponding velocities. θ varies from 0 to 2π, whereas μ becomes zero for the symmetry plane. μ and θ are not orthogonal surface coordinates except near the symmetry-plane. z is nondimensionalized by $a/\sqrt{R}$ where R ($=V_\infty a/\nu$, ν being the kinematic viscosity) is the Reynolds number, and w by $V/\sqrt{R}$. u, v are nondimensionalized with V_∞. The inviscid velocities U and V are also nondimensionalized by V_∞, and pressure by ρV_∞^2. Then the pertinent boundary-layer equations[7,8] for three variables, u_μ ($=\partial u/\partial\mu$), v, and w are

$$\frac{\partial v}{h_\theta \partial\theta}+\frac{u_\mu}{h_\mu}+\frac{\partial w}{\partial z}=0 \tag{1a}$$

$$\frac{v\partial v}{h_\theta\partial\theta}+w\frac{\partial v}{\partial z}=\frac{-\partial p}{h_\theta\partial\theta}+\frac{\partial^2 v}{\partial z^2} \tag{1b}$$

$$\frac{v\partial u_\mu}{h_\theta\partial\theta}+w\frac{\partial u_\mu}{\partial z}+\frac{(u_\mu)^2}{h_\mu}-\frac{v^2}{h_\mu h_\theta}\frac{\partial}{\partial\mu}\left(\frac{\partial h_\theta}{\partial\mu}\right)=-\frac{\partial}{\partial\mu}\left(\frac{\partial p}{h_\mu\partial\mu}\right)+\frac{\partial^2 u_\mu}{\partial z^2} \tag{1c}$$

The metric coefficients h_μ, h_θ, nondimensionalized by a, appear as

$$h_\mu = 1 \tag{2a}$$

$$h_\theta=(r_1^2\cos^2\theta+r_2^2\sin^2\theta)^{1/2} \tag{2b}$$

where $r_1=b/a$ and $r_2=c/a$.

The corresponding boundary conditions are

$$v=V,\qquad u_\mu=U_\mu\left(=\frac{\partial U}{\partial\mu}\right)\quad \text{at } z\to\infty \tag{3a}$$

$$v=w=u_\mu=0\qquad \text{at } z=0 \tag{3b}$$

The inviscid inputs are

$$U_\mu=\frac{\partial U}{\partial\mu}=g_1\sin\theta+g_2\cos\theta \tag{4a}$$

$$\frac{\partial p}{h_\theta\partial\theta}=\frac{-V(g_1\sin\theta+g_2\cos\theta)}{h_\theta(r_1^2\cos^2\theta+r_2^2\sin^2\theta)^{1/2}}-\frac{V^2}{h_\theta}\frac{(r_1^2-r_2^2)\cos\theta\sin\theta}{(r_1^2\cos^2\theta+r_2^2\sin^2\theta)} \tag{4b}$$

$$\frac{\partial}{\partial\mu}\left(\frac{\partial p}{h_\mu\partial\mu}\right)=\frac{\partial^2 p}{h_\mu\partial\mu^2}=-U_\mu^2 \tag{4c}$$

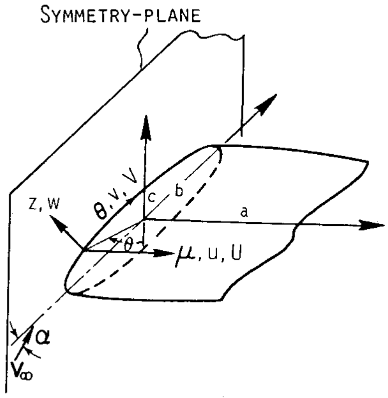

Fig. 1 Geometry and coordinates.

Received April 13, 1983; revision received Aug. 8, 1983.

*Professor, Aerospace Engineering and Engineering Mechanics. Member AIAA.

$$\frac{\partial}{\partial \mu}\left(\frac{\partial h_\theta}{\partial \mu}\right) = -(r_1^2\cos^2\theta + r_2^2\sin^2\theta)^{1/2} = -h_\theta \quad (4d)$$

where

$$g_1 = \frac{2\cos\alpha}{2-\beta_0} r_1 \quad (5a)$$

$$g_2 = \frac{2\sin\alpha}{2-\gamma_0} r_2 \quad (5b)$$

with

$$\beta_0 = r_1 r_2 \int_0^\infty \frac{d\xi}{(\xi + r_1^2)\delta} \quad (5c)$$

$$\gamma_0 = r_1 r_2 \int_0^\infty \frac{d\xi}{(\xi + r_2^2)\delta} \quad (5d)$$

$$\delta = [(\xi+1)(\xi+r_1^2)(\xi+r_2^2)]^{1/2} \quad (5e)$$

The elliptical integrals β_0, γ_0 can be explicitly evaluated.[9]

The skin friction $c_{f\theta}$ is given by

$$c_{f\theta} = \frac{1}{\sqrt{R}}\left(\frac{\partial v}{\partial z}\right)_{z-0} \quad (6)$$

Results

The above equations were solved in the same way as before,[1,2] using the same method and computer program. The skin-friction variations for three different cases are presented here corresponding to three different axis ratios *a:b:c,* each at various incidences. While calculations were made using the eccentric angle θ, a chordwise coordinate defined by $\nu = \cos(270\text{ deg} - \theta)$ was, however, introduced in presenting the results. Following the usual convention in the airfoil theory, $\nu = 1.0$ at the trailing edge ($\theta = 270$ deg) and -1.0 at the leading edge ($\theta = 90$ deg).

Case 1: Typical Problem

The first case is for the ratios a:b:c=30:6:1. This corresponds to a typical situation for the conventional large aspect ratio wing. Figure 2a shows the skin-friction variation. When the incidence remains below 10.5 deg, $c_{f\theta}$ always drops monotonically until it becomes zero, and the separation point moves continually forward. At $\alpha = 10.75$ deg, the skin friction decreases first to a minimum and rises somewhat before finally falling to zero. At slightly higher incidence, $\alpha = 10.85$ deg, the minimum skin-friction point shifts further downward, and the separation point moves backward instead of forward. As this trend continues, the minimum skin friction touches zero at $\alpha = 11$ deg, at which point the separation point takes a discontinuous jump forward.

Case 2: Longer Chord

Case 2 is for a:b:c=30:8:1, where a and c are kept constant while b is increased from 6 to 8. The corresponding distribution of the skin friction is shown in Fig. 2b. A longer chord makes the wing more sensitive to an increase of incidence. The nonmonotonic decrease of skin friction as a characteristic of the separation jump phenomenon becomes noticeable at smaller incidence, and the critical incidence for the jump decreases to $\alpha = 8.7$ deg. Comparing case 1, the jump here is more pronounced and covers more than half of the chord length. Hence, an increase of b with a and c fixed, considerably enhances the "separation jump" phenomenon.

Case 3: Shorter Chord

Case 3 is for a:b:c=20:5:1. In comparison with case 1, span a is reduced from 30 to 20 and chord b is reduced from 6 to 5.

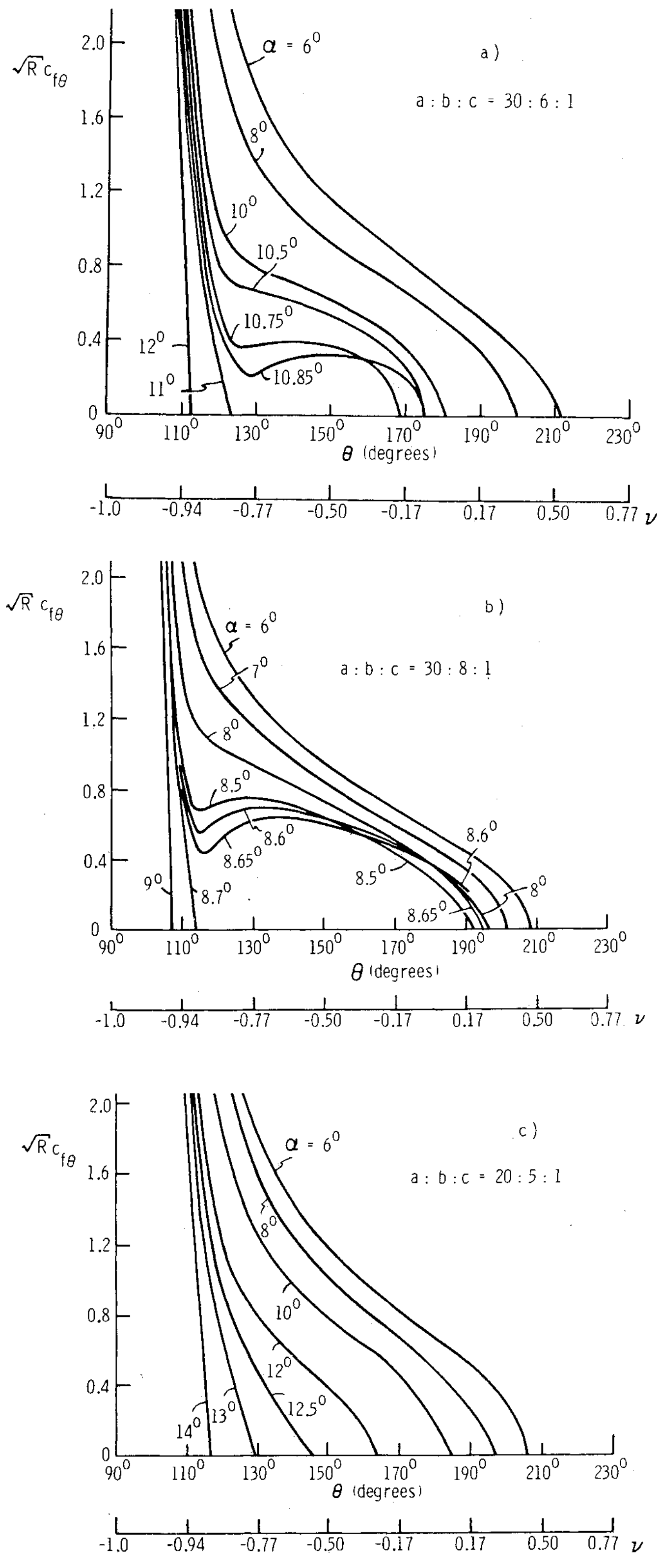

Fig. 2 Leeside skin friction.

The resulting skin friction $c_{f\theta}$ is shown in Fig. 2c. Surprisingly, for all incidences, $c_{f\theta}$ always decreases monotonically to zero, the separation point moves forward continuously, and the aforementioned separation jump was not found. In a separate case not reported here, it was found that reduction of a from 30 to 10 with b and c held constant does not affect the separation jump; hence, the disappearance of the separation jump for the present case must be due to the shortening of b rather than a.

The reason for the occurrence of separation jump with a flat ellipsoid is the same as that for a body of revolution, that is, the interplay between the pressure gradient $\partial p / h_\theta \partial \theta$ and the lateral pressure curvature $\partial^2 p / h_\mu \partial \mu^2 \sim U_\mu^2$. Their effects on the profiles of v and u_μ and hence the skin friction were explained in Ref. 2 and in more detail in Ref. 10. We shall omit such discussion herein.

Acknowledgment

This work was supported by AFOSR under Contract F49620-76-C-0004 and Grant AFOSR-81-0109.

References

[1] Wang, K.C., "Three-Dimensional Boundary Layer near the Plane of Symmetry of a Spheroid at Incidence," *Journal of Fluid Mechanics,* Vol. 43, No. 1, 1970, pp. 187-200.

[2] Wang, K.C., "Laminar Boundary Layer near the Symmetry-Plane of a Prolate Spheroid," *AIAA Journal,* Vol. 12, July 1974, pp. 949-958.

[3] Cebeci, T., Khattab, A.K., and Stewartson, K., "On Nose Separation," *Journal of Fluid Mechanics,* Vol. 97, No. 3, 1980, pp. 435-454.

[4] Wang, K.C., "Separation Patterns of Boundary Layer over an Inclined Body of Revolution," *AIAA Journal,* Vol. 10, Aug. 1972, pp. 1044-1050.

[5] Wang, K.C., "Separation of Three-Dimensional Flow," *Proceedings of the Lockheed-Georgia Company Viscous Flow Symposium,* Atlanta, Ga., LG77ER0044, 1977, pp. 341-414; also, Martin-Marietta Labs., Balitomore, Maryland, TR 76-54C, 1976.

[6] Wang, K.C., "On the Disputes About Open Separation," AIAA Paper 83-0296, Jan. 1983; also, San Diego State University AE&EM TR-82-02, July 1982.

[7] Lamb, H., *Hydrodynamics,* 6th Ed., Dover, New York, 1945.

[8] Wang, K.C., "Separation Jump and Sudden Stall over an Ellipsoidal Wing at Incidence," Martin-Marietta Labs., Baltimore, Maryland, TR 79-22C, 1979.

[9] Grobner, W. and Hofreiter, N., *Integraltafel, Erster Teil,* Springer-Verlag, New York, 1965, pp. 78-79.

[10] Wang, K. C., "Three-Dimensional Laminar Boundary Layer over Body of Revolution at Incidence, Part V. Further Investigation Near the Plane of Symmetry," Martin-Marietta Corp., Baltimore, Maryland, RIAS TR 71-14C, Sept. 1971.

Wall Shear Fluctuations in a Turbulent Boundary Layer

M. A. Badri Narayanan,* S. Raghu,†
and
Kamal Poddar†
Indian Institute of Science, Bangalore, India

Introduction

In the last two decades, the instantaneous structure of a turbulent boundary layer has been examined by many in an effort to understand the dynamics of the flow. Distinct and well-defined flow patterns that seem to have great relevance to the turbulence production mechanism have been observed in the wall region.[1,2] The flow near the wall is intermittent with periodic eruptions of the fluid, a phenomenon generally termed "bursting process." Earlier investigations in this field were limited to liquid flows at low speeds and the entire flow pattern was observed using flow visualization techniques. Study was later extended to boundary-layer flows in wind tunnels at higher speeds and Reynolds numbers using hot-wire signals for the analysis of the bursting phenomenon.

Using a selective filtering technique, Rao et al.[3] found that the occurrence rate of the intermittent signals was constant across an entire given boundary layer, with the average time interval T between two consecutive events scaling with the freestream velocity U and the thickness of the boundary layer δ. The value of UT/δ was around 5.0. The time scales obtained from autocorrelation measurements of the fluctuating signals[4,5] have also yielded the same values as those of Rao et al.[3] A further study of the instantaneous hot-wire records by Badri Narayanan et al.[6] indicated that T could also be obtained from the zero crossings of the fluctuating signals. Recent measurements of boundary layers over highly curved walls by Ramaprian and Shivaprasad[8] substantiate the above view.

The fact that the same time scale T has been obtained by different methods scaled with the other variables clearly suggests that large-scale eddy-like structures exist in a boundary layer and that they span the entire thickness of the layer. A number of speculations have been made about the shape of these eddies.[6,7] However, a well-defined picture has yet to emerge.

In the present investigation, the wall shear fluctuations are examined. It is observed that, while the zero crossings do yield the time scale for the large-scale motions, the average period of the overall fluctuations is governed by the wall shear.

Experimental Setup

The experiments were conducted in the turbulent boundary layer formed on the top wall of a low-speed wind tunnel having a 30 cm^2 test section. In the region where the measurements were made, the thickness of the boundary layer was about 25 mm and it remained nearly constant in the freestream velocity range of 5-30 m/s. A thin-film heat-transfer gage (1 mm wide, 2 mm long), operated at constant temperature and an overheat ratio of 1.05, was employed to sense the fluctuating wall shear. The output signals from the system were recorded on a film after filtering frequencies beyond 5000 Hz.

Results and Discussion

The output signals from the thin-film heat-transfer gage were directly analyzed for 1) an average period for the fluctuations T_l and 2) the rate of zero crossings around the

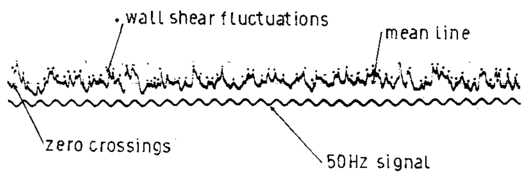

Fig. 1 Sample trace of the wall shear fluctuations (this trace has 78 zero crossings and 90 shear fluctuations).

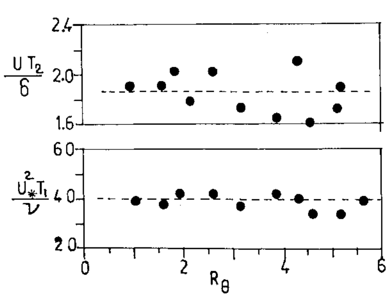

Fig. 2 Scaling of T_l with friction velocity and T_2 with boundary-layer thickness.

Received Jan. 4, 1983; revision received Oct. 4, 1983.

*Professor, Department of Aerospace Engineering.

†Research Student, Department of Aerospace Engineering.