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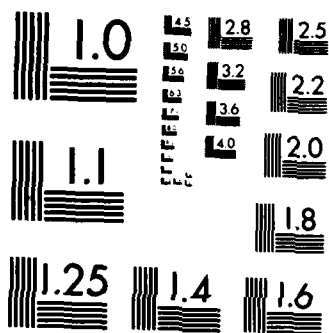
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**DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER**

Bethesda, Maryland 20084



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**AN INTEGRAL PREDICTION METHOD FOR
THREE-DIMENSIONAL FLOW SEPARATION**

by

T. C. Tai

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Presented as Paper AIAA-84-0014 at the
22nd Aerospace Sciences Meeting
Reno, Nevada, on 9-12 January 1984

**AVIATION AND SURFACE EFFECTS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT**

May 1984

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AN INTEGRAL PREDICTION METHOD FOR THREE-DIMENSIONAL FLOW SEPARATION

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coupled with the streamline equation and integrated using the fourth-order Runge-Kutta scheme. Cross flow derivatives are evaluated and accounted for during the integration. A prolate spheroid at incidence in an incompressible turbulent flow is considered as a test case. Good comparison between the theory and the experiment has been observed for the case of $\alpha = 10$ degrees. For the case of high incidence, the method predicts a qualitative trend but deviated quantitatively due to the large crossflow involved.

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TABLE OF CONTENTS

	Page
LIST OF FIGURES	iii
ABSTRACT	1
NOMENCLATURE	1
INTRODUCTION	1
CALCULATION OF VISCOUS STREAMLINES	1
INTEGRAL SOLUTION TO THREE-DIMENSIONAL TURBULENT BOUNDARY LAYERS	2
NUMERICAL INTEGRATION	3
RESULTS AND DISCUSSION	4
CONCLUDING REMARKS	6
REFERENCES	6
APPENDIX	7
INITIAL DISTRIBUTION	8

LIST OF FIGURES

1 - Streamlines in a Boundary Layer	2
2 - Coordinate Systems	2
3 - Streamwise Boundary Layer Shape Factor of Flow over a Prolate Spheroid at $\alpha = 10$ Deg and $V_{\infty} = 45$ m/s	4
4 - Streamwise Momentum Thickness of Flow over a Prolate Spheroid at $\alpha = 10$ Deg and $V_{\infty} = 45$ m/s	4
5 - Streamwise Skin Friction Coefficients of Flow over a Prolate Spheroid at $\alpha = 10$ deg and $V_{\infty} = 45$ m/s	4
6 - Direction of Wall Shear Stress of Flow over a Prolate Spheroid at $\alpha = 10$ deg and $V_{\infty} = 45$ m/s	4
7 - Comparison of Calculated and External Inviscid Streamlines	5
8 - Crossflow Velocity Profiles and Resulting Shear Stress Derivatives along Streamline $\eta = 3$ of Flow over a Prolate Spheroid at $\alpha = 10$ deg and $V_{\infty} = 45$ m/s	5
9 - Crossflow Skin Friction Coefficients of Flow over a Prolate Spheroid at $\alpha = 10$ deg and $V_{\infty} = 45$ m/s	5
10 - Flow Separation Pattern on a Prolate Spheroid at $\alpha = 10$ deg and $V_{\infty} = 45$ m/s	6
11 - Flow Separation Pattern on a Prolate Spheroid at $\alpha = 20$ deg and $V_{\infty} = 45$ m/s	6

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An Integral Prediction Method for Three-Dimensional Flow Separation

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AN INTEGRAL PREDICTION METHOD FOR THREE-DIMENSIONAL FLOW SEPARATION

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Abstract

A three-dimensional integral boundary-layer approach is developed and coupled with the streamline method for theoretically determining the vortex-type flow separation. The governing equations are solved in a streamwise system using a power-law profile for the streamwise flow and the Mager profile for the crossflow. The reduced ordinary system is then coupled with the streamline equation and integrated using the fourth-order Runge-Kutta scheme. Crossflow derivatives are evaluated and accounted for during the integration. A prolate spheroid at incidence in an incompressible turbulent flow is considered as a test case. Good comparison between the theory and the experiment has been observed for the case of $\alpha = 10$ degrees. For the case of high incidence, the method predicts a qualitative trend but deviates quantitatively due to the large crossflow involved.

Nomenclature

- a, b = major and minor axes of an ellipsoid
 C_E = entrainment coefficient, defined in Eq. (9)
 C_f = skin friction coefficient
 f = local body radial distance from the centerline
 H = shape factor, δ_1/θ_{11}
 h = $(H - 1)/2$
 h_1, h_2 = metric coefficients for coordinates ξ, η
 K_1 = curvature parameter, $\frac{1}{h_1 h_2} \frac{\partial h_1}{\partial \eta}$
 K_2 = curvature parameter, $\frac{1}{h_1 h_2} \frac{\partial h_2}{\partial \xi}$
 M = Mach number
 P = static pressure
 Re = Reynolds number, $\rho V_\infty a / \mu$
 s, n = distance along and normal to a streamline
 U = velocity at edge of boundary layer
 u, v = velocity components in streamwise coordinates
 V_∞ = freestream velocity
 x, ϕ = body-oriented orthogonal coordinates
 $\bar{x}, \bar{y}, \bar{z}$ = Cartesian coordinates
 α = angle of attack
 β = wall shear angle between external inviscid streamline and corresponding limiting streamline
 γ = ratio of specific heats
 δ = boundary layer thickness
 δ_1 = streamwise displacement thickness
 $= \int_0^\delta \left(1 - \frac{u}{U}\right) d\zeta$
 δ_2 = crosswise displacement thickness
 $= \int_0^\delta -\frac{v}{U} d\zeta$
 θ_{11} = streamwise momentum thickness
 $= \int_0^\delta \left(1 - \frac{u}{U}\right) \frac{u}{U} d\zeta$

- θ_{12} = crossflow momentum thickness
 $= \int_0^\delta \left(1 - \frac{u}{U}\right) \frac{v}{U} d\zeta$
 θ_{21} = crossflow momentum thickness
 $= \int_0^\delta \frac{u}{U} \frac{v}{U} d\zeta$
 θ_{22} = crossflow momentum thickness
 $= \int_0^\delta \left(\frac{v}{U}\right)^2 d\zeta$
 θ = streamline angle
 λ = $\tan \beta$
 μ = viscosity
 ξ, η, ζ = streamwise coordinates
 ρ = density
 τ = shearing stress

Subscripts

- w = wall
 ∞ = freestream
 ξ, η = ξ, η direction

Introduction

In three-dimensional flows, the envelope of limiting streamlines has been used as the separation line. Thus defined, the determination of the separation line has been found to be very difficult analytically even with the most sophisticated numerical techniques available. For most flows of practical interest, however, the separation is of the vortex type where vortices are created as a result of the convergence of viscous streamlines above the line of separation. The line of separation can be properly determined by the envelope of viscous streamlines in the boundary layer.¹

The problem, therefore, is to determine the realistic streamline pattern based on realistic pressure or shear stress, either by experimental measurements or by means of viscous-inviscid interactions. An attempt at using pure inviscid pressure along with a simple friction model has had limited success.² A more general theoretical method is yet to be developed. The purpose of this paper is to describe a theoretical procedure for determining the vortex-type flow separation using a three-dimensional integral boundary-layer solution coupled with the streamline method.¹ As opposed to the usual boundary-layer approach, this method deals with the convergence of streamlines rather than with the vanishing of skin friction. A prolate spheroid at incidence in an incompressible turbulent flow is considered as a test case.

Calculation of Viscous Streamlines

To simulate the physical flow so that the flow separation can be detected, it is necessary to consider the streamlines inside the boundary layer; see Fig. 1. It is assumed that the envelope of converging viscous streamlines is above, but close to, that of the converging wall-limiting streamlines. Therefore, the line of separation can be determined by the envelope of converging streamline equations derived earlier:^{1, 2}

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*Research Aerospace Engineer, Aviation and Surface Effects Department. Associate Fellow AIAA.

$$\frac{D\phi}{Ds} = \frac{\sin \theta}{f} \quad (1)$$

$$\frac{Dx}{Ds} = \cos \theta \quad (2)$$

$$\frac{D\theta}{Ds} = \frac{1}{\gamma M^2 P} \left(\frac{\partial P}{\partial x} \sin \theta - \frac{1}{f} \frac{\partial P}{\partial \phi} \cos \theta + \frac{\partial \tau_\eta}{\partial \xi} \right) - \frac{df}{dx} \frac{\sin \theta}{f} \quad (3)$$

where conventional symbols have been used with geometric variables illustrated in Fig. 2. For incompressible flows, the potential flow solution¹ can be used for the pressure gradients $\partial P / \partial x$ and $\partial P / \partial \phi$ in Eq. (3). The problem, therefore, is to provide proper values for the shear stress derivative $\partial \tau_\eta / \partial \xi$.

Integral Solution to Three-Dimensional Turbulent Boundary Layers

A simple analytic model for the shear stress derivative has shown some promise.² However, in more general cases, where the flow separation is predominantly of the vortex type, a more rigorous theoretical form is in order. While it is not straightforward to derive a universal theoretical friction model, it is possible, in most cases, to provide the required friction values numerically. In so doing, the use of the integral method seems to be appropriate because of its compactness and compatibility with the streamline approach. The (longitudinal) integration can be performed along a streamline.

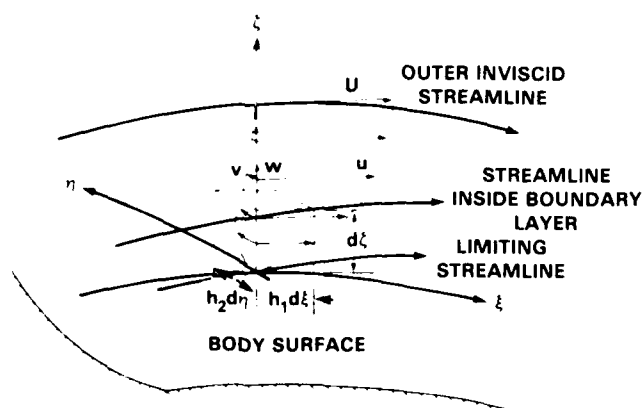


Fig. 1 - Streamlines in a boundary layer

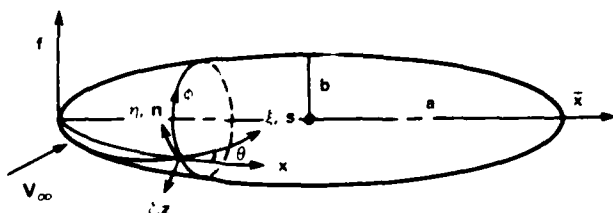


Fig. 2 - Coordinate systems

The integral equations for an incompressible, three-dimensional, turbulent boundary layer in streamwise coordinates are:

ξ — momentum

$$\frac{1}{h_1} \frac{\partial \Theta_{11}}{\partial \xi} + \frac{1}{h_2} \frac{\partial \Theta_{12}}{\partial \eta} + \frac{2\Theta_{11}}{U h_1} \frac{\partial U}{\partial \xi} + \frac{\partial \tau_\eta}{\partial \xi} = (\Theta_{11} - \Theta_{22}) K_2 \quad (4)$$

η — momentum

$$\frac{1}{h_1} \frac{\partial \Theta_{21}}{\partial \xi} + \frac{1}{h_2} \frac{\partial \Theta_{22}}{\partial \eta} + \frac{2\Theta_{21}}{U h_2} \frac{\partial U}{\partial \eta} + \frac{\partial \tau_\eta}{\partial \eta} = (\Theta_{11} - \Theta_{22} + \delta_1) K_1 - \frac{\tau_\eta}{U^2} \quad (5)$$

Continuity

$$\frac{1}{h_1} \frac{\partial (\delta - \delta_1)}{\partial \xi} + \frac{1}{h_2} \frac{\partial \delta_2}{\partial \eta} + \left(K_2 + \frac{1}{U h_1} \frac{\partial U}{\partial \xi} \right) (\delta - \delta_1) - \left(K_1 + \frac{1}{U h_2} \frac{\partial U}{\partial \eta} \right) \delta_2 = C_t \quad (6)$$

To close the system, streamwise and crossflow velocity profiles, auxiliary relations for the skin friction, and flow entrainment are needed. The streamwise velocity profile is assumed to be the power-law form for two-dimensional flow; that is,

$$\frac{u}{U} = \left(\frac{z}{\delta} \right)^h$$

or

$$\bar{u} = z^h \quad (7)$$

where $z = \xi / \delta$, $h = (H - 1)/2$, and H is the shape factor. The crossflow velocity profile takes the form suggested by Mager,⁴

$$\frac{v}{U} = \frac{u}{U} \left(1 - \frac{z}{\delta} \right)^2 \tan \beta$$

or

$$\bar{v} = \bar{u} (1 - z)^2 \lambda \quad (8)$$

where $\lambda = \tan \beta$. The boundary-layer solution procedure in the present work is similar to that of Smith,⁵ but differs in several aspects which will appear later.

The entrainment coefficient C_t is given as a function of the shape factor H by Green,⁶ with the constant term being modified from 0.022 to 0.032:

$$C_t = 0.025H - 0.032 \quad (9)$$

The skin friction coefficient is related to the shape factor H and the Reynolds number based on the streamwise momentum thickness $Re_{\Theta_{11}}$,⁶

$$\left(\frac{C_{ft}}{C_{f0}} + 0.5 \right) \left(\frac{H}{H_0} - 0.4 \right) = 0.9 \quad (10)$$

where C_{f0} and H_0 are functions of $Re_{\Theta_{11}}$:

$$C_{f0} = \frac{0.01013}{2n Re_{\Theta_{11}} - 1.02} - 0.00075$$

$$H_0 = \frac{1}{1 - 6.55 \sqrt{0.5 C_{f0}}}$$

and the $Re_{\Theta_{11}}$ and C_f are defined:

$$Re_{\Theta_{11}} = \frac{\rho U \Theta_{11}}{\mu}$$

$$C_f = \frac{\tau_w}{\frac{1}{2} \rho U^2}$$

The expressions for the curvature parameters K_1 and K_2 are derived in terms of quantities along a streamline. For K_1 , the geometric relationship between two surface coordinate systems (x, ϕ) and (ξ, η) is used:

$$\frac{\partial \phi}{\partial \xi} = \frac{h_1 \sin \theta}{f}; \quad \frac{\partial \phi}{\partial \eta} = \frac{h_2 \cos \theta}{f}$$

Taking cross differentiation and letting

$$\frac{\partial^2 \phi}{\partial \eta \partial \xi} = \frac{\partial^2 \phi}{\partial \xi \partial \eta}$$

result in

$$\begin{aligned} K_1 &= \frac{1}{h_1 h_2} \frac{\partial h_1}{\partial \eta} \\ &= \cot \theta \left(\frac{1}{h_1 h_2} \frac{\partial h_2}{\partial \xi} - \frac{1}{h_2} \frac{\partial \theta}{\partial \eta} - \frac{1}{f h_1} \frac{\partial f}{\partial \xi} \right) \\ &\quad - \frac{1}{h_1} \frac{\partial \theta}{\partial \xi} + \frac{1}{f h_2} \frac{\partial f}{\partial \eta} \\ &= \frac{1}{\gamma M^2 P} \left(-\frac{\partial P}{\partial x} \sin \theta + \frac{1}{f} \frac{\partial P}{\partial \phi} \cos \theta \right) \end{aligned} \quad (11)$$

where the sum of the three terms in parentheses is zero,⁷ and the inviscid form of Eq. (3) has been used.

To find K_2 , the continuity equation is written for the external flow in both the x, ϕ coordinate system and the ξ, η system. By equating, there results

$$\begin{aligned} K_2 &= \frac{1}{h_1 h_2} \frac{\partial h_2}{\partial \xi} \\ &= \frac{1}{\gamma M^2 P} \left(\frac{\partial P}{\partial x} \cos \theta + \frac{1}{f} \frac{\partial P}{\partial \phi} \sin \theta \right) \end{aligned} \quad (12)$$

Numerical Integration

Equations (4) through (6), with the aid of Eqs. (7) through (12), allow solutions for three basic unknowns: the shape factor H , the streamwise displacement Θ_{11} , and the tangent of the angle between the external inviscid streamline and the corresponding limiting streamline λ . These equations are recast into the form of streamwise derivatives:

$$\frac{DH}{Ds} = G_1 \quad (13)$$

$$\frac{D\Theta_{11}}{Ds} = G_2 \quad (14)$$

$$\frac{D\lambda}{Ds} = G_3 \quad (15)$$

where $D/Ds = (1/h_1) \partial/\partial \xi$, and G_1 , G_2 , and G_3 contain:

- (a) geometric properties and outer edge flow properties
- (b) variables H , Θ_{11} , λ , etc. and
- (c) crossflow derivatives of H , Θ_{11} , and λ

The detailed expressions for G_1 , G_2 , and G_3 are presented in the Appendix.

With the viscous solution in hand, the crossflow shear derivative required by Eq. (3) is obtained by differentiating Eq. (8) with the aid of the following relationships:

$$\begin{aligned} \tau_\eta &= \epsilon \frac{\partial v}{\partial \xi} \\ &= \frac{U \epsilon \lambda}{d} \left[-2(1-z)\bar{u} + (1-z)^2 \frac{\partial \bar{u}}{\partial z} \right] \end{aligned} \quad (16)$$

and

$$\begin{aligned} \frac{\partial \tau_\eta}{\partial \xi} &= \frac{\partial}{\partial \xi} \left(\epsilon \frac{\partial v}{\partial \xi} \right) \\ &= \frac{U \epsilon \lambda}{d^2} \left[2 \left(1 - \frac{1-z}{\epsilon} \frac{\partial \epsilon}{\partial z} \right) \bar{u} - (1-z) \left(4 - \frac{1-z}{\epsilon} \frac{\partial \epsilon}{\partial z} \right) \frac{\partial \bar{u}}{\partial z} \right. \\ &\quad \left. + (1-z)^2 \frac{\partial^2 \bar{u}}{\partial z^2} \right] \end{aligned} \quad (17)$$

To eliminate the unknown eddy viscosity ϵ and its derivative $\partial \epsilon / \partial z$, the ϵ value is correlated with the streamwise shear stress such that

$$\tau_\xi = \epsilon \frac{\partial u}{\partial \xi} = \frac{U \epsilon}{d} \frac{\partial \bar{u}}{\partial z} \quad (18)$$

and

$$\begin{aligned} \frac{\partial \tau_\xi}{\partial \xi} &= \frac{\partial \epsilon}{\partial \xi} \frac{\partial u}{\partial \xi} + \epsilon \frac{\partial^2 u}{\partial \xi^2} \\ &= \frac{U \epsilon}{d^2} \left(\frac{1}{\epsilon} \frac{\partial \epsilon}{\partial \xi} \frac{\partial \bar{u}}{\partial z} + \frac{\partial^2 \bar{u}}{\partial z^2} \right) \end{aligned} \quad (19)$$

It is further assumed that the streamwise shear stress varies linearly across the boundary layer:

$$\tau_\xi = \tau_{\xi w} (1-z) = \frac{1}{2} \rho U^2 C_{f\ell} (1-z) \quad (20)$$

which yields

$$\frac{1}{\gamma M^2 P} \frac{\partial \tau_\xi}{\partial \xi} = -\frac{C_{f\ell}}{2d} \quad (21)$$

With the aid of relations (18) through (21), along with basic profiles (7) and (8), one obtains

$$\begin{aligned} \frac{1}{\gamma M^2 P} \frac{\partial \tau_\eta}{\partial \xi} &= \frac{C_{f\ell} \lambda (1-z)}{d} \left\{ \left(\frac{z}{h} - \frac{1-z}{2} \right) \times \right. \\ &\quad \left. \left[1 - \frac{(1-h)(1-z)}{z} \right] - 2(1-z) \right\} \end{aligned} \quad (22)$$

where z is set to d_1/d for actual calculations. The choice, although arbitrary, is considered to be the most appropriate in capturing the overall property of the boundary layer.

Equations (4) through (6) are coupled with Eqs. (1) through (3) and integrated simultaneously along a streamline. The fourth-order Runge-Kutta scheme is used in the numerical integration. To account for the crossflow derivatives, the integration is performed along at least two adjacent streamlines simultaneously. The differences in the resulting variables are then evaluated as the crossflow derivatives and immediately fed into the source terms of Eqs. (4) through (6); see Appendix. This whole procedure has been coded in BASIC language using an H-P 9836 desk-top computer. Calculated flow patterns are instantly displayed graphically to facilitate locating the streamline convergence.

Results and Discussion

Numerical results are calculated for a prolate spheroid ($a/b = 5.91$) at $V_\infty = 45$ m/s (147.6 ft/s) and $\alpha = 10$ and 20 deg. The flow is largely turbulent. In the calculation, the flow is tripped to turbulent at $s/a = 0.1$, where the initial conditions $H = 1.35$, $\Theta_{11} = 0.0005$, and $\lambda = 0$ are applied. Results of the streamwise shape factor H and the momentum thickness Θ_{11} along streamlines of $\eta = 1, 3, 10$, and 70 for the case of $\alpha = 10$ deg are shown in Figs. 3 and 4, respectively. The Θ_{11} values rise significantly in all four streamlines as they proceed downstream. Nevertheless, the downstream flow exhibits reasonable stability as indicated by declining H values in that region.

Figures 5 and 6 show the calculated results of the streamwise skin friction coefficient $C_{f\ell}$ and the direction of the wall shear stress λ , along the above streamlines. Comparison of the present $C_{f\ell}$ values with those obtained by a finite difference scheme⁸ and by experiment⁹ is made. Agreement is within the range of the data scattering; see Fig. 5. The crossflow characteristics are represented by the value λ ($\lambda = \tan \beta$). Generally, λ takes on a positive value in the upstream region and turns negative downstream; see Fig. 6. This indicates that the effect of viscosity makes the streamline steeper in the upstream region and flatter downstream compared with the external inviscid streamlines based on the potential flow theory; see Fig. 7. The trend is consistent with previous findings.^{10, 11} The deflection of streamlines in the leeside that causes vortex-type separation is clearly portrayed.

Contrary to intuition, the deviation of viscous streamlines from the inviscid pattern does not stem from the shear stress derivative in Eq. (3), but rather is attributed to the deficiency of the velocity inside the boundary layer. In Fig. 8, the crossflow velocity profiles and the resulting shear stress derivatives are plotted at five locations along the streamline $\eta = 3$. At $z = d_1/d$, where the layer is set for the present computation, the numerical values for $\partial \tau_w / \partial z / \gamma M^2 P$ from Eq. (22) are negative in the upstream region (Points A, B, and C in Fig. 8) then change to positive downstream (Points D and E). In fact, these friction values provide resistance to the change of the streamline direction from its external pattern.

The change in the sign of the wall shear angle from positive to negative implies that a zero crossflow skin friction line exists, since $C_{f\eta} = \lambda C_{f\ell}$. The calculated crossflow skin friction coefficients along these lines are presented in Fig. 9. Based on the framework of the present theory, this zero crossflow skin friction line (portrayed in Fig. 10) is apparently not a line of separation. This is in agreement with experimental observation.¹²

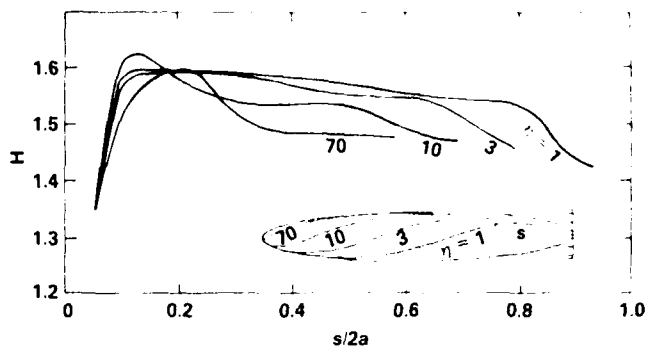


Fig. 3 - Streamwise boundary layer shape factor of flow over a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

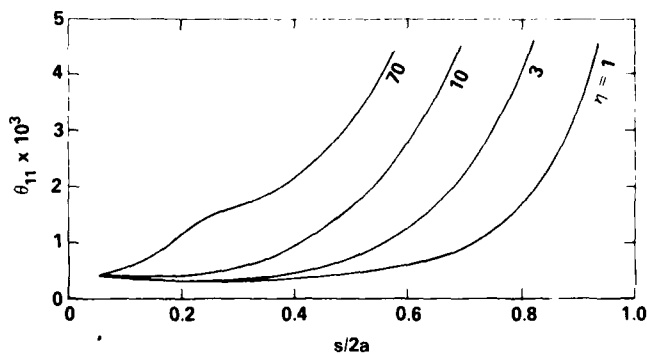


Fig. 4 - Streamwise momentum thickness of flow over a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

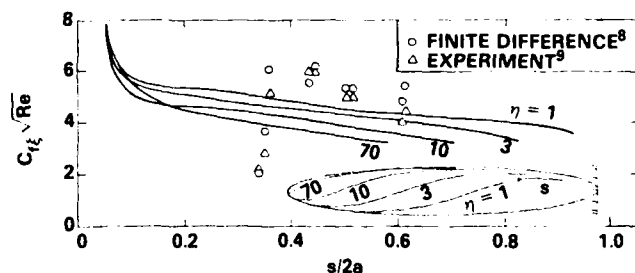


Fig. 5 - Streamwise skin friction coefficients of flow over a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

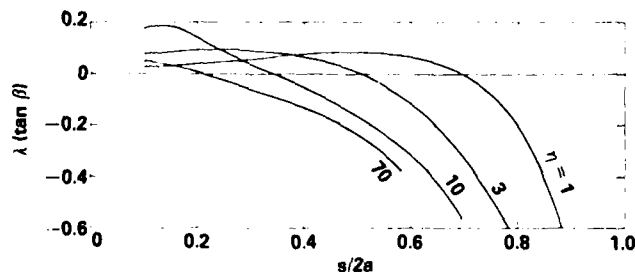


Fig. 6 - Direction of wall shear stress of flow over a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

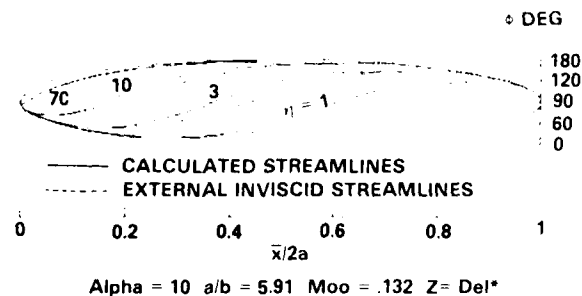


Fig. 7 - Comparison of calculated and external inviscid streamlines

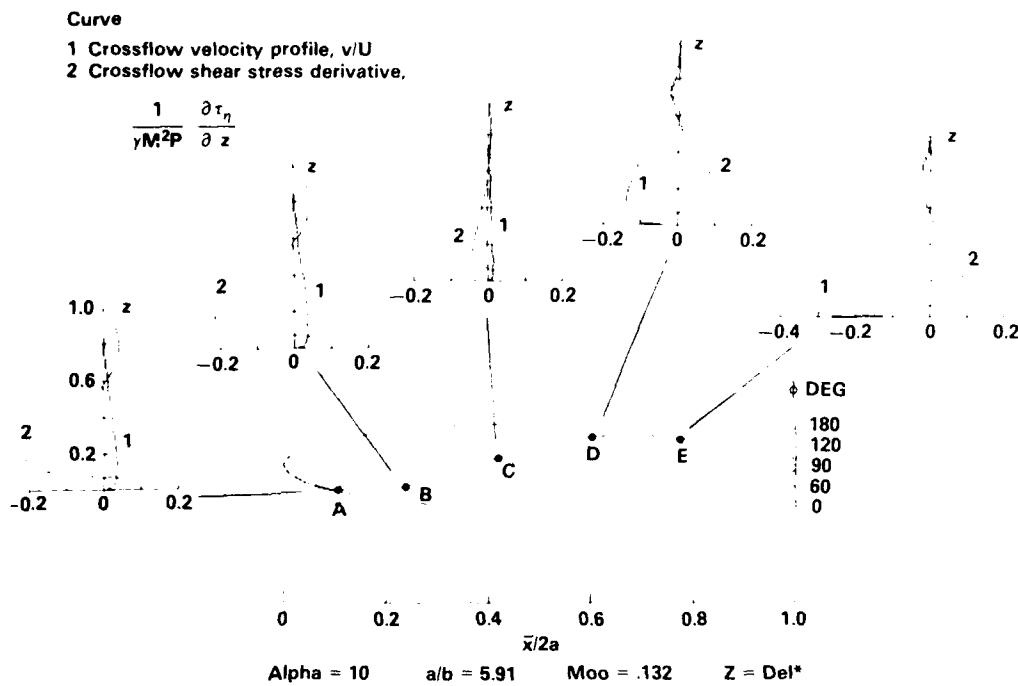


Fig. 8 - Crossflow velocity profiles and resulting shear stress derivatives along streamline $\eta = 3$ of flow over a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

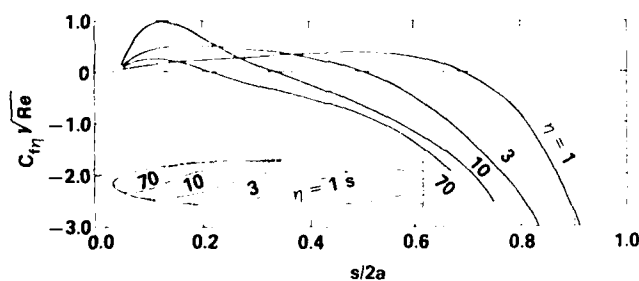


Fig. 9 - Crossflow skin friction coefficients of flow over a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

The calculated overall flow pattern is shown in Fig. 10. The flow separation is detected near the rear stagnation region. The result is compared with that obtained by the limiting streamline pattern based on the measured wall shear stresses.¹³ Agreement is very good. At the line of separation, which results from the formation of the envelope of viscous streamlines, the streamlines from the windside yield higher streamwise wall friction values than those from the leeside. This implies that the windside streamlines possess more energy and, therefore, will roll over those from the leeside. A similar conclusion was reached from the analysis based on the difference in velocity components at the edge of the boundary layer normal to the separation line.¹¹

The result of the flow pattern at $\alpha = 20$ deg is shown in Fig. 11. The line of separation emerges further in the upstream creating a larger separated region in the leeside of the flow. Although a direct comparison between calculated and experimental results cannot be made because of a lack of published data for this particular angle of attack, the present result does fall in between the measurements of the $\alpha = 10$ - to 30-deg cases.¹²

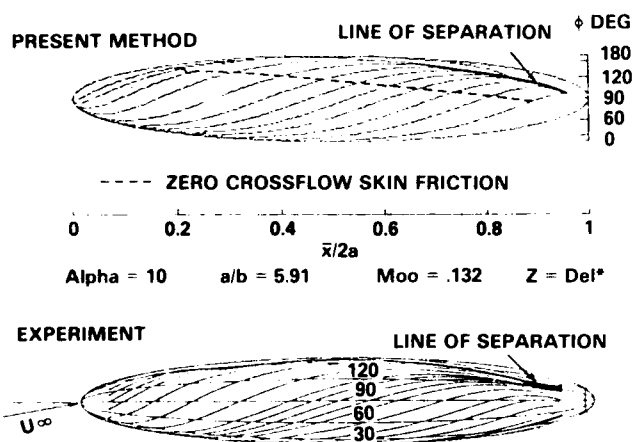


Fig. 10 - Flow separation pattern on a prolate spheroid at $\alpha = 10$ deg and $V_\infty = 45$ m/s

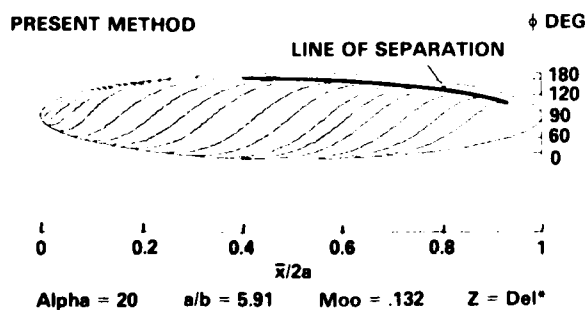


Fig. 11 - Flow separation pattern on a prolate spheroid at $\alpha = 20$ deg and $V_\infty = 45$ m/s

Concluding Remarks

A three-dimensional integral boundary-layer approach is developed and coupled with the streamline method for theoretically determining the vortex-type flow separation. The deflection of leeside streamlines that causes the vortex-type separation is found to be attributed to the deficiency of velocity inside the boundary layer. The calculated theoretical results compare very well with the experimental data for the case of the prolate spheroid at $\alpha = 10$ deg. For higher angle of attack, the approach yields qualitative agreement. The zero crossflow skin friction line exists, but it is not a line of separation.

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Appendix

Functions for G_1 , G_2 , and G_3

The detailed expressions for functions G_1 , G_2 , and G_3 in Eqs. (13) through (15) are listed below.

$$G_1 = A_1$$

$$G_2 = \frac{1}{\Theta_{11} Q_{21}} \left[A_2 - A_1 E_{21} + \frac{R_{21}(A_1 E_0 - A_1 H - A_3)}{R_0 - 1} \right]$$

$$G_3 = \frac{A_3 - A_1(E_0 - H)}{\Theta_{11}(R_0 - 1)}$$

$$A_1 = B_1 - \frac{E_{12}}{h_2} \frac{\partial \Theta_{11}}{\partial \eta} - \Theta_{11} \left(\frac{Q_{12}}{h_2} \frac{\partial \lambda}{\partial \eta} + \frac{R_{12}}{h_2} \frac{\partial H}{\partial \eta} \right)$$

$$A_2 = B_2 - \frac{E_{22}}{h_2} \frac{\partial \Theta_{11}}{\partial \eta} - \Theta_{11} \left(\frac{Q_{22}}{h_2} \frac{\partial \lambda}{\partial \eta} + \frac{R_{22}}{h_2} \frac{\partial H}{\partial \eta} \right)$$

$$A_3 = B_3 + \frac{E_2}{h_2} \frac{\partial \Theta_{11}}{\partial \eta} + \Theta_{11} \left(\frac{Q_2}{h_2} \frac{\partial \lambda}{\partial \eta} + \frac{R_2}{h_2} \frac{\partial H}{\partial \eta} \right)$$

$$B_1 = \frac{C_{11}}{2} - \Theta_{11} \left[\frac{(1+E_1)}{U h_1} \frac{\partial U}{\partial \xi} + (2E_{21} - E_2) \left(K_1 + \frac{1}{U h_2} \frac{\partial U}{\partial \eta} \right) + (1 - E_{22}) K_2 \right]$$

$$B_2 = \frac{C_{12}}{2} - \Theta_{11} \left[2E_{21} \left(\frac{1}{U h_1} \frac{\partial U}{\partial \xi} + K_2 \right) + \frac{2E_{22}}{U h_2} \frac{\partial U}{\partial \eta} - (1 - E_{22} + H) K_1 \right]$$

$$B_3 = C_E - \Theta_{11} \left[(E_0 - H) \left(\frac{1}{U h_1} \frac{\partial U}{\partial \xi} + K_2 \right) - E_2 \left(\frac{1}{U h_2} \frac{\partial U}{\partial \eta} + K_1 \right) \right]$$

$$\delta = E_0 \Theta_{11}$$

$$\delta_1 = E_1 \Theta_{11}$$

$$\delta_2 = E_2 \Theta_{11}$$

$$\Theta_{12} = E_{12} \Theta_{11}$$

$$\Theta_{21} = E_{21} \Theta_{11}$$

$$\Theta_{22} = E_{22} \Theta_{11}$$

$$E_0 = \frac{H(H+1)}{H-1}$$

$$E_1 = H$$

$$E_2 = -\lambda E_0 \left(\frac{2}{H+1} - \frac{4}{H+3} + \frac{2}{H+5} \right)$$

$$E_{12} = \lambda E_0 \left(\frac{1}{H} - \frac{4}{H+1} + \frac{1}{H+2} - \frac{4}{H+3} + \frac{2}{H+5} \right)$$

$$E_{21} = E_2 + E_{12}$$

$$E_{22} = -\lambda^2 E_0 \left(\frac{1}{H} - \frac{4}{H+1} + \frac{6}{H+2} - \frac{4}{H+3} + \frac{1}{H+4} \right)$$

$$Q_2 = \frac{\partial E_2}{\partial \lambda} = \frac{E_2}{\lambda}$$

$$Q_{12} = \frac{\partial E_{12}}{\partial \lambda} = \frac{E_{12}}{\lambda}$$

$$Q_{21} = \frac{\partial E_{21}}{\partial \lambda} = \frac{E_{21}}{\lambda}$$

$$Q_{22} = \frac{\partial E_{22}}{\partial \lambda} = \frac{E_{22}}{\lambda}$$

$$R_0 = \frac{\partial E_0}{\partial H} = \frac{H(H-2)+1}{(H-1)^2}$$

$$R_2 = \frac{\partial E_2}{\partial H} = \frac{E_2 R_0}{E_0} + \lambda E_0 \left[\frac{2}{(H+1)^2} - \frac{4}{(H+3)^2} + \frac{2}{(H+5)^2} \right]$$

$$R_{12} = \frac{\partial E_{12}}{\partial H} = \frac{E_{12} R_0}{E_0} + \lambda E_0 \left[\frac{1}{H^2} - \frac{4}{(H+1)^2} + \frac{1}{(H+2)^2} + \frac{4}{(H+3)^2} - \frac{2}{(H+5)^2} \right]$$

$$R_{21} = \frac{\partial E_{21}}{\partial H} = R_2 + R_{12}$$

$$R_{22} = \frac{\partial E_{22}}{\partial H} = \frac{E_{22} R_0}{E_0} + \lambda^2 E_0 \left[\frac{1}{H^2} - \frac{4}{(H+1)^2} + \frac{6}{(H+2)^2} - \frac{4}{(H+3)^2} + \frac{1}{(H+4)^2} \right]$$

$$\frac{1}{h_2} \frac{\partial \Theta_{11}}{\partial \eta} \cong \left(\frac{\Delta \Theta_{11}}{h_2 \Delta \eta} \right)_\xi = \left[\frac{(\Theta_{11})_{\eta+\Delta \eta} - (\Theta_{11})_\eta}{\Delta \eta} \right]_\xi$$

$$\frac{1}{h_2} \frac{\partial \lambda}{\partial \eta} \cong \left(\frac{\Delta \lambda}{h_2 \Delta \eta} \right)_\xi = \left(\frac{\lambda_{\eta+\Delta \eta} - \lambda_\eta}{\Delta \eta} \right)_\xi$$

$$\frac{1}{h_2} \frac{\partial H}{\partial \eta} \cong \left(\frac{\Delta H}{h_2 \Delta \eta} \right)_\xi = \left(\frac{H_{\eta+\Delta \eta} - H_\eta}{\Delta \eta} \right)_\xi$$

$$\frac{1}{h_1} \frac{\partial U}{\partial \xi} = \cos \theta \frac{\partial U}{\partial x} + \frac{\sin \theta}{f} \frac{\partial U}{\partial \phi}$$

$$\frac{1}{h_2} \frac{\partial U}{\partial \eta} = \frac{\cos \theta}{f} \frac{\partial U}{\partial \phi} - \sin \theta \frac{\partial U}{\partial x}$$

Errata: An Integral Prediction Method for
Three-Dimensional Flow Separation

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[AIAA Paper No. 84-0014]

Equation (12) on page 3 of the paper should read:

$$\begin{aligned} K_2 &= \frac{1}{h_1 h_2} \frac{\partial h_2}{\partial \xi} \\ &= \frac{1}{\gamma M^2 P} \left(\frac{\partial P}{\partial x} \cos \theta + \frac{1}{f} \frac{\partial P}{\partial \phi} \sin \theta \right) + \frac{1}{U} \left[\left(\frac{\partial u}{\partial x} + \frac{1}{f} \frac{\partial v}{\partial \phi} \right) + \frac{u}{f} \frac{df}{dx} \right] \end{aligned}$$

Equations for B_1 and Q_{22} in the Appendix of the paper should read:

$$\begin{aligned} B_1 &= \frac{C_{f\xi}}{2} - \theta_{11} \left[\frac{(2+E_1)}{U h_1} \frac{\partial U}{\partial \xi} + (2E_{21} - E_2) \left(K_1 + \frac{1}{U h_2} \frac{\partial U}{\partial \eta} \right) \right. \\ &\quad \left. + (1-E_{22}) K_2 \right] \end{aligned}$$

$$Q_{22} = \frac{\partial E_{22}}{\partial \lambda} = \frac{2E_{22}}{\lambda}$$

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