Numerical Investigation of Crossflow Separation on a Tangent-Ogive Forebody at High Angle of Attack*

Shing-Chung ONN**, Nai-Chung YANG***,
Jih-Lan HSIUNG**** and Chieng-Kuo WEI***

A "sublayer-mass flow" method is developed as a new tool for analysis of crossflow separation. It is found that the critical points of sublayer-mass flow are located at the points of convergence of surface streamlines. Thus, the critical points indicate where the flow is separated. This representation can be used to identify the primary and secondary separation points of crossflow separation. This is the first successful capture of crossflow separation points in a three-dimensional flow computation.

Key Words: Crossflow Separation, High Angle of Attack, Turbulence Model, Subsonic Flow, Sublayer-Mass Flow Method

1. Introduction

High-angle-of-attack flows over a slender body are characterized by large regions of three-dimensional separated flow. The separated flow leaves the surface of the body to form organized vortical structures. Two types of separated flow in terms of topology, global and local, have been classified by Tobak and Peak⁽¹⁾. A "local separation" is also called an "open separation"⁽²⁾ or a "crossflow separation"⁽³⁾.

It is well known that no saddle point is associated with crossflow separation⁽³⁾⁻⁽⁶⁾. Due to the lack of a sudden variation in fluid properties when the crossflow separation begins, there is no precise mathematical definition of the separation line.

In the past, it has been proven that the point where the crossflow velocity changes sign is not located on the crossflow separation line. Yates and Chapman⁽⁴⁾ further concluded that there are no sudden changes in the pressure, the vorticity or the skin

friction upon the crossflow separation. Levy et al.⁽⁵⁾ defined a normalized helicity for graphical visualization of concentrated vortices. The three-dimensional critical point of global separation can be determined by tracing the core of the vortex back to forward of a forebody. Unfortunately, it is impossible to determine crossflow separation by the same method as that for global separated flow^{(4),(6)}. It is believed that the crossflow separation on a tangent-ogive is a gradual process with no abrupt change in the flow properties⁽³⁾⁻⁽⁶⁾.

Modern computers can be used to calculate various flowfields via solution of Navier-Stokes equations. Analysis of the numerical solutions allows one to "visualize" the entire flowfield including the viscous effect. Several detailed works^{(4),(5),(7)}, on three-dimensional separation flowfields have been performed. Skin friction lines and surface streamlines are usually used to study the surface flow. Generally, the crossflow separation line is defined as the line on which surface streamlines⁽⁷⁾ or skin-friction lines⁽⁴⁾ converge. A projection of the convergent streamlines on the two-dimensional surface of the body can be represented as a separation line in a complex three-dimensional flowfield.

A full turbulent flowfield over a five-caliber tangent-ogive cylinder was chosen for the present computational study. In this paper, the "sublayer-mass flow" is introduced as a new tool to deal with the

* Received 31st August 1995.

** Department of Weapon System Engineering, Chung Cheng Institute of Technology, Ta-Hsi, Tao-Yuan, Taiwan, R.O.C.

*** Graduate Student, Department of Weapon System Engineering, Chung Cheng Institute of Technology, Ta-Hsi, Tao-Yuan, Taiwan, R.O.C.

**** Chung-Shan Institute of Science and Technology, Tao-Yuan, Taiwan, R.O.C.

separation line. This method can be employed to identify the primary and secondary separation points. These data can provide clear information about singular points above the body of the flowfield. This is the first successful capture of crossflow separation points in a three-dimensional flow computation.

Nomenclature

- D : diameter
 $\tilde{E}, \tilde{F}, \tilde{G}$: flux vectors in the transformed coordinate system
 F : scaled sublayer-mass flow
 f : sublayer-mass flow
 l : mixing length for turbulent viscosity
 M_∞ : freestream Mach number
 m : mass
 P : pressure
 $\tilde{Q}$: transformed vector of dependent flow variables
 Re : Reynolds number
 $\vec{S}$: a small control surface area vector above the body
 $\tilde{S}$: viscous flux with the thin-layer assumption
 S : a small control surface area
 t : time
 $\vec{V}$: velocity
 V : control volume
 x, y, z : Cartesian coordinates
 α : angle of attack, degree
 δ^* : a small distance normal to the body surface
 Φ : circumferential angle, degree
 ρ : density
 ξ, η, ζ : generalized coordinates in transformed coordinate system
 τ : dimensionless time
 Subscript
 ∞ : freestream condition

2. Theoretical Analysis

Consider the conservation of mass flow through a control volume at time t ; we have

$$\frac{Dm}{Dt} = \iint_{cs} \rho \vec{V} \cdot d\vec{S} + \frac{\partial}{\partial t} \iiint_{cv} \rho dV = 0. \quad (1)$$

The net mass efflux through the control surface at any time t equals the rate of decrease of mass inside the control volume at time t .

A small control volume element on the body surface filled with moving fluid is shown in Fig. 1. The attached flow on the flank of the body from the windward side of the body changes its direction at the separation line. As the boundary layer separates from the body, the fluid particles leave the body and roll up to form a vortex structure on the leeward side of the

Fig. 1 Small control volume on the body surface (side view)

body.

For analogy to oil-flow techniques, a small control volume on the surface of the body is considered. The simple ideal is based on the following. The mass efflux in the axial direction through the small control surface $d\vec{S}$ in the ζ - η plane should be decreased if separation occurred since the direction of movement of the fluid particles changes abruptly at the separation position. Some of the fluid particles pass through the ξ - η surface of the control volume and then develop a strong vortex downstream of the axial direction (Fig. 1).

Generally, the mass efflux in the axial component is a continuous function of the circumferential angle Φ for each cross plane of the body. The sublayer-mass flow f is defined as the mass efflux in the x -component across a small control surface $d\vec{S}$ in the ζ - η plane above the body, which can be represented by

$$f = \iint \rho \vec{V} \cdot d\vec{S}. \quad (2)$$

In this study, the small control surface area ΔS in the ζ - η plane can be computed by

$$\Delta S = \delta^* \cdot \Delta \eta. \quad (3)$$

Here, a sufficiently small normal distance δ^* from the body surface within the sublayer is selected as the height of the control volume. The value of δ^* should be less than the mixing length l because separation occurs on the surface of a body.

A nondimensional sublayer-mass flow F can be further scaled by the freestream property as follows:

$$F = \frac{\iint \rho \vec{V} \cdot d\vec{S}}{\iint \rho_\infty \vec{V}_\infty \cdot d\vec{S}}. \quad (4)$$

Since F is a continuous function of the circumferential angle Φ , if F has a relative maximum or minimum value at a specific η_0 , then the first deriva-

tive of F must be zero at $\eta = \eta_0$. For the present study, η_0 corresponding to the relative minimum F will be used to determine the circumferential angle at the crossflow separation point.

3. Computational Procedure

3.1 Numerical algorithm

The three-dimensional thin-layer Navier-Stokes (TLNS) equations written in a general curved coordinate system are used as governing equations. These equations are derived from the Navier-Stokes equations based on the assumption that the normal gradient of viscous stress terms is more important than the streamwise and circumferential gradients. The governing equations take the following form:

$$\partial_\tau \tilde{Q} + \partial_\xi \tilde{E} + \partial_\eta \tilde{F} + \partial_\zeta \tilde{G} = Re^{-1} \partial_\xi \tilde{S}. \quad (5)$$

Its finite difference equations are constructed employing the Ying-Steger method⁽⁸⁾. It is an implicit two-factored scheme in which upwind differencing in the ξ direction and central differencing in both the η and the ζ direction are used. Artificial dissipation operators are used in the central space differencing directions to maintain computational stability. The differencing method has second-order accuracy in both space and time. Detailed description of those equations and their specific forms can be found in Ref. (8).

3.2 Grid generation

In this work, a C-O grid was used for the forebody model. The three-dimensional grid geometry for the five-caliber tangent-ogive cylinder is shown in Fig. 2. The two-dimensional plane (ξ - ζ) was obtained by solving a hyperbolic differential equation. It consists of 64 points in the streamwise direction and 49 points in the direction normal to the forebody surface extended approximately 10 body diameters. Mesh lines are nearly orthogonal to the body surface and are clustered near the body surface with a minimum spacing of $\Delta\zeta = 2.0 \times 10^{-5}D$. The third dimension was generated by rotating the two-dimensional grids about the projectile axis for every 5-degree increment. Eleven additional grid points are added at the longitudinal boundaries to minimize the effect of downstream boundary conditions. The grid system (Fig. 3) then consists of $64 \times 73 \times 49$ points in the axial, circumferential and radial directions.

3.3 Boundary conditions

At the outflow boundary, constant freestream values were used for all variables. On the solid body surface, a viscous no-slip condition was applied. The pressure gradient at the projectile surface was computed from $\partial P / \partial \zeta = 0$. At the downstream boundary, a zero-axial-gradient extrapolation condition was applied. All variables were extrapolated at the

upstream axis line. An implicit periodic condition was used in the circumferential direction of the grid.

3.4 Turbulence model

To simulate the turbulence flow on a subsonic forebody at large angles of attack, the turbulence model should be modified for considering physical characteristics. The two-layer turbulence model of Baldwin and Lomax⁽⁹⁾ has been widely used for the attached boundary-layer and the wake flows. Various modifications to this turbulence model have been made. The Baldwin-Lomax model is used to compute the turbulence length scale based on the distance to the free shear layer. Degani and Schiff⁽¹⁰⁾ found that

Fig. 2 Geometry of the five-caliber tangent-ogive cylinder and coordinate systems

Fig. 3 Three-dimensional C-O type grid system ($64 \times 73 \times 49$)

at high angle of attack, the length scale overpredicts the eddy viscosity in the outer region. They suggested a "cutoff" distance concept to select the correct value of the function in the Baldwin-Lomax turbulence model based on physical considerations. The modified turbulence model was used to determine in detail the vortex flow structure in this work.

4. Results and Discussion

In the present study, the body has a five-caliber tangent-ogive forebody with a cylindrical afterbody. This body geometry has been extensively tested by Bauer and Hensch⁽¹¹⁾ in a 7'×10' wind tunnel. The computational results presented here were obtained for $M_\infty=0.2$, $Re=1.3\times 10^6$ and $\alpha=35^\circ$. The flow parameters were chosen to match the experimental conditions described in Ref. (11). In the computation full turbulent flow was assumed.

Computed surface pressure coefficients and experimental results⁽¹¹⁾ for $x/D=2.50$ are shown in Fig. 4. The computational results indicate that symmetric flow fields were obtained in the computation. The computed pressure coefficients lie close to the average of the windward and leeward side because no disturbance was added in this numerical study. It is believed that the high degree of asymmetry obtained in experimental studies is induced mainly by the imperfection of the nose of a forebody⁽¹²⁾. More realistic simulation of asymmetry can be achieved by adding a small disturbance to the slender body near the nose^{(12),(13)}; however, this is beyond the scope of the present work.

A front-quarter view of the off-surface streamlines is shown in Fig. 5. The flow pattern shows the presence of strong vortical structures and the sizes of the primary leeward-side vortices increase with dis-

Fig. 4 Surface pressure coefficients at $x/D=2.50$ ($M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3\times 10^6$)

tance, which represents a typical crossflow flowfield.

Computational surface flow patterns are shown in Figs. 6 and 7. Figure 6 shows a top view of surface streamlines. It shows that the symmetry of the computed flowfield is maintained at angles of attack as in the case shown in Fig. 4, which also confirms the results of Degani and Schiff⁽¹²⁾.

A side view of the surface flow pattern is shown in Fig. 7. As mentioned above, the separation line is defined as the line of streamline convergence. From the graphic visualization of surface streamlines it is found that the primary separation line originates from the nose tip and the secondary separation line originates from about $1.25 D$. The computed surface streamlines show qualitative agreement with the experimental oil-flow photos shown in Ref. (14).

A small distance δ^* of about $2.0\times 10^{-5} D$ (grid dependent) from the body surface and $\Delta\Phi=5$ degrees were selected as upper limits of integration for computing the scaled sublayer-mass flow. By integration of Eq. (4), the scaled sublayer-mass flow F of each cross section was computed. A typical scaled sublayer-mass flow curve along the circumferential direction at $x/D=2.5$ is shown in Fig. 8. It has two concave upward regions, i.e., $F''>0$, between $\Phi=90^\circ$ and $\Phi=160^\circ$. The relative minimum points, $F'=0$, indicate that the direction of flow of the fluid particles changes abruptly. By careful examination, it is found that these local minimum points are located on the primary or secondary separation line, determined

Fig. 5 Off-surface streamlines ($M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3\times 10^6$)

Fig. 6 Surface flow pattern: $M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3\times 10^6$ (top view)

Fig. 7 Surface flow pattern: $M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3\times 10^6$ (side view)

using the visualization technique as shown in Fig. 7.

Analysis of the sublayer-mass flow curves near the front of the forebody (Fig. 9) reveals that each curve has only one primary separation point before $x/D=1.25$. The curves gradually form the second concave upward region. There are always two critical points after $x/D=1.25$. This observation concludes that the crossflow separation forms by a gradual process. It is consistent with experimental results in Ref. (3).

A side view of the critical points of the forebody is shown in Fig. 10. It shows good agreement with the primary separation line and secondary separation line determined using the visualization technique.

It can also be seen that there is a concave downward region between the two concave upward ones in

Fig. 8 Scaled sublayer-mass flow at $x/D=2.50$
($M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3 \times 10^6$)

Fig. 9 Scaled sublayer-mass flow ($M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3 \times 10^6$)

Fig. 10 Computed separation points and surface flow pattern ($M_\infty=0.2$, $\alpha=35^\circ$, $Re=1.3 \times 10^6$)

Fig. 8. The local maximum critical points are located between the primary point and the secondary point where the surface streamlines diverge. This indicates that the sublayer-mass flow through this point is the largest one in the local region. This point behaves like a source. Thus, this point is suggested to be the reattachment point in the crossflow separation.

Numerical results suggest that the crossflow separation points can be determined using the local minimum sublayer-mass flow. This method can be defined mathematically. Moreover, the coordinates of every separation point can be determined precisely and no complex visualization technique is required for doing so. Improvement of the resolution is possible if fine grids are used for the circumferential direction.

Experiments⁽¹⁴⁾ have shown that high-angle-of-attack flows over a slender body are characterized by laminar, transition and turbulent regions. Strictly speaking, a computed surface flowfield near the nose of the slender body should not be expected to agree with experimental results, because in the computation a fully turbulent flow was assumed in the complex transition region. However, the computed results show that there is no secondary separation before $x/D=1.25$ as shown in Fig.10. This trend is consistent with the experimental results⁽¹⁴⁾ obtained for laminar flow. Further research in laminar flows is expected.

5. Conclusions

A five-caliber tangent-ogive forebody with a cylindrical afterbody was modeled numerically. The computed three-dimensional separated flow exhibits crossflow separation. Solution of Navier-Stokes equations was used to examine the relationship between the crossflow separation line and the critical points of sublayer-mass flow. The results show that if a local minimum sublayer-mass flow in the axial component exists, the critical point will be located on the line at which the surface streamlines converge. This method allows determination of both primary and secondary separations on the body surface. The data provide more information on crossflow separation than does the visualization technique.

Acknowledgement

The work presented in this paper was supported by the National Science Council of the Republic of China under Contract No. NSC-85-2212-E-014-016. The authors are also grateful to acknowledge the grant of computer time by the National Center for High-performance Computing, R. O. C.

References

- (1) Tobak, M. and Peak, D.J., Topology of Two-Dimensional and Three-Dimensional Separated Flows, AIAA Paper 79-1480, (1979).
- (2) Wang, K.C., On the Current Controversy of Unsteady Separation, AIAA Paper 83-0296, (1983).
- (3) Chapman, G.T., Topological Classification of Flow Separation on Three-Dimensional Bodies, AIAA Paper 86-0485, (1986).
- (4) Yates, L.A. and Chapman, G.T., Numerical Investigation of Crossflow Separation on a Three-Caliber Tangent Ogive Cylinder, AIAA Journal, Vol. 26, No. 10 (1988), p. 1223.
- (5) Levy, Y., Degani, D., and Seginer, A., Graphical Visualization of Vortical Flows by Means of Helicity, AIAA Journal, Vol. 28, No. 8 (1990), p. 1347.
- (6) Chapman, G.T. and Yates, L.A., Topology of Flow Separation on Three-Dimensional Bodies, Applied Mechanics Reviews, Vol. 44, No. 7 (1991), p. 329.
- (7) Ying, S.X., Schiff, L.B., and Steger, J.L., A Numerical Study of Three-Dimensional Separated Flow Past a Hemisphere Cylinder, AIAA Paper 87-1207, (1987).
- (8) Ying, S.X., Three-Dimensional Implicit Approximately Factored Schemes for Equations in Gasdynamics, Ph. D. Thesis, Stanford University, CA, U. S. A. (1986).
- (9) Baldwin, B.S. and Lomax, H., Thin-Layer Approximation and Algebraic Model for Separated Turbulent Flows, AIAA Paper 78-257 (1978).
- (10) Degani, D. and Schiff, L.B., Computation of Turbulent Supersonic Flows around Pointed Bodies Having Crossflow Separation, Journal of Computation of Physics, Vol. 66, No. 1 (1986), p. 173.
- (11) Bauer, S. X. S. and Hemsch, M. J., Alleviation of Side Force on Tangent-Ogive Forebodies Using Passive Porosity, Journal of Aircraft, Vol. 31, No. 2 (1994), p. 354.
- (12) Degani, D. and Schiff, L.B., Numerical Simulations of the Effect of Spatial Disturbances on Vortex Asymmetry, AIAA Journal, Vol. 29, No. 3 (1991), p. 344.
- (13) Degani, D., Effect of Geometrical Disturbances on Vortex Asymmetry, AIAA Journal, Vol. 29, No. 4 (1991), p. 560.
- (14) Keener, E. R., Flow-Separation Patterns on Symmetric Forebodies, NASA-TM-86016 (1986).