EXPERIMENTAL STUDY OF THREE-DIMENSIONAL SEPARATED FLOW SURROUNDING A HEMISPHERE-CYLINDER AT INCIDENCE

Andrew J. Meade, Jr.
Department of Mechanical Engineering
and Materials Science
Mail Stop 321
Rice University
Houston, Texas, 77251-1892, USA
Phone: (713) 527-8101 ext. 3590
email: meade@rice.edu

Lewis B. Schiff
NASA Ames Research Center
Mail Stop 258-1
Moffett Field, CA 94035-1000, USA
Phone: (415) 604-4467
email: Lewis_Schiff@qmgate.arc.nasa.gov

To be submitted to Experiments in Fluids, 1995

ABSTRACT

Detailed experimental surface pressure coefficient measurements were obtained for a hemisphere-cylinder-flare model in the low supersonic Mach number range ($M_\infty = 1.2$) at various angles of incidence (0° to 27.5°). The surface pressure values at each angle of incidence were smoothed and checked against their respective oil-flow photographs. The smoothed results were then used to validate a theory which relates the number and type of topological singular points observed in the oil-flow patterns with local surface pressure extrema.

Presented as Paper 87-2492 at the AIAA Atmospheric Flight Mechanics Conference, Monterey, CA, August 17-19, 1987.
This work is supported under NASA grant NCC 2-334.

EXPERIMENTAL STUDY OF THREE-DIMENSIONAL SEPARATED FLOW SURROUNDING A HEMISPHERE-CYLINDER AT INCIDENCE

Andrew J. Meade, Jr.
Department of Mechanical Engineering
and Materials Science
Mail Stop 321
Rice University
Houston, Texas, 77251-1892, USA
Phone: (713) 527-8101 ext. 3590
email: meade@rice.edu

Lewis B. Schiff
NASA Ames Research Center
Mail Stop 258-1
Moffett Field, CA 94035-1000, USA
Phone: (415) 604-4467
email: Lewis_Schiff@qmgate.arc.nasa.gov

INTRODUCTION

One of the current problems of interest in aerodynamics is to understand, and ultimately to control, three-dimensional boundary-layer separation and the resultant vortex-dominated flows. This interest is prompted in part by the requirements on flight vehicles for enhanced maneuverability, which in turn leads to flight at large angles of incidence.

At present, reliable theoretical and numerical analysis of these phenomena are just beyond the reach of the scientific community. Advances in the understanding of steady [1] - [19] and unsteady [20], [21] conditions have principally come from experimental studies utilizing flow visualization techniques. Of particular use in this regard has been the oil-flow (also known as the oil-streak) technique for displaying skin-friction line patterns on the surfaces of wind tunnel models [22].

Researchers have worked under the theory that patterns of skin-friction lines reflect the properties of continuous vector fields allowing the characterization of patterns on a model surface by a restricted number of singular points (nodes, saddle points, and foci). Using the the restricted number of singular points and the topological rules that they obey as building

blocks, it has been proposed that a comprehensive and reliable method can be constructed to describe how three-dimensional separated flows originate and evolve with the variation of relevant parameters (i.e., Mach number, Reynolds number, angle of incidence). To build this comprehensive theory, researchers have concentrated on the flows about geometrically simple bodies.

The steady flow over a hemisphere-cylinder body has been the subject of several experimental and computational investigations [23] - [31]. Among these, Peake and Tobak [26] carried out an experimental wind tunnel investigation at a low supersonic Mach number ($M_\infty = 1.2$) in the Ames 6- by 6-Foot Supersonic Wind Tunnel, in which extensive surface oil-flow and vapor-screen photographs were obtained. Although the body geometry is simple, the flow surrounding a hemisphere-cylinder at incidence is quite complex. In addition to the primary and secondary crossflow separation patterns usually observed on a body of revolution at incidence, the topology of the limiting streamlines at the surface contain a variety of singular points when visualized by the surface oil-flow technique. These include nodes of attachment, nodes of separation, and saddle points. In particular, spiral nodes of separation pairs, or foci, are observed on the leeward side of the body near the hemisphere-cylinder junction.

In the course of analyzing the topology of the steady separated hemisphere-cylinder flows, Tobak [32] proposed a theory which links the existence of each of the singular points observed in the surface oil-flow to the existence of a local extremum in the surface pressure distribution. The existence of a local pressure extremum, however, need not be associated with a singular point. Specifically, his preliminary analysis showed that a local pressure maximum should exist in the vicinity of each node of attachment, a local pressure minimum should exist near each node of separation (or focus) in the oil-flow, and each saddle point in the oil-flow should be associated with a saddle point in the pressure distribution. In order to examine the validity of Tobak's theory, a hemisphere-cylinder-flare pressure model was constructed and tested at flow conditions matching those of Peake and Tobak's experiment. Surface pressure measurements were made and the locations of local pressure extrema were

determined. In addition, surface oil-flow photographs were examined to determine the type and location of surface singular points.

DESCRIPTION OF EXPERIMENT

The experiment was conducted by T.T. Lim in the 6- by 6-Foot Supersonic Wind Tunnel at the NASA Ames Research Center. Test conditions were $M_\infty = 1.2$, $Re_D = 6.5 \times 10^5$, with angles of incidence (α) of 0°, 5°, 10°, 15°, 19°, and 27.5°. The hemisphere-cylinder-flare model is shown schematically in Fig. 1, together with the coordinate system used. The model consisted of a 2.6 inch diameter cylinder section, 12.5 inches long, with a hemispherical nose cap and a 3.0 inch long, 14° half-angle conical afterbody. Axial distances along the model are indicated in terms of S/D, where S is the arc length along the model measured from the hemisphere-cylinder junction.

The model was instrumented with 421 pressure orifices, each 0.018 inches in diameter, grouped in 8 rows equispaced about the body circumference. The orifices were spaced 0.3125 inches apart axially along their respective rows ($\triangle$S/D = 0.120), and were staggered so that each orifice had a unique axial location. The pressure taps were connected to 12 mechanical scanivalves, each having its own differential pressure transducer, and the output of each transducer was recorded on the wind tunnel data acquisition system. In this manner the time-averaged values of the surface pressures were obtained at each tap. Surface oil-flow photographs (Fig. 5(b)-10(b)) were obtained to ensure, by comparison with the earlier work of reference [26] (Fig. 5(a)-10(a)), that the presence of the flare had not altered the properties of the upstream flow.

At each fixed angle of incidence, data were taken from all pressure taps while the model was rolled remotely in increments ($\triangle\phi = 3°$) about its own axis of symmetry. The 421 pressure measurements at each roll angle were interlaced to yield a surface pressure distribution of 50,520 data points per angle of incidence. At $\alpha = 19°$ a finer roll increment was used ($\triangle\phi = 1.5°$), yielding a surface pressure distribution of 101,040 data points.

In the course of analyzing the experimental data the rough data were displayed, for each angle of incidence, as a surface in space (C_p as a function of circumferential angle ϕ and axial distance S/D). In this manner, the major structures of the pressure field could be examined and errors reduced. Sources of surface measurement error were classified as either systematic or random. The existence of systematic error was assumed from the beginning, since the pressure data were measured on twelve different transducers each with its own calibration error. This systematic type of error was quite apparent when viewing the raw data surface. As a result, the data points were corrected or eliminated. Random measurement errors were seen as small-amplitude, short-spatial-wavelength jitter within the raw pressure surface and eliminated by numerical smoothing [33].

Figure 2 shows top and side views of the unsmoothed surface C_p contours for $\alpha = 19°$ superimposed on the body of the test model. The analogous contours, obtained after eliminating systematic errors and numerically smoothing the data, are shown in Fig. 3. The smoothed contours are seen to be in the same relative positions as those shown in Fig. 2. Most importantly, the details of the contour pattern in the vicinity of the hemisphere-cylinder junction on the leeward side of the body are now clearly seen.

RESULTS

Flow Structure

The main flow features observed on the leeward side of the body and in the leeward plane of symmetry near the nose are shown schematically in Fig. 4. Flow along the leeward symmetry plane separates at a saddle point of separation located near the hemisphere-cylinder junction. Flow leaving this saddle point circumferentially along the body surface spirals into two foci, or spiral nodes of separation, symmetrically disposed from the leeward symmetry plane. According to Tobak's theory, local pressure minima should be observed near the foci, and a pressure saddle point should exist near the saddle point of separation. A pair of saddle points, located downstream of the foci, are symmetrically displaced from the

leeward symmetry plane. Two surface streamlines emanate from each of the saddle points, one spiraling upstream into the focus, the other moving downstream and circumferentially outward.

Continuing downstream from the leeward saddle point of separation along the symmetry plane, one can see a node of attachment which should be mirrored by a local maximum in the pressure distribution. This node of attachment is conjectured to be fed from an outwardly spiraling node in the plane of symmetry which receives flow moving circumferentially inward toward the symmetry plane. The presence of this node could not be detected in the experiment, since no off-surface measurements were made, but Navier-Stokes computations of this flowfield [27], [28] suggest the possibility that it is present.

Oil-Flow Visualizations

Figure 5 compare the titanium dioxide oil-flow obtained for nominally axisymmetric flow ($\alpha = 0°$), while Figs. 6-10 compare top and side views of the oil-flow patterns observed at $\alpha = 5°$ to $\alpha = 27.5°$. The main features of the surface flow are apparent in the oil-flows. At $\alpha = 5°$, a pair of foci are observed on the leeward side of the body near the hemisphere-cylinder junction. As the angle of incidence is increased, these foci grow larger and move farther apart circumferentially (Figs. 7 and 8). In addition, for $\alpha \geq 5°$, a well-defined primary crossflow separation line is observed on the cylindrical portion of the body. A secondary crossflow separation line is visible for $\alpha \geq 10°$. Additional foci are visible in the vicinity of the cylinder-flare junction (Figs. 8(b)-10(b)). However, in this paper only the details of the flow on the hemisphere and forward portion of the cylinder are addressed.

Surface Pressure Distributions

The axial surface pressure distribution obtained for axisymmetric flow about the hemisphere-cylinder-flare is shown in Fig. 11. Although all axial stations are included in Fig. 11, only one roll angle is shown since the flow is nominally axisymmetric.

In Figs. 12-16 the smoothed surface C_p contours for $\alpha = 5°$, $10°$, $15°$, $19°$, and $27.5°$

respectively, are plotted as functions of axial distance S/D and circumferential angle ϕ. Superimposed on the pressure contours are skin-friction line patterns drawn from the oil-flow photographs shown in Figs. 6-10 and the experimental work of Peake and Tobak [26]. In this type of figure the body geometry information is not obvious; for example, the windward ray ($\phi = 180°$) is at the top and bottom edges of the figure, while the leeward ray ($\phi = 0°$) is the horizontal line through the center of the plot. In addition, the single pressure tap at the nose maps to the entire left hand border of each plot. However the relative positions of the skin-friction lines and C_p contours are readily apparent. For clarity, the C_p contours from S/D = -0.78 to -0.1 are not included in Figs. 12-16 except when displaying a local extremum since, as can be seen from Fig. 3, the large drop in pressure between the node of attachment near the nose (stagnation point) and the hemisphere-cylinder junction would yield a large number of closely spaced contours in this region. The values of the contour levels are not indicated in Figs. 12-16 since our primary interest is to display the existence and location of local pressure maxima and minima. The location of closed C_p contours, which are indicative of local pressure maxima and minima, along with the type of extrema are listed in Tables 1-5 for each nonzero angle of incidence.

The skin-friction line patterns of Figs. 6-10 were found to be consistent with the topological rules governing three-dimensional surface singular points. Specifically, the number of surface nodes and surface skin-friction saddle points were found to obey the summation relations discussed in reference [14]. In the top half of Figs. 12(a)-16(a) ($0° \leq \phi \leq 180°$), the skin-friction lines drawn show only the singular points and lines connecting them. This is termed the topological structure which acts as the skeleton of the skin-friction pattern. In the bottom half of these figures, the skeleton has been fleshed out by adding selected skin-friction lines to the pattern of singular points. In addition, Figs. 12(b)-16(b) contain an enlarged view of the topological structure near the hemisphere-cylinder junction.

As the angle of incidence is increased from 0° to 27.5°, the node of attachment (stagnation point) at the nose moves downward along the windward ray ($\phi = 180°$). In addition, the leeward skin-friction line patterns become more complex. For α = 5°, 10°, and 15°

(Figs. 12-14), the singular point patterns are similar to the one discussed for Fig. 4, and contain one pair of foci near the hemisphere-cylinder junction. At $\alpha = 19°$ and $\alpha = 27.5°$ (Figs. 15, 16) two pair of foci are observed near this junction. It is noted that at $\alpha = 27.5°$ an additional node-saddle pair is observed downstream ($S/D \approx 1$).

For the six values of α observed, comparison of the singular point locations with the pressure contours indicate that each node of attachment is associated with a local pressure maximum, and each node of separation (or focus) occurs in the vicinity of a local pressure minimum. Further, from the fact that the surface pressure distribution is continuous, it can be inferred that a saddle point in the pressure map should occur in the vicinity of each saddle point in the skin-friction pattern.

CONCLUSIONS

Detailed experimental C_p data was obtained at $M_\infty = 1.2$, for six angles of incidence ranging from 0° to 27.5°. The data in all cases were smoothed. The location of local pressure extrema were determined and the results have been presented. Comparison of the surface pressure distributions with singular point locations in the corresponding oil-flow photographs confirms the relationships postulated by Tobak. Specifically, these are that a local pressure maximum should exist near each node of attachment, a local pressure minimum should exist near each node of separation (or focus), and each saddle point in the oil-flow should be associated with a saddle point in the pressure distribution.

ACKNOWLEDGEMENTS

This work was supported by the NASA Ames Research Center, under Grant No. NCC 2-334. The financial and technical support of NASA and the collaboration of NASA personnel is appreciated. In particular the authors would like to gratefully acknowledge the helpful suggestions and assistance of T.T. Lim and Murray Tobak.

REFERENCES

[1] Maskell, E.C., "Flow Separation in Three Dimensions," *RAE Aero. Rept.* 2565, 1955.

[2] Werle, H., "Separation on Axisymmetrical Bodies at Low Speeds," *Recherche Aeronautique,* No. 90, pp.3-14, 1962.

[3] Lighthill, M.J., "Attachment and Separation in Three-Dimensional Flow," *Laminar Boundary Layers*, edited by L. Rosenhead II, pp. 72-82, Oxford University Press, 1963.

[4] Wang, K.C., "Separation Patterns of Boundary Layer Over an Inclined Body," *AIAA Journal*, Vol. 10, No.8, pp. 1044-1050, 1972.

[5] Wang, K.C., "Boundary Layer over a Blunt Body at High Incidence with an Open Type of Separation," *Proceedings of the Royal Society of London, Series A,* Vol. 340, pp. 33-35, 1974.

[6] Perry, A.E. and Fairlie, B.D., "Criticial Points in Flow Patterns," *Advances in Geophysics*, Vol. 18B, pp. 299-315, Academic Press, New York, 1974.

[7] Hsieh, T. and Wang, K.C., "Concentrated Vortices on the Nose of an Inclined Body of Revolution," *AIAA Journal*, Vol. 14, No.5, pp. 698-700, 1976.

[8] Wang, K.C., "Separation of Three-Dimensional Flow," Reviews in Viscous Flow, *Proceedings of Lockheed-Georgia Co. Symposium,* LG 77ER0044, pp. 341-414, 1976.

[9] Hunt, J.C.R., Abell, C.J., Peterka, J.A., and Woo, H., "Kinematical Studies of the Flows Around Free or Surface-Mounted Obstacles; Applying Topology to Flow Visualization," *Journal of Fluid Mechanics*, Vol. 86, pp. 179-200, 1978.

[10] Han, T. and Patel, V.C., "Flow Separation on a Spheroid at Incidence," *Journal of Fluid Mechanics*, Vol. 92, pp. 643-657, 1979.

[11] Tobak, M. and Peake, D.J., "Topology of Two-Dimensional and Three-Dimensional Separated Flows," AIAA Paper 79-1480, 1979.

[12] Peake, D.J., and Tobak, M., "Three-Dimensional Interactions and Vortical Flows with Emphasis on High Speeds," *AGARDograph* No. 252, 1980.

[13] Legendre, R., "Regular or Catastrophic Evolution of Steady Flows Depending on Parameters," *Recherche Aerospatiale*, Vol.4, pp. 41-49, 1982.

[14] Tobak, M. and Peake, D.J., "Topology of Three-Dimensional Separated Flows," *Annual Review of Fluid Mechanics*, Vol. 14, pp.61-85, 1982.

[15] Dallmann, U., "Topological Structures of Three-Dimensional Vortex Flow Separation," AIAA Paper 83-1935, 1983.

[16] Hornung, H.G. and Perry, A.E., "Some Aspects of Three-Dimensional Separation. Part I: Streamsurface Bifurcations," *Z. Flugwiss, Weltraumforsch*, No. 8, pp. 77-87, 1984.

[17] Hornung, H.G. and Perry, A.E., "Some Aspects of Three-Dimensional Separation. Part II: Vortex Skeletons," *Z. Flugwiss, Weltraumforsch*, No. 8, pp. 155-160, 1984.

[18] Zhang, H.X., "The Separation Criteria and Flow Behavior for Three Dimensional Steady Separated Flow," *Acta Aerodynamica Sinica*, pp. 1-12, 1985.

[19] Chapman, G.T., "Topological Classification of Flow Separation on Three-Dimensional Bodies," AIAA Paper 86-0485, 1986.

[20] Hui, W.H., and Tobak, M., "Topology of Steady and Unsteady Incompressible Three-Dimensional Separated Flows," *Continuum Mechanics and Its Applications*, edited by Graham and Malik, pp. 519-542, Hemisphere Publications, 1989.

[21] Pauley, L.L., "Structure of Local Pressure-Driven Three-Dimensional Transient Boundary-Layer Separation," *AIAA Journal*, Vol. 32, No. 5, 1994.

[22] Maltby, R.L., "Flow Visualization in Wind Tunnels Using Indicators," *AGARDograph*, No. 70, 1962.

[23] Hsieh, T., "Flow Field Study About A Hemispherical Cylinder In Transonic and Low Supersonic Mach Number Range," AIAA Paper 75-83, 1975.

[24] Hsieh, T., "An Investigation of Separated Flows About a Hemisphere-Cylinder at Incidence in the Mach Number Range from 0.6 to 1.5," AIAA Paper 77-179, 1977.

[25] Hsieh, T., "Calculation of Viscous, Sonic Flow Over Hemisphere-Cylinder at 19 Degree Incidence: The Capturing of Nose Vortices," AIAA Paper 81-0189, 1981.

[26] Peake, D.J. and Tobak, M., "Three-Dimensional Flows About Simple Components at Angle of Attack," *NASA Technical Memorandum* 84226, 1982.

[27] Ying, S.X., Steger, J.L., Schiff, L.B. and Baganoff, D., "Numerical Simulation of Unsteady, Viscous, High-Angle-of-Attack Flows Using a Partially Flux-Split Algorithm," AIAA Paper 86-2179, 1986.

[28] 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.

[29] Kordulla, W., Müller, B., Vollmers, H., "Comparison of Two Different Navier-Stokes Methods for the Simulation of 3-D Transonic Flows with Separation," AIAA Paper 89-0559, 1989.

[30] Hoang, N.T., and Telionis, D.T., "The Hemisphere-Cylinder at an Angle of Attack," AIAA Paper 90-0050, 1990.

[31] Wang, K.C., and Hsieh, T., "Separation Patterns and Flow Structures About a Hemisphere-Cylinder at High Incidences," AIAA Paper 92-2712, 1992.

[32] Personal communication.

[33] The IMSL Library Reference Manual, 9th edition, Vol. 2, pp. icsscu 1-4, 1982.

Table 1: Location of local pressure extrema for $\alpha = 5°$

Extrema	S/D	ϕ (deg)
Maxima	-0.74	180
	0.06	0
	0.21	0
	2.07	0
Minima	0.00	28 and 332

Table 2: Location of local pressure extrema for $\alpha = 10°$

Extrema	S/D	ϕ (deg)
Maxima	-0.70	180
	0.06	359
	0.21	0
	0.28	0
	1.60	180
	2.18	0
Minima	0.00	34 and 326

Table 3: Location of local pressure extrema for $\alpha = 15°$

Extrema	S/D	ϕ (deg)
Maxima	-0.65	180
	0.06	0
	0.25	1
	0.78	180
Minima	0.00	36 and 324
	0.13	21 and 339
	1.58	84 and 276
	3.06	36 and 324

Table 4: Location of local pressure extrema for $\alpha = 19°$

Extrema	S/D	ϕ (deg)
Maxima	-0.62	180
	-0.03	0
	0.52	180
	2.30	0
Minima	0.00	60 and 300
	0.26	36 and 324
	1.55	72 and 288
	2.60	45 and 315

Table 5: Location of local pressure extrema for $\alpha = 27.5°$

Extrema	S/D	ϕ (deg)
Maxima	-0.55	180
	-0.19	0
	-0.03	359
	0.16	180
	0.21	0
	1.81	0
Minima	-0.13	72 and 288
	-0.04	85 and 275
	0.16	39 and 321
	0.36	24 and 336
	1.11	57 and 303
	1.71	30 and 330