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Technical Notes

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Three-Dimensional Separated Flow over a Prolate Spheroid

Wenhan Su,* Bo Tao,† and Li Xu†
Beijing University of Aeronautics and Astronautics, Beijing 100083, People's Republic of China

Introduction

THE investigation of three-dimensional separated flow is one of the important aspects of aerodynamic research. A typical case of this investigation is the separated flow over a prolate spheroid. It has been investigated for many years. Recent experimental results can be found in Refs. 1-3. Although great progress has been made, some challenging problems still need to be further clarified. For example, 1) how does an open separation occur, 2) what is the relationship between open separation and vortex flow, 3) what is the topological property of the starting point of an open separation line and how can the starting point be identified, and 4) what are the topological structures of the separated flows and their evolution with changing parameters? This Note will present the experimental results of three-dimensional separated flow over a prolate spheroid. Some opinions about the aforementioned problems will be suggested. Some flow visualization tests were conducted in a water channel at a speed of about 0.04 m/s by dye injection and laser sheet technique. The test model is a prolate spheroid with an axis ratio of 1/4. The Reynolds number based on the length of the model is about 1×10^4. The angle of attack varied from 0 to 70 deg. The dye was injected onto the proper place on the body surface. In this way the behavior of the near-wall streamline and the separated shear layer can be visualized; therefore, the surface flow pattern (approximate) and the spatial flow pattern can be observed simultaneously.

Results and Conclusions

1) The occurrence of the open separation: Figure 1 shows some flow patterns in the α region of 3-15 deg with side and top views (except for $\alpha = 10$ deg); the freestream direction is from right to left. It can be seen that an unclosed bubble forms on the rear part of the body. The upstream boundary of the bubble is a closed separation line. In front of the closed separation line a free shear layer sheds from an open separation line. It seems that the open separation results from the meeting and crowding of the two streams with opposite crossflow direction in the three-dimensional boundary layer. Under the conditions studied, the open separation begins to occur at very low angles of attack, and the closed separation line has never broken up; it just changes its form and its topological structure.

2) Open separation and vortex flow: Figure 1 shows that at low α, although open separation occurs, no vortex flow is formed. Figure 2 shows that in the α region of 15-30 deg the free shear layer shed from the open separation line rolls up into a weak vortex. No vortex core is formed. As α increases, the open separation line and the bubble move forward. In the α region of 30-45 deg, the free shear layer shed from the

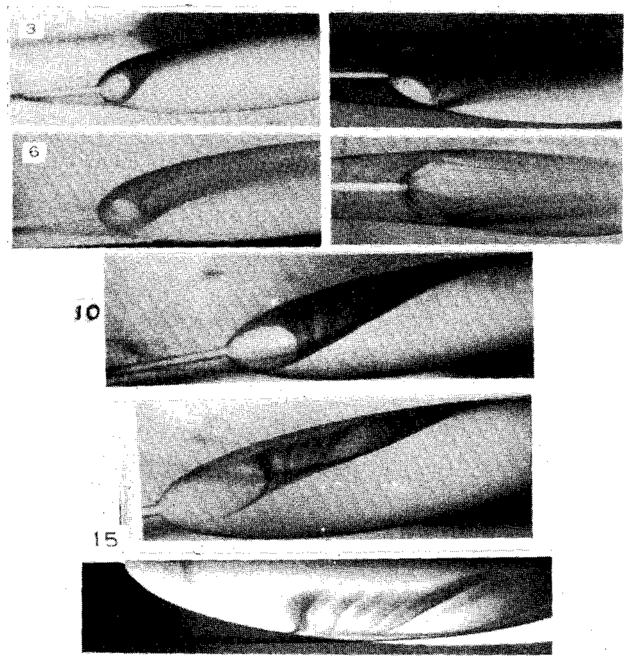

Fig. 1 Occurrence of the open separation.

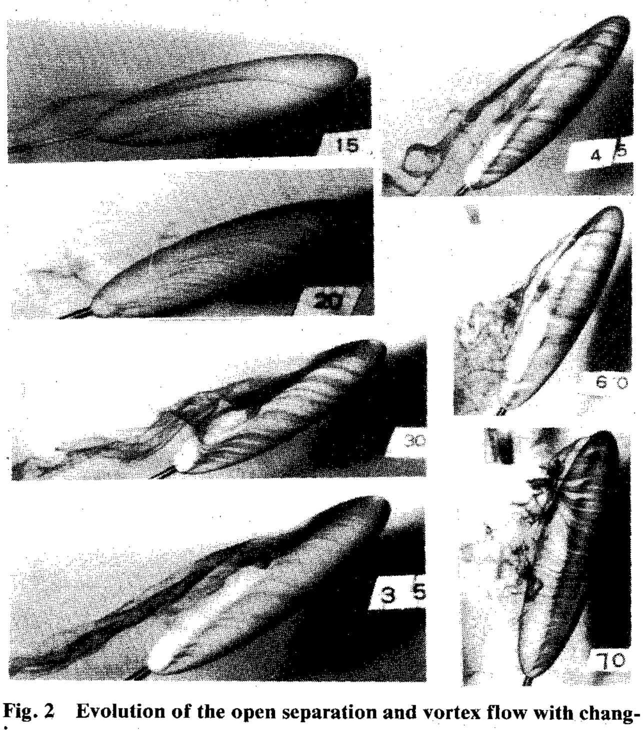

Fig. 2 Evolution of the open separation and vortex flow with changing α.

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*Professor, Fluid Mechanics Institute.
†Graduate Student, Fluid Mechanics Institute.

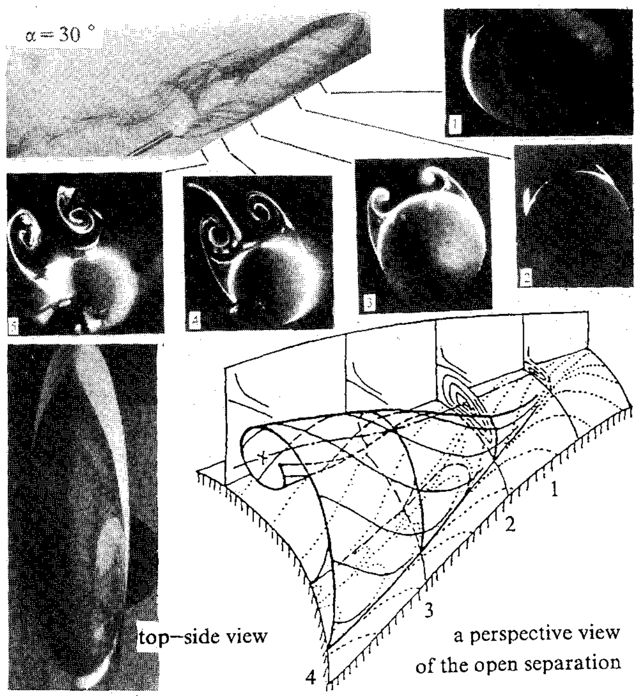

Fig. 3 Features of the open separation and the vortex formation.

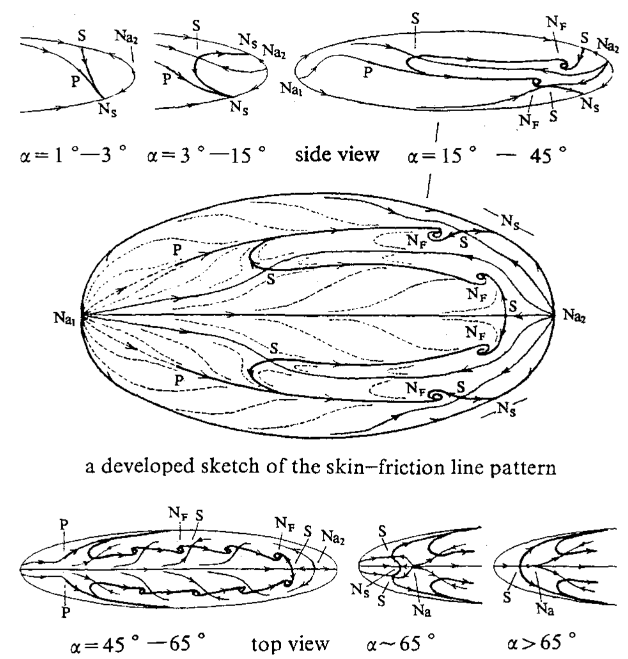

Fig. 4 Topological structures of the separated flows and their evolution with changing α.

primary separation line rolls up into a concentrated vortex above the body. The outer boundary of the bubble becomes the aft segment of the primary separation line, and so only the fore segment of it is the open separation line practically. In the α region of 45–65 deg, the vortex bursts above the body and is called a bursting vortex. The flowfield becomes unsteady and asymmetric. At about 65 deg, the two open separation lines join up and become a closed separation line. There is another type of vortex: the vertical vortex shed from the aft segments of the primary and secondary separation line (see the photo of $\alpha = 30$ deg). It is very weak and unsteady. When $\alpha > 65$ deg, the flow becomes unsteady vortex shedding (see $\alpha = 70$ deg). Figure 3 gives some results from the laser sheet technique. It can be seen that the free edge of the separation surface from open separation is a spiral streamline, which is around the vortex axis instead of coinciding with it.

3) The topological property and identification of the starting point of open separation: Figures 1–3 show that there is not any singular point in the starting region of an open separation, including the body surface and the flowfield concerned. However, we have found that the open separation leads to a fold of the near-wall stream surface; it is just a cusp catastrophe, and the cusp point on the wall can be used to define and identify the starting point of open separation.[4]

4) The topological structures of the separated flow and their evolution with changing α are shown in Fig. 4. It is from a topological analysis to the experimental results obtained. In Fig. 4, P–N_S (or P–N_F) denotes the open separation line, and S–N_S (or S–N_F) denotes the closed separation line. The N_F is the footprint of the vertical vortex. The developed sketch of a surface flow pattern can be obtained by cutting the body surface from N_{a_1} to N_{a_2} and developing it in a topological manner. In the α region of 45–65 deg, there are several unsteady pairs of N_F–S on the secondary separation line. The theoretic foundation of the previous topological analysis is in Ref. 5.

Acknowledgment

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References

[1]Costis, C. E., Hoang, N. T., and Telionis, D. P., "Laminar Separating Flow over a Prolate Spheroid," *Journal of Aircraft,* Vol. 26, No. 9, 1989, pp. 810–816.

[2]Wang, K. C., Zhou, H. C., Hu, C. H., and Harrinton, S., "Three-Dimensional Separated Flow Structure over Prolate Spheroids," *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences,* Vol. 421, 1990, pp. 73–90.

[3]Su, W., Tao, B., and Xu, L., "Experimental Investigation of Three-Dimensional Separated Flow over a Prolate Spheroid," *Recent Advances in Experimental Fluid Mechanics, Proceedings of the 1st International Conference on Experimental Fluid Mechanics,* edited by F. G. Zhuang, International Academic Publishers, Beijing, People's Republic of China, 1992, pp. 205–210.

[4]Su, W., and Tao, B., "Topological Properties of Three-Dimensional Boundary Layer and Three-Dimensional Separation," *Proceedings of the 2nd International Conference on Fluid Mechanics,* (Beijing, People's Republic of China), Peking Univ. Press, Beijing, People's Republic of China, 1993, pp. 539–544.

[5]Lighthill, M. J., "Attachment and Separation in Three-Dimensional Flow," *Laminar Boundary-Layers,* Vol. II 2.6, edited by L. Rosenhead, Oxford Univ. Press, Oxford, England, UK, 1963, pp. 72–82.

Reynolds Stress Profiles in the Near Wake of an Oscillating Airfoil

Seung O. Park* and Boo Il Lee†
Korea Advanced Institute of Science and Technology, Taejon 305-701, Republic of Korea

Introduction

MOST previous research efforts concerning unsteady aerodynamics of oscillating airfoils were directed to unsteady wing loading associated with separation and dynamic stall phenomena. Relatively little attention, however, has been given to the study of oscillating wakes. Ho and Chen[1] studied experimentally the unsteady wake of a plunging airfoil at incidence using a hot-wire rake. De Ruyck and Hirsch[2] measured the instantaneous velocity

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*Professor, Department of Aerospace Engineering. Member AIAA.
†Research Assistant, Department of Aerospace Engineeing.