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Flow Separation on Bodies of Revolution at Incidence

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SUMMARY Flows over bodies of revolution at angles of incidence up to 30° are considered. Details of the separated flow patterns are presented and classified according to the recently developed kinematical approach to the analysis of flow patterns. Several previously doubtful areas of the separated flow over bodies are clarified and a new flow structure identified which appears to be one of the most commonly occurring structures in simple three-dimensional separations.

1 INTRODUCTION

Stability and control deficiencies caused by flow separations continue to be an area of major concern to aircraft designers. In aircraft manoeuvres at high incidence, asymmetric flow separation from the forebody can produce large side forces and yawing moments which induce lateral departure (yaw-off or nose-slice). Interest in such areas of post-separation aerodynamics of both aircraft forebodies and of missiles has led to many attempts to predict such flows using boundary-layer approaches. Comparison of the results of these analyses with experiment, even for the simpler case of symmetric separation from bodies of revolution, has suffered from an inadequate knowledge of the types of three-dimensional separation which can occur in practice and their possible locations, as well as ignorance of the detailed flow pattern applicable to a particular case.

This paper presents the results of an investigation of the flow over two simple bodies of revolution - a prolate spheroid, and a hemisphere-cylinder - at angles of incidence of up to 30°. The prolate spheroid was chosen since it has been the subject of many experimental and theoretical investigations, e.g. Werle (1962), Wang (1974,1975), Han and Patel (1977), and contains most of the essential elements of boundary-layer interest - a finite body smoothly closed at both ends, so that both favourable and adverse pressure gradients occur along both lateral and longitudinal diretions. The hemisphere-cylinder is also well covered by previous investigations, e.g. Werle (1962), Hsieh (1977), and provides a shape which is common in aerospace applications. Although both these bodies have been extensively studied, details of, the structures of their separating flow patterns still remain largely unknown. The major aim of the investigation was therefore to produce surface flow patterns of sufficient detail to allow complete definition of these structures.

In interpreting the flow patterns obtained, use has been made of the recently developed kinematical approach to the classification of flow patterns. This approach attempts to classify points in the flow where the shear stress is zero (critical points) in terms of their topological characteristics as saddles or nodes (Perry and Fairlie (1974)) rather than as separation or reattachment points. Recognition of the occurrence of such critical points is an essential prerequisite to the understanding of the overall flow phenomena. The real question is, however, which critical points occur in a given flow, and where they are located. The kinematical approach allows the use of a wealth of well proven topological constraints governing the number and types of critical points which can occur, and Hunt et al. (1978) have recently developed an arithmetic for this purpose. Perhaps the major contribution of this type of theory is in ensuring that flow patterns inferred from experiment are kinematically possible.

2 EXPERIMENTAL DETAILS

From all the evidence gathered to date, separation patterns appear to be independent of Mach number, at least while there are no shock waves present in the flow. All testing was therefore conducted at a Mach number of 0.55, which corresponds to the maximum dynamic pressure conveniently available in the transonic wind tunnel at A.R.L. The dynamic pressure thus obtained (approximately 20 kPa) is approximately an order of magnitude greater than that found in typical low-speed tunnel tests, and allowed the production of surface oil flow patterns containing considerably more detail than is usually obtained in low-speed tunnels. Operation at this Mach number also allowed the use of the Schlieren technique to visualise vortex shedding associated with flow separations.

The models used in the investigation were of wooden construction with a highly polished black surface finish. The models were 400 mm in length. The maximum diameter for the hemisphere-cylinder was 125 mm and for the spheroid 100 mm (giving a ratio of major to minor diameters of 4:1). Both models were attached via 25 mm diameter stings to the tunnel incidence change mechanism, the prolate spheroid body contour being faired smoothly into the sting.

Initially it was hoped to achieve natural boundary-layer transition on all models. (Reynolds number based on maximum diameter was about 1.5×10^6). However, early testing indicated that natural transition tended to occur very nonuniformly, its position varying widely with angle of incidence. It was therefore decided to fix transition close to the nose of each body, using a band of fine carborundum particles, and all results presented are with transition fixed in this way.

Surface streamlines were made visible by the familiar surface oil flow technique. For these tests a suspension of titanium dioxide in silicone oil was used. A small amount of oleic acid was added to control the agglomeration of the titanium dioxide particles, thus giving an effective control over the fineness of the pattern produced.

3 RESULTS

The development of the flow patterns over both bodies will be considered as the angle of incidence is increased from 0° to 30°.

3.1 Prolate Spheroid

At zero incidence the axisymmetric flow separates at a fixed parallel located at approximately 96% of the body length. This is in good agreement with the positions of turbulent axisymmetric separation quoted by Han and Patel (1977) of 97% from theory and 96% from experiment.

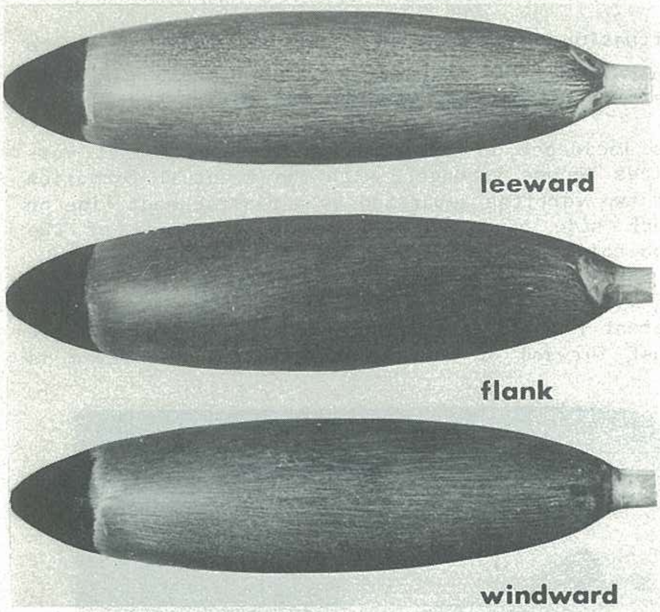


Figure 1 Spheroid : Angle of incidence 5°

Figure 1 shows the effect of an increase in angle of incidence to 5°. The extra complication relative to the axisymmetric case introduced by this small change in incidence is readily apparent. Perhaps the most interesting feature of the flow is the appearance of two pairs of spiral nodes (stable foci) on the sides of the body. An enlarged three quarter rear view of these foci is presented in Figure 2. Also noticeable in this photograph is the reversal of the circumferential flow towards the windward side implying the existence of a saddle type critical point on the upstream boundary of the low energy flow region indicated by the lack of movement of the oil mixture. A sketch of the surface flow pattern implied by these photographs is shown in Figure 3. The number of nodes and saddles complies with the rules of Hunt et al. (1978) keeping in mind the existence of a node at the upstream attachment point and the semi-infinite extent of the body.

To aid in the comparison with data from other sources, the conjectured flow pattern which would exist

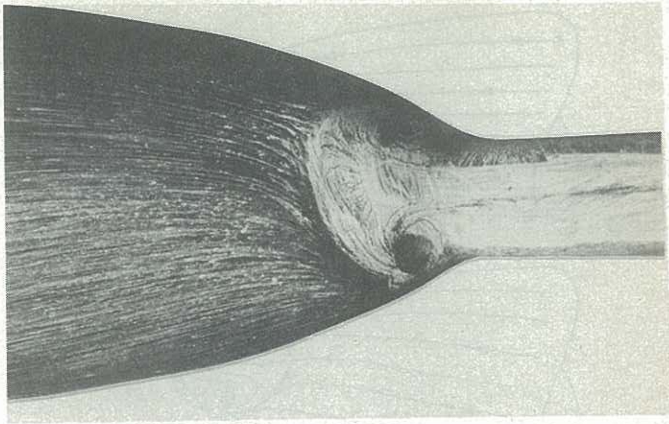


Figure 2 Flow detail : Spheroid 5°

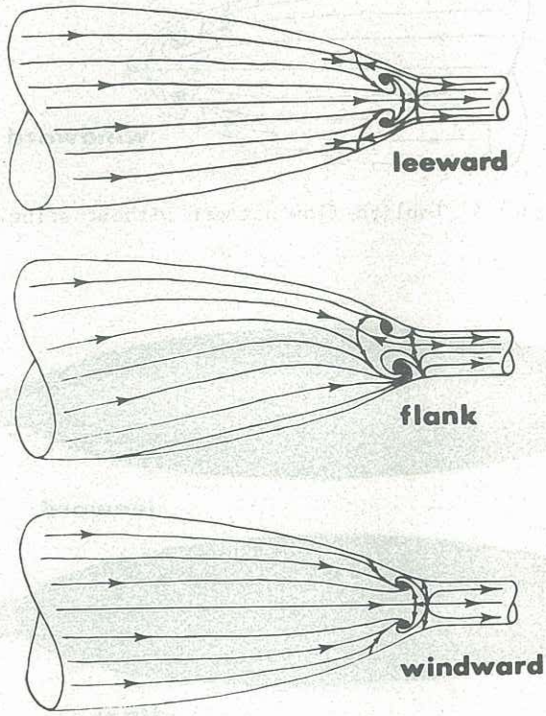


Figure 3 Implied flow pattern : Spheroid 5°.

in the absence of the sting is shown in Figure 4.

These flow patterns are consistent with the smoke studies of Han and Patel (1977) but differ considerably from their sketches. As in all previous investigations, their sketches ignored the existence of the two pairs of spiral nodes on the rear of the body.

As the angle of incidence is increased, the flow pattern of the rear separation remains similar to that at 5°, but becomes more and more distorted. The divergence of the streamlines on the lee side over the middle of the body also increases and leads to a merger of the stream lines. The line along which this merger occurs is identified with a free vortex type of separation as defined by Maskell (1965) or an open separation line in the terminology of Wang (1976). This line is clearly visible in the flow at an angle of incidence of 15° shown in Figure 5, and it is along this line that the boundary layer rolls up into a longitudinal vortex.

Further increases in incidence produce flow patterns

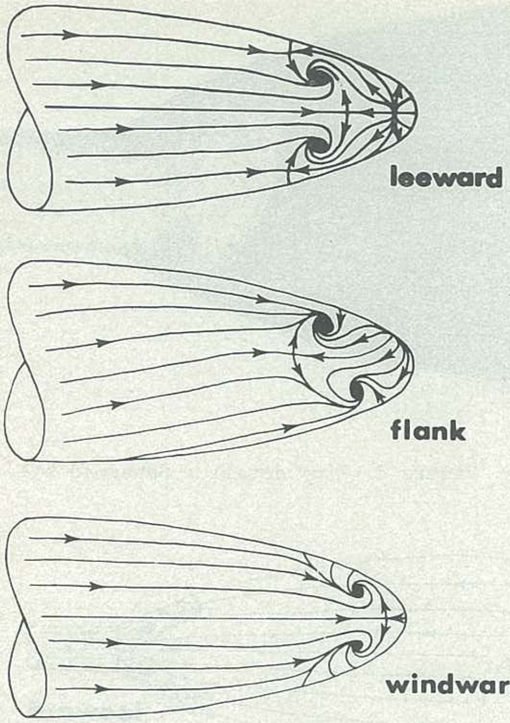


Figure 4 Implied flow pattern without sting.

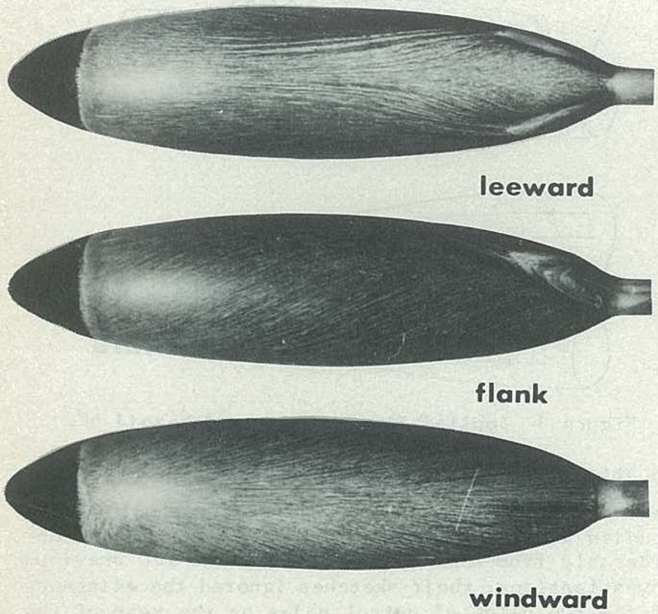


Figure 5 Spheroid : Angle of incidence 15°.

quite similar to that at 15°, the major difference being the formation of secondary longitudinal vortices. In Figure 6, at an angle of incidence of 30°, at least two free vortex separation lines are visible. In this case the rear separation has been distorted almost beyond recognition, but still retains the same basic nature of the low incidence case.

3.2 Hemisphere-Cylinder

At zero incidence, the flow is once again axisymmetric but in this case there is no separation present on the body. The existence of a turbulent boundary layer is apparently sufficient to avoid the commonly observed shoulder separation. This

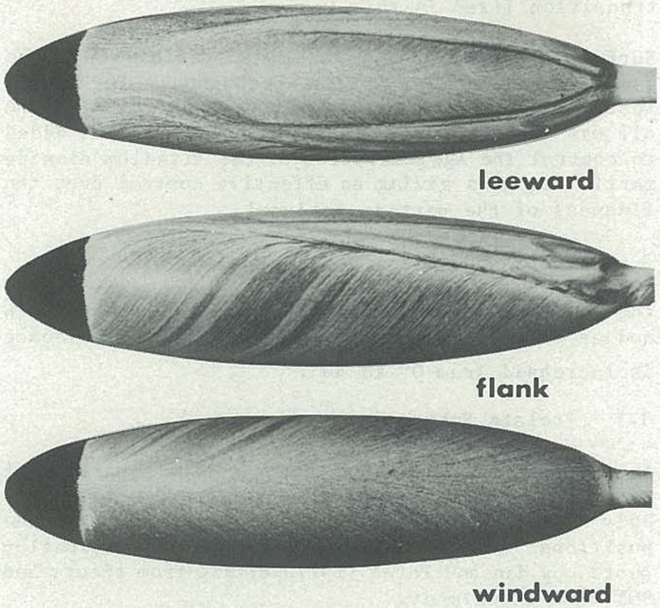


Figure 6 Spheroid : Angle of incidence 30°.

situation is maintained up to angles of incidence approaching 10° when longitudinal vortex formation becomes visible towards the rear of the body.

As incidence is increased these longitudinal vortices become stronger, with the eventual formation of two vortices separated by a reattachment line on each side of the body, as in the case of the spheroid.

At an angle of incidence of 17.5°, a completely different type of separation forms on the leeward side just forward of the shoulder. This separation is

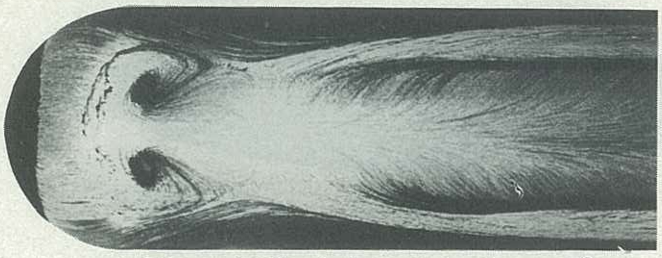


Figure 7 Hemisphere-cylinder : 25°.

shown in Figure 7 for an angle of incidence of 25°, where the flow pattern has developed sufficiently for the details to have become clear. This separation is apparently the source of the "nose vortices" first observed by Werle (1962) and later by Hseih (1977). This pattern, which is sketched in Figure 8, is identical with that found on the rear of the spheroid (c.f. Figure 4). From its appearance when viewed from above, this pattern has been named the "owl" structure. Each of the two spiral nodes symmetrically placed about the leeward plane of symmetry gives rise to a quite strong vortex shed downstream. These vortices appear plainly in Schlieren observations of the flow field, the vortices leaving the surface at a finite angle and quickly approaching the free stream flow direction.

In discussing the longitudinal vortices shed from the rear of the body, many authors have drawn streamline patterns for the flow in planes normal to the body major axis. In a large number of cases, these crossflow streamline patterns have been kinematically impossible. The case with two "free

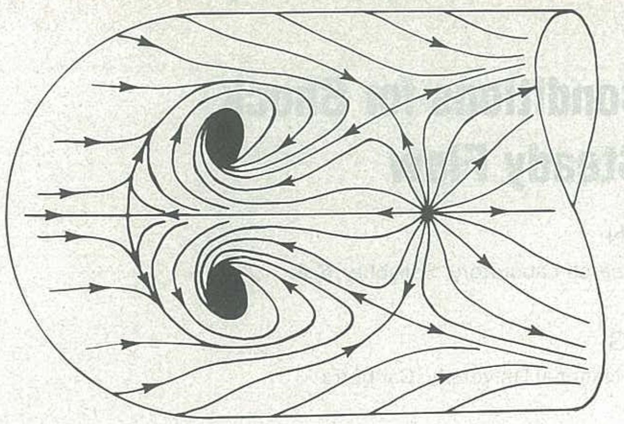
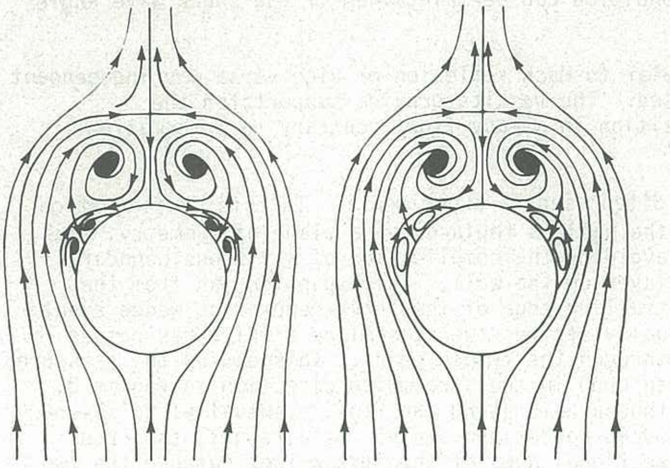


Figure 8 Implied flow pattern.

vortex" separation lines is sketched in Figure 9.



(a) (b)

Figure 9 Crossflow streamline patterns.

The two alternative patterns are each topologically correct and no distinction in favour of one or the other can be made on topological grounds. This situation is similar to that existing for the flow in the plane of symmetry upstream of a surface mounted protruberance . In this case Norman (1972) called the two possibilities the "jet-maze model" (equivalent to Figure 9(b)) in which each of the vortices is fed by a separate slice of the approaching flow, and the "stairstep model" (equivalent to Figure 9(a)) in which only the primary vortices are fed from the free stream flow.

4 DISCUSSION

One of the more interesting observations of this investigation has been the identification of the "owl" structure on all of the bodies studied, but in two quite different situations. From the work of Werle (1962) it appears reasonable to expect the appearance of similar structures on the nose of a spheroid at higher incidence than reached here, and this would appear to be the case for all fairly blunt nosed bodies of revolution. Indeed the "owl" structure, or slight variations of it, seems to be one of the most commonly ocurring structures to be found in three-dimensional separations. It has been observed in the separation of the flow about nominally two-dimensional aerofoils, in the flow downstream of surface mounted protruberances , in separation in nominally two-dimensional diffusers, and perhaps most surprisingly, in what has been suggested by Hunt et al. (1978) as almost the simplest kind of three-dimensional separated flow - the flow over shallow bell-shaped hills. It has been found in both laminar and turbulent flows, and at speeds ranging from close to zero up to Mach numbers of at least 2.5.

In our progress toward an understanding of three-dimensional separation, our knowledge of two-dimensional separation has really been a mixed blessing. A nodal or saddle point of separation or reattachment is easy to comprehend intuitively and follows easily from our two-dimensional experience; a spiral node or focus involves a more complex flow structure, but admission of their existence seems necessary for the understanding of even the simplest of three-dimensional cases.

5 CONCLUSIONS

The results of this investigation have clarified the details of the separated flow over simple bodies of revolution. Several previously unknown aspects of the separating flow patterns have been revealed. The results will provide a basis for comparison with theoretical predictions of this type of flow. It is intended to extend the investigation to cover angles of incidence which give rise to the asymmetric vortex formation so important to practical aerodynamic design, and to bodies of non-circular cross-section.

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