Technical Notes

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Laminar Boundary Layer in Symmetry Plane of Blunt-Nosed Body

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Introduction

THIS work investigates the laminar boundary layer in the plane of symmetry on the hemispherical nose of a blunt cylindrical body at angle of attack. The resulting boundary-layer properties are computed by a numerical procedure and examined to determine the influence of angle of attack on the position of laminar flow separation in the symmetry plane. The unique nature of the leeside separation, i.e., streamwise flow reversal or embedded vortex crossflow, is examined.

Wang[1,2] pointed out the existence of the vortex-like crossflow on an inclined body of revolution,[1] and further amplified this occurrence to postulate a general explanation of three-dimensional separation[2] on a body of revolution. We apply Wang's results to study and interpret the behavior of the flow on the blunt nose of a slender cylinder afterbody. In contrast to Wang's investigation, the pressure distribution is based on experiment[3] rather than inviscid flow theory. Thus the separation phenomena does not introduce a large perturbation on to the prescribed pressure distribution, as would be the case for the idealized inviscid pressure distribution. The computed results for the body shape considered largely support Wang's postulated behavior and give additional support to this explanation of three-dimensional separation.

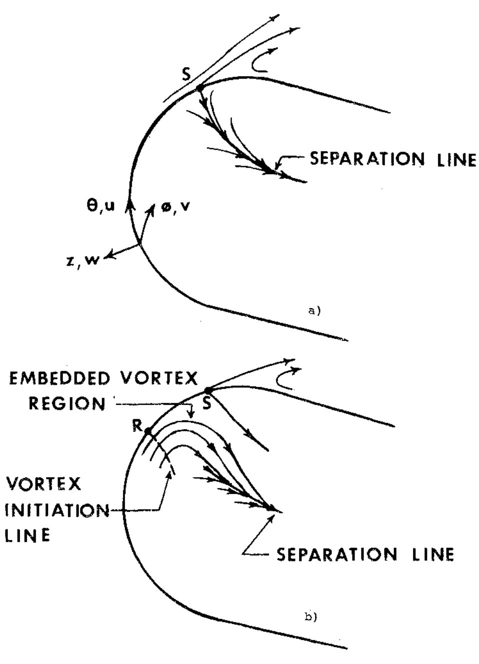

Fig. 1 Separation in three-dimensional flow.

The well established occurrence of flow reversal in two-dimensional problems, e.g., the cylinder in crossflow, suggests a somewhat analogous behavior in three-dimensional flow. This is illustrated in Fig. 1a, where the separation line passes through the point of zero wall friction (point S) in the plane of symmetry. This concept of separation has been suggested by Maskell,[4] Cooke and Brebner,[5] and Eichelbrenner and Oudart.[6] Wang's results[1] identified an embedded vortex region beginning in the plane of symmetry at a position (point R) upstream of streamwise flow reversal (Fig. 1b). The point R separates an upstream region where the streamlines for the leeside flow (off the plane of symmetry) are directed towards the symmetry plane from a downstream region where the leeside flow streamlines are directed away from the symmetry plane. The identification of this region allowed Wang to explain[2] certain observed surface streamline patterns which were inconsistent with the separation suggested by Fig. 1a. More importantly, the physical feature of the crossflow vortex prompted Wang to describe a separation phenomena governed by the vortex rather than flow reversal. The resulting separation line is open, i.e., it does not form a closed envelope of limiting streamlines, and it lies between the line of vortex initiation and the surface streamline passing through the point of flow reversal. This is illustrated in Fig. 1b.

It appears reasonable that the embedded vortex region should be of some finite size if a vortex induced separation is to occur. The size of this region is in part described by the distance between the points R and S in the plane of symmetry. Wang showed that for the prolate spheriod for very high angle of attack, greater than 45°, and for very low angle of attack less than about 2°, the difference between points R and S was negligible on the leeward side, and thus inferred that the separation was due to flow reversal. In the range of angles of attack between 2 and 45°, the distance between the points R and S was quite substantial and thus of sufficient size to allow an embedded vortex to grow and cause separation. At a fixed angle of attack of 12° Wang's computations showed that increasing the spheriod thickness ratio (i.e., increasing bluntness) reduced the size of the leeside distance between "R" and "S" until it became negligibly small at a thickness ratio of approximately 0.8.

The virtual disappearance of the embedded vortex region for blunt spheriods and for slender spheriods at high angle of attack raises a question of the existence of an embedded vortex region on the blunt hemispherical nosed body at angle of attack, as either of these cases might be used to describe the nose region of a blunt-nosed body such as the one considered herein. We were consequently motivated in this investigation, first, to extend Wang's work by considering a problem in which the pressure distribution was based on experiment rather than an idealized formulation, and second, to examine the possibility of the existence and size of an embedded vortex region on the hemispherical nose.

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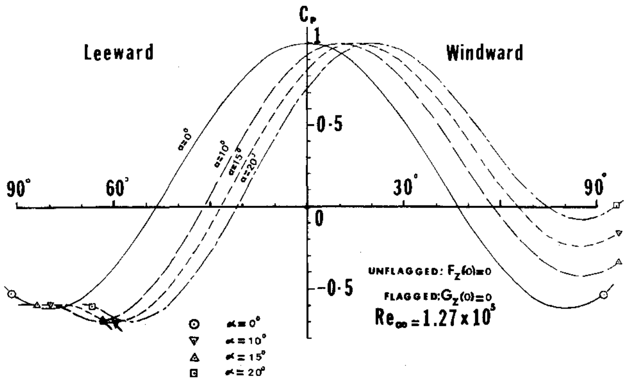

Fig. 2 Location of positions of zero surface friction components and pressure coefficients in the meridional plane.

Method of Solution

The governing equations in the solution were the three-dimensional boundary-layer equations in orthogonal coordinates (e.g., see Ref. 1). The finite-difference procedure applied to the hemispherical nose problem considered herein generally follows that used by Wang[1] and is described in some detail in Ref. 7. Included in Ref. 7 is the method by which the experimental pressure distribution[3] was utilized in the solution. It can be noted that the prolate-spheriodal coordinates used by Wang were simplified to spherical coordinates for the hemispherical nose. The spherical coordinates are noted in Fig. 1a. Solutions were obtained for angles of attack of zero, 10, 15, and 20° for which the experimental pressure data was available.

Prediction of Vortex Induced Separation

As noted by Wang[1] the embedded vortex can be identified with the reversal of the crossflow velocity profile, $v(z)$. In the plane of symmetry this condition is inferred by $(\partial v_\phi/\partial z)|_w = 0$, where the subscript ϕ refers to the partial derivative with respect to the ϕ-coordinate variable and the subscript w means the term is evaluated at the surface $z = 0$. The ordinary reversal of the boundary-layer velocity in the plane of symmetry is inferred by the condition of zero surface friction, $(\partial u/\partial z)|_w = 0$. For sake of simple notation, hereafter we substitute $G = v_\phi$ and $F = u$. Thus $G_z(0) = (\partial v_\phi/\partial z)|_w$ and $F_z(0) = (\partial u/\partial z)|_w$.

Using the experimental pressure distribution on the hemispherical nose, the condition $G_z(0) = 0$ occurred on the leeward side at angles of attack of 10 and 15°. The condition $G_z(0) = 0$ did not occur on the leeward side at an angle of attack of 20°. $G_z(0) = 0$ never occurred on the windward side for the conditions considered (angles of attack of 10, 15, and 20°).

The position and occurrence of $F_z(0) = 0$ and $G_z(0) = 0$ and their relation to the experimental pressure coefficient C_p are summarized in Fig. 2. The distance between the occurrence of $G_z(0) = 0$ and $F_z(0) = 0$ on the leeward side at an angle of attack of 10 and 15° suggests the possibility of the vortex induced separation noted by Wang. On the other hand, the absence of the condition $G_z(0) = 0$ on the leeward meridian at an angle of attack of 20° suggests a separation similar to two-dimensional phenomena where streamwise flow reversal near the surface governs separation. These results are consistent with Wang's results on the prolate spheriod where the position $F_z(0) = 0$ moved upstream at high angle of attack to a point just downstream of the point $G_z(0) = 0$. On the windward side the absence of the condition $G_z(0) = 0$ implies that the separation there involved only flow reversal. It should be noted that these results are valid only for the Reynolds number range for which the pressure data is accurate. In particular, transition of the laminar flow to turbulent flow in the boundary layer will have a significant influence on the pressure distribution.

Table 1 Comparison of computed and experimental results

Angle of attack degrees	Computed zero $G_z(0) = 0$	Surface friction $F_z(0) = 0$	Separation point (experiment)
	Distance from stagnation point, degrees		
10	73	93	83
20	...	87	83

Comparison with Experiment

Smith and Evbouma noted in their experimental results[3] on the model from which the pressure data was obtained that the leeward separation line appeared to cross the plane of symmetry at a position of 83° from the stagnation point for angles of attack of 10 and 20°. This is compared with the computed position of $F_z(0) = 0$ and $G_z(0) = 0$ in Table 1.

The experimental data was taken using surface oil drops exposed to the flow at the same Reynolds number at which the pressure data was obtained. The prediction of the separation is not precise in this method and the difference of 4° noted at an angle of attack of 20° is considered good agreement. Hence, reasonable confirmation of the computed results predicting a separation exhibiting streamwise flow reversal is obtained. The experimental results at angle of attack of 10° might be indicative of a vortex induced separation which would occur between the position for $G_z(0) = 0$ and $F_z(0) = 0$. It should be noted that this would be an "open-type" separation line and would not cross the plane of symmetry at this point. The failure to observe an open separation line is attributed to lack of sufficient definition of the surface streamlines by the oil drops, and it is believed that a vortex-induced separation did occur at low angles of attack.

Conclusions

Computations of the three-dimensional boundary layer in the plane of symmetry using experimental pressure distribution suggest the existence of an embedded vortex on the leeward side for angles of attack of 10 and 15°. This vortex does not occur for 20° angle of attack. The size of the region of the embedded vortex suggests a vortex-induced separation at 10 and 15° angle of attack. The adverse pressure gradient near the shoulder on the windward side causes a flow reversal type of separation. No embedded vortex occurs on the windward side. The qualitative behavior of the separation phenomena on the leeward side is in strong agreement with Wang's analysis[1] and postulated behavior of three-dimensional separation on inclined bodies of revolution.

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