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BOUNDARY LAYER TRANSITION ON AN AXISYMMETRIC BODY AT INCIDENCE IN SUBSONIC FLOW

M.L. ROBINSON

WEAPONS SYSTEMS RESEARCH LABORATORY

DEFENCE RESEARCH CENTRE, SALISBURY, S.A. 5108 AUSTRALIA

SUMMARY The boundary layer on the windward face of an axisymmetric body at incidence to a subsonic airstream has been investigated using surface hot film sensors. The location of transition is related to two manifestations of the basic Tollmien-Schlichting instability mechanism namely the amplification of disturbances along streamlines away from the attachment line, and the amplification, neutral stability or decay of disturbances along the attachment line. A plausible pattern of transition boundaries is given, and criteria for the existence of laminar, transitional or turbulent flow on the attachment lines of the bodies investigated are given in terms of a characteristic Reynolds number. Such criteria are useful for assessing the validity of sub-scale wind tunnel results for their applicability to full scale flight vehicles.

1 INTRODUCTION

The work reported in this paper forms part of a continuing investigation into the behaviour of the boundary layer on an axisymmetric body inclined at an angle of incidence to a subsonic airstream. This investigation is a logical extension of previous studies by Robinson (1977, 1980) in which the dominant influence of the boundary layer on the aerodynamic characteristics of bodies at incidence was described. In a recent paper Poll (1982) has reported on this subject, and has provided further insight into the transition mechanisms on a body at incidence and the resulting aerodynamic effects. The motivation for the present work is the desire to improve the quality of wind tunnel results in their application to full scale flight vehicles operating at Reynolds numbers between one and two orders in excess of the wind tunnel simulations.

Australia has a particular need to be circumspect in aerodynamic experimentation because of the inadequacy of the available wind tunnel facilities (Pollock and Robinson, 1982). The need for upgraded facilities has been recognised and a plan for the upgrading of facilities is being developed. In the specification for any new wind tunnel facility, it is essential to nominate a maximum Reynolds number capability which will provide the required level of accuracy in the range of experiments envisaged. Since a high Reynolds number is synonymous with high cost (and often operational inconvenience), an upgraded facility should achieve a sub-scale Reynolds number at which acceptable results can be obtained with or without the use of flow manipulators. The findings of the present investigation provide a useful guide to the selection of an appropriate minimum Reynolds number at which the aerodynamic characteristics of axisymmetric flight vehicles can be determined with confidence.

The work described herein is concerned with surface hot film measurements of boundary layer characteristics on an axisymmetric body of finite length. The effects of nose shape and body attitude were studied to give a more complete description of the state of the boundary layer than has been available previously.

2 FLOW ON BODY AT INCIDENCE

The flow on an axisymmetric body at incidence α to a freestream velocity vector U_0 is shown in figure 1. Over a range of angles of incidence the crossflow boundary layer separates along a line located between extremes of 80° (subcritical flow) and 150° (critical flow) from the attachment line, resulting in the formation of two or more possibly asymmetric streamwise vortices. A crossflow drag which is non-linear with incidence is associated with the separation of the boundary layer and the vortex formation. The nature of the separation, the characteristics of the vortices and the magnitude and direction of the resultant force are each dependent on the state of the boundary layer approaching separation. A comprehensive review of vortex-induced aerodynamic loads has been given by Ericsson and Reding (1980).

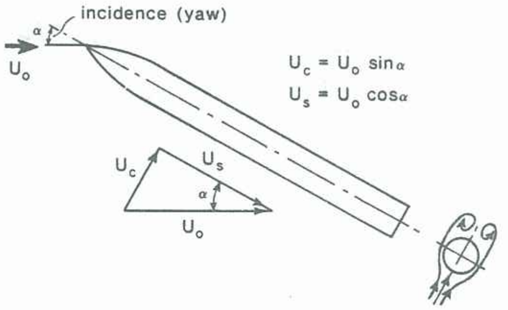


Figure 1 Flow over body at incidence

At zero incidence the flow is purely axial, and the boundaries between laminar and transitional flow, and between transitional and turbulent flow are fronts normal to the axis of the body. It is well established that the position of these transition fronts on a smooth surface depends primarily on Reynolds number, pressure gradient and freestream turbulence, with other factors such as compressibility and heat transfer playing a lesser role. For the nose shapes used in the present experiments, experimental evidence showed that at the test Reynolds number R_d of 0.16 million transition occurred naturally in the adverse pressure gradient downstream of the nose-cylinder junction.

It has been shown previously by, for example, Cumpsty and Head (1969) that the potential of the attachment line boundary layer to propagate or support disturbances depends on the Reynolds number based on a characteristic length of the attachment line boundary layer. For consistency with previous similar studies, the laminar momentum thickness θ has been chosen as the characteristic length, where $\theta = 0.404\ (\nu/u'_c)$. In this equation u'_c is the velocity gradient, at the attachment line, of the component of potential flow normal to the axis of the inclined body. The length θ, as defined herein, represents the momentum thickness of a hypothetical two dimensional laminar boundary layer which would have existed on the attachment line at the specified flow conditions. This leads to a Reynolds number R_θ which is 0.384 times Poll's (1982) similarity parameter $\bar{R}$. Robinson (1977) has shown that the characteristic Reynolds number can be expressed in terms of the Reynolds number R_d based on freestream velocity and body diameter, and on incidence as follows:

$$R_\theta = 0.20\ (R_d)^{\frac{1}{2}} \cot\alpha\ (\sin\alpha)^{\frac{1}{2}}. \qquad (1)$$

Evidence from previous investigations shows that the attachment line boundary layer will sustain a turbulent or quasi-turbulent boundary layer for R_θ values less than 100 in the presence of large disturbances such as those produced by a transition strip comprising roughness with a height of the order of boundary layer thickness. In the presence of small disturbances such as those pertaining to relative motion of a slender-nosed smooth body in a low turbulence fluid, R_θ values in excess of 400 may be required to sustain a turbulent boundary layer on the attachment line. At 30° incidence Reynolds numbers R_d corresponding to R_θ values of 100 and 400 are 0.17 million and 2.7 million respectively.

3 EXPERIMENTAL INVESTIGATION

The test configurations comprised a cylindrical body in which two surface hot film sensors were mounted, and three nose shapes which were attached to the body. Geometrical details of the configurations are given in figure 2. The nose shapes covered the fineness ratio (nose length/diameter) range from 2 (nose A) to 0.5 for the hemispherical nose. The nose lengths were such that the hot film sensors were located 3 and 5 calibres from each nose tip. All surfaces were ground to achieve a high standard of finish, and care was taken to avoid a step at the nose-cylinder junction. The body was mounted on a slender rear support which was attached to a turntable in the sidewall of the 386 mm x 300 mm working section of the tunnel. This allowed the body to be pitched through an incidence range in excess of ±40°. Results were obtained around the surface of the body by rotating the body about its axis through fixed increments of roll angle ϕ.

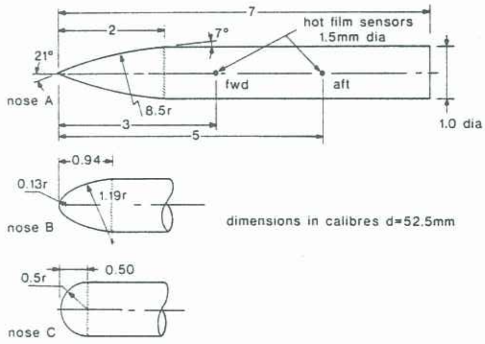


Figure 2 Body geometry

There is a discontinuity of 7° in surface slope where the contour of the ogival nose A joins the cylindrical body, whereas the contours of noses B and C are tangential to the cylindrical body at the nose-cylinder junction. Because of the discontinuity in surface slope of the body with nose A, and the bluntness of noses B and C, there is a region of significant adverse pressure gradient downstream of the junction. This creates the potential for amplification of disturbances in this region at relatively low Reynolds numbers.

Commercial Thermo Systems Inc (TSI) hot film sensors 1.5 mm dia were installed within 0.01 mm of the local surface of the 52.5 mm dia body. Great care was taken in the mounting of the films to ensure that the disturbance to the flow would be negligible. The sensors were located on the windward side of the body in the plane of incidence for positive angles of incidence α and zero roll angle ϕ. The hot film elements were operated in conjunction with a TSI 1050 anemometer at an overheat ratio of 1.3, and average (DC) and wideband root-mean-square (rms) voltage outputs were recorded. Tests were conducted in a low speed wind tunnel with a maximum airspeed of 49 m/s giving a Reynolds number R_d of 0.16 million based on the 52.5 mm diameter of the body. The natural level of longitudinal velocity fluctuations of the flow in the working section was about 0.1% as measured using the hot wire technique. The test programme was carried out at conditions for which the boundary layer as measured by the hot film sensor at x/d = 3 was fully turbulent at zero incidence. This required a Reynolds number R_d in excess of 0.14 million for nose A and lesser Reynolds numbers for noses B and C.

4 PRESENTATION OF RESULTS

Results obtained for the forward sensor in the roll angle range from 0° (attachment line) to 90° (approaching separation) are shown in figure 3. The rms results represent the measured root-mean-square signal divided by the corresponding signal for turbulent flow at zero incidence where both signals are corrected for wind-off system noise. An e^*_{rms} value of about unity generally represents a fully turbulent condition and a value approaching zero represents a laminar condition. Other values of e^*_{rms} greater or less than unity represent a transitional boundary layer.

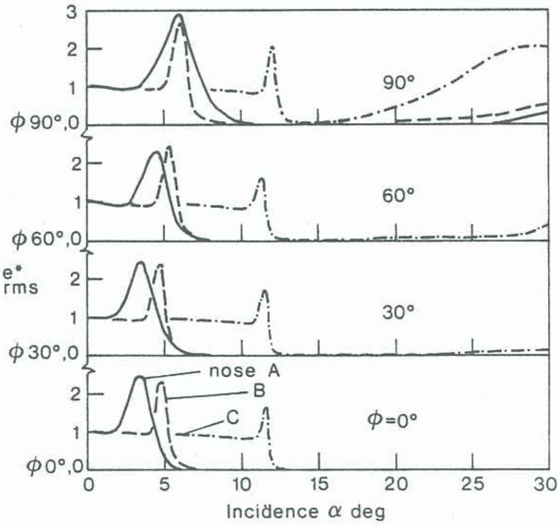
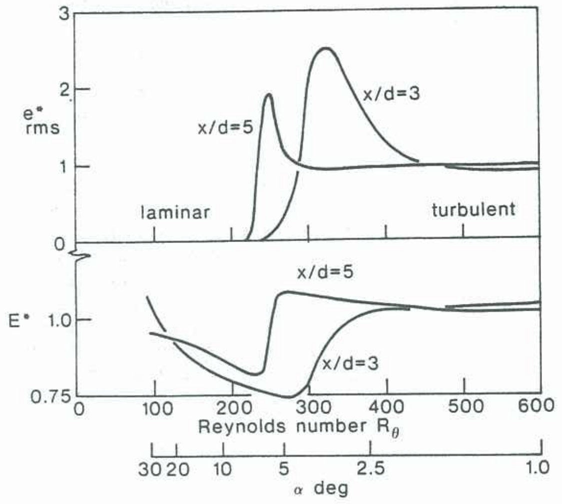


Figure 3 Hot film rms signals, forward sensor, $R_d = 1.6 \times 10^5$

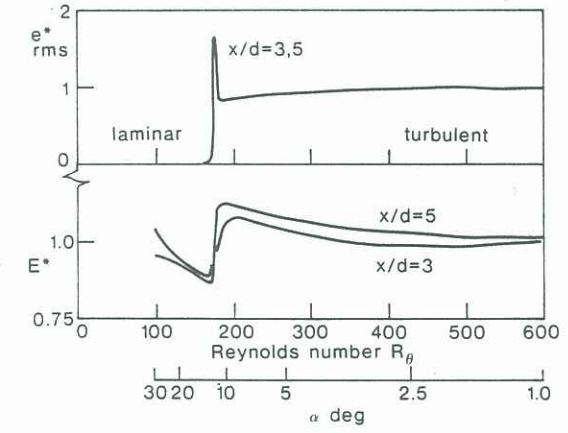
The primary observation that arises from the results given in figure 3 is that at low angles of incidence, the flow is completely turbulent and as incidence increases there is a range of incidence angles for which the flow is completely laminar. At the higher angles of incidence shown, the boundary layer on the attachment line is fully laminar but the disturbance level increases away from the attachment line (increasing ϕ) giving evidence of the amplification of disturbances along streamlines originating at the attachment line.

As incidence increases the rms signals undergo a change which is characteristic of a transitional front moving across the sensor. The signals first increase as a result of large amplitude transients, and then decrease to zero as both signal amplitude and intermittency decrease. The incidence angle at which the turbulent boundary layer starts to break down increases as a direct function of nose bluntness; this is particularly evident for the hemispherical nose C where a turbulent boundary layer exists on the attachment line to an incidence of about 11°.

With increasing distance from the attachment line (increasing ϕ), both the incidence angle at which the turbulent boundary layer starts to break down and the range of incidence angle over which the boundary layer is transitional tend to increase. This is particularly evident for the body with nose A where the forward sensor is one calibre from the nose-cylinder junction. However, with nose C the position of the transitional front on the incidence scale is independent of circumferential position in the roll angle range from 0° to 60°.



(a) nose A



(b) nose C

Figure 4 Hot film signals on attachment line, $R_d = 1.6 \times 10^5$

Mean and rms signals from sensors located on the attachment line of the body are shown in figure 4 for noses A and C. The abscissa scale is the characteristic Reynolds number R_θ which was computed from equation (1); the appropriate scale of incidence is included in the figures. The mean (DC) voltage E* is the ratio of the voltage increment at the test condition to the voltage increment pertaining to a fully turbulent boundary layer at zero incidence, where each voltage increment is measured relative to the appropriate wind-off value. Therefore, except at high incidence angles, values of E* of unity or more correspond to a turbulent boundary layer. Since the mean voltage output of a hot film sensor is a function of the local skin friction, values of E* less than unity are indicative of a transitional or laminar boundary layer. It appears from the results in figure 4 that the root-mean-square quantity e^*_{rms} which is a measure of the fluctuating component of skin friction is the more sensitive indicator of a transitional boundary layer.

There is a marked effect of axial position on the results obtained for nose A; this effect does not occur for nose C where the results are virtually independent of axial position. For nose A the boundary layer on the attachment line does not become turbulent at x/d = 3 until R_θ exceeds about 500 where the corresponding angle of incidence is about 2°. This result suggests that at low angles of incidence a nose influence exists such that the attachment line boundary layer ahead of the forward sensor supports a lower amplification rate than that pertaining to an equivalent flow over a body of infinite length. A possible explanation for this effect is that the actual value of θ is less than that calculated for an infinite body, and therefore a lesser amplification rate would be expected. The lack of an influence of axial position on the results for nose C probably occurs because the forward sensor is relatively remote (2.5 calibre) from the nose-cylinder junction and because of the increased crossflow velocity component at the 11° incidence angle limit for turbulent flow.

TABLE 1

TRANSITION CRITERIA FOR ATTACHMENT LINE

NOSE	R_θ			
	x/d = 3 (fwd)		x/d = 5 (aft)	
	La – Tr	Tr – Tu	La – Tr	Tr – Tu
A 	230	500	220	300
B 	240	320	230	280
C 	160	190	160	190

Characteristic Reynolds numbers R_θ representing the laminar-transitional front (La-Tr) and the transitional-turbulent front (Tr-Tu) are given in Table 1. The attachment line boundary layer is likely to be laminar for R_θ less than the La-Tr values given and turbulent for R_θ greater than the Tr-Tu values shown. Clearly, the much lower value of R_θ for turbulent flow on the body with nose C shows that this nose produces larger disturbances than do the more slender noses A and B. Therefore it is concluded that nose geometry, through its effects on disturbance level and local amplification rate influences transition on a body at incidence.

5 TRANSITION BOUNDARIES

It is possible to draw up plausible transition boundaries from the experimental data, and these are shown for nose A in figure 5. Regions of the body for which the boundary layer is laminar, transitional or turbulent are indicated. The location of these regions is uncertain on the nose and the forward part of the cylindrical body since there are no experimental results to verify the patterns shown. The type 1 patterns shown in figure 5(a) to (c) are most likely to occur when the Reynolds number is not greatly in excess of the minimum value required to achieve a turbulent boundary layer downstream of the nose-cylinder junction at zero incidence. As incidence angle increases from zero, the transition fronts distort progressively as shown in figure 5(a), (b) and (c), giving rise to a complex flowfield especially on the leeward side of the body. The flow is largely turbulent on the body for the range of incidence angles pertaining to figure 5(a). The fronts on the attachment line move aft with increasing incidence such that at $\alpha = 7.5^{\circ}$ the boundary layer is laminar from the nose to x/d = 5 whereas transition on the leeward generator occurs well forward on the nose. At higher incidence angles laminar flow extends completely over the windward face of the body as shown in figure 5(d). At relatively large angles of incidence, the flow shown in figure 5(e) is possible on slender-nosed bodies at Reynolds numbers well in excess

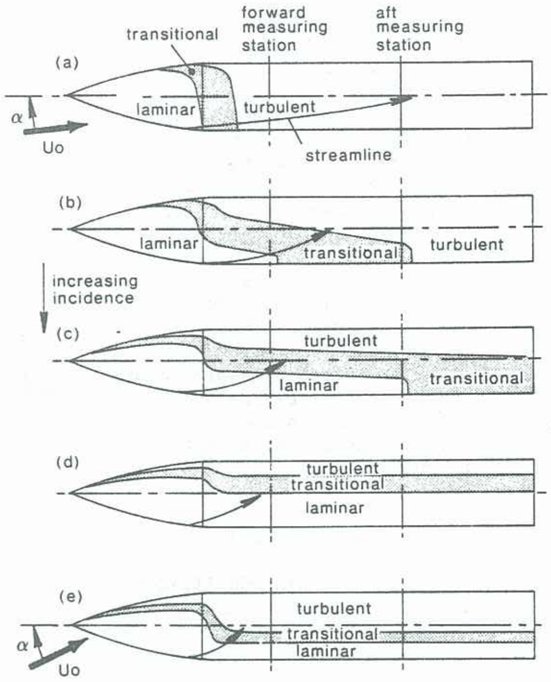


Figure 5 Transition boundaries on body at incidence, type 1

of that of the present tests. Here the attachment line boundary layer is laminar, and disturbances amplify along streamlines breaking down to form a turbulent boundary layer prior to separation.

A modified pattern of transition boundaries may occur where the nose is sufficiently blunt so that disturbances amplify rapidly in the resulting adverse pressure gradient. A local region of turbulent flow develops on the attachment line as shown in figure 6, where incidence angle increases between figure 6(a) and 6(b). Because disturbances are damped away from the nose, the attachment line boundary layer reverts to the laminar state and a quasi-two dimensional crossflow is established. The surface hot film results for nose C show that the position of each transition front is extremely sensitive to incidence angle, as indicated in figure 3. For incidence angles in excess of 30° the patterns shown in figure 6 are representative of flows to be expected in wind tunnels operating at Reynolds numbers R_d of 0.5 million or less. The crossflow separation is either laminar (subcritical) or transitional (critical or supercritical). At flight Reynolds numbers R_d of two million or more, R_θ exceeds 346 at 30° incidence and a fully turbulent flow field is highly probable with a turbulent (transcritical) crossflow separation. In these circumstances, wind tunnel results are likely to be spurious unless adequate steps are taken to represent the correct flow.

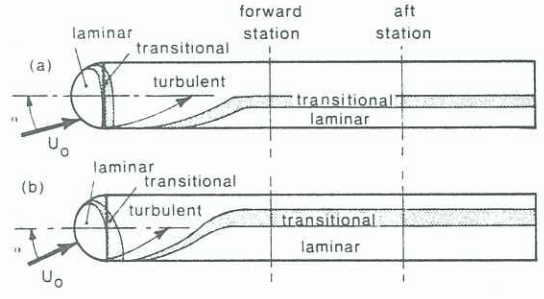


Figure 6 Transition boundaries on body at incidence, type 2

6 CONCLUSIONS

The state of the boundary layer on the surface of an axisymmetric body at incidence has been determined using surface hot film sensors. In the Reynolds number R_d range from about 0.15 to 0.5 million encountered in Australian wind tunnels an initially turbulent boundary layer on the windward face of a smooth body is replaced by a laminar boundary layer as incidence increases. The conditions for the occurrence of a particular type of attachment line boundary layer are given in terms of a characteristic Reynolds number R_θ. Under low turbulence conditions a turbulent boundary layer can be expected if R_θ exceeds about 300. Under conditions of moderate disturbances resulting from a relatively blunt nose or from a moderate freestream turbulence level, a turbulent boundary layer is produced if R_θ exceeds 180.

At flight Reynolds numbers exceeding 1 to 2 million it is predicted that except for a region on the nose, a fully turbulent flowfield exists on a typical body over a range of incidence angle extending from 0° to in excess of 40°, in agreement with the findings of Poll (1982). Because of the likelihood of laminar or transitional crossflows at high incidence angles in sub-scale wind tunnel simulations, results should be assessed in terms of present criteria for their applicability to full scale flight vehicles.

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