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The Attachment Line Boundary Layer on a Body at Incidence in Subsonic Flow

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SUMMARY The flow on a body at incidence in subsonic flow is described with reference to the origins of transition and the factors affecting the stability of the attachment line boundary layer. Measurements made in the attachment line boundary layer on an axisymmetric body using hot film sensors have shown that an initially turbulent flow reverts to a laminar state at an incidence which is determined by a characteristic Reynolds number. The characteristic Reynolds number is dependent on the disturbance level in the flow. In force measurement tests, the controlling influence of the attachment line boundary layer on the crossflow has been established in the range of variables examined.

1 INTRODUCTION

The behaviour of the boundary layer on an axisymmetric body inclined at an angle of incidence to an airstream (yawed body) has a dominant influence on the aerodynamic characteristics of the body because of the interaction of the boundary layer with the external flow. This study of the boundary layer on a yawed body forms part of an investigation of the attachment line boundary layer and its role in determining the crossflow on the body. The work was originally motivated by the lack of soundly based data on boundary layer transition on yawed bodies, and the desire to specify the range of applicability, if any, of low Reynolds number wind tunnel force measurements to full-scale flight conditions at Reynolds numbers one to two orders larger than those of the wind tunnel experiments.

Robinson (1977) observed that the flow on the attachment line of a finite, yawed body has characteristics in common with that on the attachment line of a swept wing with a leading edge of constant radius. Because the characteristics of the attachment line boundary layer on a swept wing had been determined by, for example, Gaster (1965) and Cumpsty and Head (1969), it was possible to apply this information to obtain an improved understanding of the flow on a yawed body. The analogy between the yawed body and swept wing is illustrated in figure 1 which shows the flow over an axisymmetric body inclined at an angle of incidence α to the direction of the freestream velocity U_0; the crossflow or chordwise velocity component is U_c and the spanwise or axial velocity component is U_s. Clearly, the body depicted in the figure could equally well be considered as a "wing" of circular cross-section swept at an angle φ to the flow direction where the sweep angle φ is the complement of the incidence angle α.

The first phase of the experimental investigation described herein was undertaken to determine the state of the attachment line boundary layer on a typical yawed body as a function of nominal disturbance level and characteristic Reynolds number. The measurements were made with surface hot film sensors on a body of finite length where the nose could be expected to influence the flow on the attachment line. The work therefore differs from a number of previous investigations of the flow on swept wings in which end effects were largely

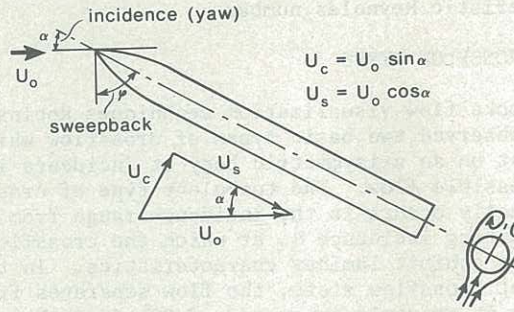


Figure 1 Flow over body at incidence

eliminated by simulating infinite span conditions. In the second phase of the investigation, force measurements were made on a body to determine the effect on the crossflow of a single roughness element located on the surface of the body just downstream of the nose-mainbody junction.

2 FLOW ON YAWED BODY

On an axisymmetric body of the type shown in figure 1, transition at zero incidence in incompressible flow moves upstream from the rear of the body with increasing Reynolds number, and approaches the junction of the nose and the mainbody at a Reynolds number based on diameter of about 10^5. At higher Reynolds numbers, transition may move ahead of the nose-mainbody junction. In the absence of artificial transition inducing devices, this axial flow transition may act as a source of contamination of an attachment line boundary layer by seeding the layer with turbulent spots. Alternatively, the turbulent spots may be generated artificially by roughness, by vibrating ribbons or by acoustic methods. Whether these naturally occurring or artificially induced turbulent spots grow, remain neutrally stable or decay depends on the Reynolds number based on a characteristic length of the attachment line boundary layer.

In conformity with previous experimental investigations, the laminar momentum thickness θ has been chosen as the characteristic length, where $\theta = 0.404\ (\nu/u_c')^{\frac{1}{2}}$. 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 yawed body. Poll (1979) prefers a characteristic length

$\eta = (\nu/u_c')^{\frac{1}{2}}$ because it is always representative of boundary layer thickness and does not depend on the state of the layer. Nevertheless, irrespective of the actual state of the boundary layer, θ can be interpreted as the momentum thickness of a laminar layer which does or would have existed on the attachment line at the specified flow conditions.

Robinson (1977) has shown that the characteristic Reynolds number R_θ can be expressed in terms of the Reynolds number R_d based on diameter, and incidence α as follows:

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

The characteristic Reynolds number R_θ is shown as a function of R_d and α in figure 1 of Robinson (1977).

Gaster (1965) and Cumpsty and Head (1969) carried out experimental studies of the boundary layer on the attachment line of a swept wing with a circular arc leading edge profile. Their results showed that, with large upstream disturbances, the boundary layer will remain turbulent provided that R_θ exceeds 100, but R_θ must be not less than 140 if the boundary layer is to have the properties of a turbulent flow corresponding to much higher values of the characteristic Reynolds number.

3 CROSSFLOW TYPES

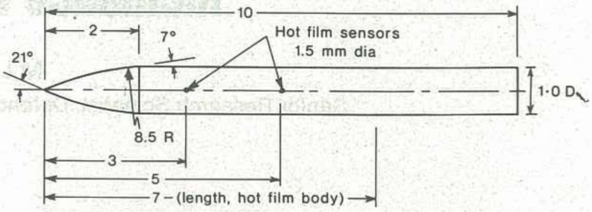
Using smoke flow visualization techniques Robinson (1977) observed two basic types of crossflow which may exist on an axisymmetric body at incidence in incompressible flow. The turbulent type of crossflow usually occurs in the incidence range from 0° to a limiting incidence α_ℓ at which the crossflow begins to exhibit laminar characteristics. In the turbulent crossflow state, the flow separates from the body at an angle in excess of 90° from the attachment line, and the crossflow drag coefficient is less than 0.7.

At an incidence in excess of α_ℓ, assuming that transition has not occurred as a result of Tollmien-Schlichting instability, the crossflow on most of the body is characteristically laminar. A pocket of turbulent flow may exist on the nose at the location where axial flow transition occurs. Separation from the body occurs at or less than 90° from the attachment line in the laminar crossflow state, and the crossflow drag coefficient exceeds 1.0. It is a reasonable assumption that, because of Tollmien-Schlichting instability, a purely laminar crossflow does not occur if the crossflow Reynolds number, $R_c = R_d \sin\alpha$, exceeds the critical value for a cylinder, namely 2×10^5.

4 SURFACE FLOW MEASUREMENTS

Surface measurements were made with hot film sensors at two locations 3 and 5 calibres from the nose of the axisymmetric body shown in figure 2. 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. The sensors were located on the windward side of the body in the plane of incidence, and at positive angles of incidence they were situated on the attachment line of the body. The hot film elements were operated in conjunction with a TSI model 1050 anemometer at an overheat ratio of 1.3, and average (DC) and wide-band rms voltage outputs were measured. Tests were conducted in a low speed wind tunnel with a maximum airspeed of 49 m/s, giving a maximum Reynolds number R_d of 1.7×10^5 with the 52.5 mm dia body. The natural level of longitudinal velocity fluctuations of the flow in the working section was about 0.1%.

Additional tests were made with an artificially high turbulence level produced by a 0.4 mm dia wire located in the plane of incidence of the body 45 mm upstream of the nose tip. This arrangement gave a narrow region of locally high turbulence which intersected the attachment line of the body throughout the available incidence range.



BODY	DIAM mm	LENGTH mm
Force	29.2	292
Hot film	52.5	367

dimensions in calibres

Figure 2 Body geometry

The theoretical pressure distribution on the body at zero incidence in subsonic flow shows that there is a highly favourable pressure gradient on the curved nose portion and a highly adverse pressure gradient on the first half calibre of the cylindrical mainbody. The influence of the nose should therefore be evident in the measurements obtained at the forward sensor which is located one calibre downstream of the nose-mainbody junction. Measurements obtained at the rearward sensor location, x/d = 5, are expected to be representative of the infinite span condition, since the pressure gradient at this point is only slightly adverse and the boundary layer is likely to be approaching an equilibrium state.

Data were measured at conditions for which the boundary layer as determined by the hot film signal at x/d = 3 was fully turbulent at zero incidence, that is for $R_d \geqslant 10^5$ at the natural turbulence level of 0.1%. At lower Reynolds numbers, the attachment line boundary layer was laminar at all incidence angles.

Results obtained in the attachment line boundary layer at a Reynolds number R_d of 1.7×10^5 are shown in figure 3 for the naturally occurring turbulence level of the tunnel. The rms results (e_{rms}) are corrected for wind-off background noise and made

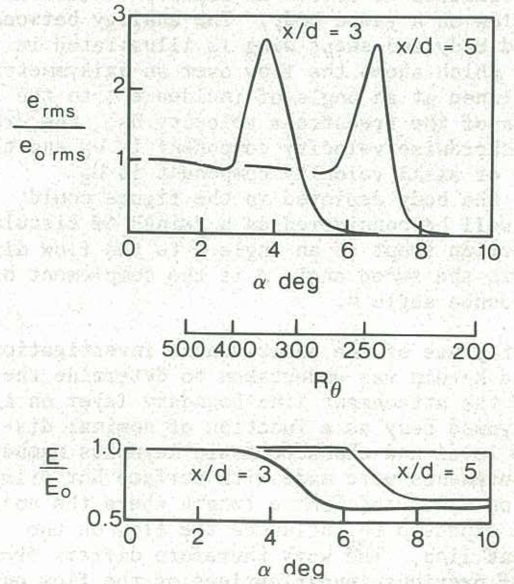


Figure 3 Hot film signals, low turbulence level, $R_d=1.7\times10^5$

non-dimensional in terms of the rms voltage measured in the fully turbulent state at zero incidence. Similarly, the mean results (E) are expressed at net DC voltages made non-dimensional in terms of the net DC voltage at zero incidence. The rms and mean results are shown as functions of incidence, and the scale of the characteristic Reynolds number based on the theoretically-derived laminar momentum thickness θ is included in the figure. The character of the attachment line boundary layer starts to change at $\alpha = 2.8^\circ$ for x/d = 3 and at $\alpha = 5.4^\circ$ for x/d = 5; the corresponding R_θ values are 400 and 275. As incidence increases further and R_θ decreases, the rms voltage rises to a peak which occurs at a different incidence for each sensor position, and then falls rapidly to zero as the intermittency decreases and the flow becomes increasingly laminar. At the condition of peak rms output at each sensor position, the signal has a distinctive spiky appearance which is markedly different from the fully turbulent signal.

The mean(DC) voltage from a hot film sensor gives an indication of the mean skin friction at the surface. The mean results in figure 3 show that the skin friction in the turbulent boundary layer increases slightly with incidence until the limiting incidence α_ℓ is reached. At this incidence the skin friction decreases markedly with further increase in incidence, giving positive supporting evidence that reversion to laminar flow is occurring. At a higher angle of incidence, the skin friction reaches a minimum value indicating a fully laminar boundary layer, and increases again with increasing incidence.

An interesting feature of these and other results obtained at low turbulence levels is that the attachment line boundary layer approaches the fully turbulent state at a higher value of the characteristic Reynolds number R_θ at x/d = 3, which is in the vicinity of a highly adverse pressure gradient, than at x/d = 5 where the pressure gradient is only slightly adverse. This suggests that either the characteristic length θ calculated for a laminar attachment line boundary layer on a yawed body of infinite length is greater than the actual value of θ at x/d = 3, or the net amplification of disturbances is reduced by the pressure gradients in the nose region. The scope of the present experimental programme did not permit resolution of the cause of this difference in results.

Results of sensor measurements which were made at an artificially induced high turbulence level are shown in figure 4. In these tests in which turbulence was produced by a wire in the incidence plane ahead of the body, it became apparent that the wire was effective in destabilizing the attachment line boundary layer only if the wire was located within one or two wire diameters of the incidence plane. No measurements of the turbulence levels induced by the wire were made. The results of figure 4 clearly show that the high turbulence level effectively destabilizes the attachment line boundary layer such that the layer is fully turbulent at both x/d = 3 and x/d = 5 in an incidence range extending to 19° at which $R_\theta = 140$. Although the disturbance levels in the boundary layer did not decline to the very low values observed in the low turbulence tests, nevertheless, the state of the layer was diagnosed as laminar at incidence angles in excess of 35° at which $R_\theta = 90$.

The present hot film sensor measurements give support to the hypothesis that the state of the attachment line boundary layer on a yawed body

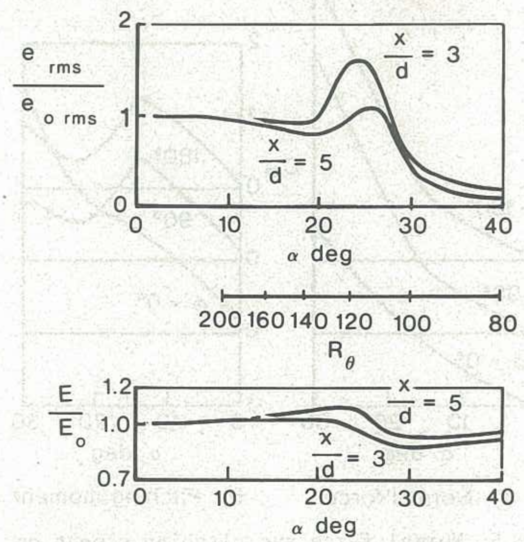


Figure 4 Hot film signals, high turbulence level, $R_d = 1.7 \times 10^5$

depends on the characteristic Reynolds number R_θ and the disturbance level in or adjacent to the layer. The decrease in the rms component of the hot film signals as incidence increases and R_θ decreases is positive evidence of the attenuation of disturbances in the boundary layer below a threshold value of R_θ which is dependent on the disturbance level.

5 FORCE MEASUREMENT

Force measurement tests were made at a Mach number of 0.5 on a body with the form shown in figure 2, but devoid of the hot film sensors. The body diameter was 29.2 mm and the length to diameter ratio was 10. Results of tests on this body shape in smooth condition and with two types of roughness band have been given by Robinson (1977). In the present experiments a single roughness element 0.35 mm dia was attached to the surface of the body 5 mm downstream of the nose-mainbody junction. For positive angles of incidence, the roughness element was located on the attachment line (windward generator) at zero roll angle, $\phi = 0^\circ$. At $\phi = 90^\circ$ the roughness element was located on a generator of the body 90° from the attachment line, and at $\phi = 180^\circ$ the element was on the leeward side of the body in the incidence plane. Normal force and pitching moment results expressed in non-dimensional coefficient form C_N and C_m are shown in figure 5, where the pitching moment is measured about the mid-point of the body 5 calibres from the nose tip.

For incidence angles in excess of 14°, the normal force and pitching moment at $\phi = 0^\circ$ clearly differ from the results at $\phi = 90^\circ$ and $\phi = 180^\circ$. Analysis of the force and moment results indicated that at $\phi = 0^\circ$ the crossflow was turbulent over the body downstream of the roughness element in the incidence range 0° to 30°, whereas at $\phi = 90^\circ$ and $\phi = 180^\circ$, reversion to laminar flow began at $\alpha = 14^\circ$. This angle for reversion to laminar flow is the same as that for the smooth body, and therefore the roughness element in the $\phi = 90^\circ$ and $\phi = 180^\circ$ positions has no effect on the flow. However, at $\phi = 0^\circ$ the presence of turbulent crossflow in the incidence range from 14° to 30° is convincing evidence that the roughness element contaminates the attachment line boundary layer which then acts as a turbulent source for the total flow over the body downstream of the element. It was found that the roughness

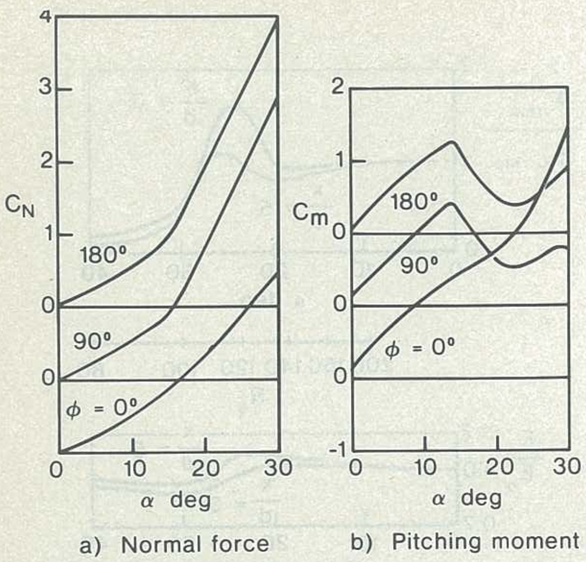
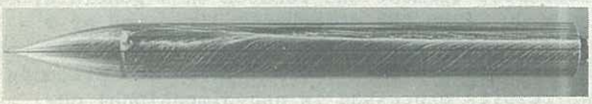


Figure 5 Normal force and pitching moment on body with single roughness element, M=0.5, $R_d=2.0\times10^5$

element which subtended an angle of 1.4° at the body surface contaminated the attachment line boundary layer only when the centre of the element was located within ±4° of the attachment line.

The effect of the roughness element on the surface flow is shown in the oil flow observations, figure 6, which were obtained at α = 20°. On the smooth body the position of the separation line, which occurs at approximately 90° from the attachment line, shows that the boundary layer is laminar over most of the body length. However, on the body with the roughness element, the separation line in the region of flow influenced by the element is located at an angle in excess of 90° from the attachment line, indicating that the crossflow boundary layer is turbulent prior to separation.

smooth body



body with roughness element

Figure 6 Oil flow patterns, M=0.5, $R_d=2\times10^5$, α=20°, ϕ=0°

6 CORRELATION OF RESULTS

Convincing experimental evidence has been gathered in the present investigation to show that the state of the attachment line boundary layer on a yawed body depends on the characteristic Reynolds number R_θ and disturbance level. Using data from a variety of sources including Robinson (1977) and the present investigation, an attempt has been made in figure 7 to correlate the characteristic Reynolds number at which reversion to laminar flow begins as a function of turbulence or disturbance level. As stated previously, the characteristic Reynolds number R_θ is based not on the actual momentum thickness of the attachment line boundary layer which may be laminar, transitional or turbulent,

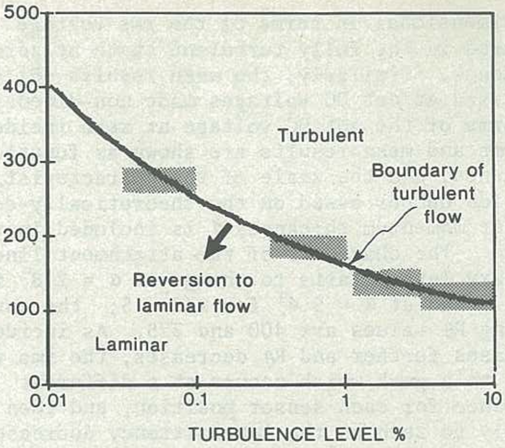


Figure 7 Correlation of R_θ for reversion to laminar flow with turbulence level

but on the momentum thickness of the laminar layer which would have existed at the same conditions. The grey areas in the figure indicate approximately the regions where results have been obtained.

The indicated turbulence levels, which were not measured in most cases, are subject to considerable uncertainty. Nevertheless, it is believed that the results shown in figure 7 give a fair indication of the state of the attachment line boundary layer on a body at incidence in an airstream.

7 CONCLUSIONS

Surface hot film measurements have confirmed the observation that two basic flow states are possible in the attachment line boundary layer of a body inclined at incidence in an airstream. The turbulent flow state is normally experienced in the low incidence range, and reversion to laminar flow occurs at a limiting incidence which is determined by the characteristic Reynolds number R_θ. At high disturbance levels in the flow, the limiting value of R_θ for turbulent flow is between 100 and 140, and at low disturbance levels R_θ may exceed 300.

Force measurement tests on a body with a single roughness element attached to the surface have shown conclusively that effective contamination of the attachment line boundary layer produces a turbulent crossflow in the region of the body downstream of the element. For the conditions of the experiments, contamination occurs only when the centre of the element is located within ±4° of the attachment line.

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