STUDIES OF METHODS AND PHILOSOPHIES FOR DESIGNING HYBRID LAMINAR FLOW WINGS

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Abstract

An investigation into methods of controlling attachment line, crossflow and Tollmien-Schlichting instabilities in order to delay transition and the implications for designing hybrid laminar flow (HLFC) wings for civil transport aircraft has been carried out. The control of these instability modes has been investigated in the form of a parametric study for a range of pressure distributions and flow conditions. A control technique commonly used is surface suction in the leading edge region. Results show that with this technique, the structural constraint of requiring the porous surface to be forward of the wing front spar would limit the extent of laminar flow that can be obtained. This constraint may be overcome by the use of surface cooling instead of suction downstream of the front spar for suppressing TS instability in order to achieve a greater extent of laminar flow.

For HLFC wing design, it is important to consider the drag rise characteristics and lift capability in addition to viscous drag reduction. Analysis of the aerodynamic performance characteristics of aerofoils with different types of pressure distribution suggests that the same type of upper surface pressure distribution with an adverse 'rooftop' gradient may be chosen for an HLFC wing as for a turbulent wing. This type of pressure distribution may be suitable for the inner wing leading to performance benefits in terms of lift increment and skin friction drag reduction.

Notation

C_D Drag coefficient
C_L Lift coefficient.
C_p Pressure coefficient.
D Drag.
L Lift.
M Mach number.
n N-factor in stability analysis (amplitude ratio).
Re Freestream Reynolds number.
$\overline{R}$ Attachment line Reynolds number.
T Temperature.
U_∞ Freestream velocity.
U_e Boundary layer edge velocity.
V_s Suction velocity, non-dimensionalised by freestream velocity.
x/c Streamwise ordinate, non-dimensionalised by chord.
x_t Transition location.
α Angle of incidence.
η Wing spanwise station.
θ External flow angle.
Λ Sweep angle.

Subscripts

crit Critical value.
L Local conditions.
n Normal to leading edge sweep.
w Wall conditions.
∞ Freestream conditions.

1 Introduction

The achievement of extensive regions of laminar flow on aircraft wings and empennages remains a long-term aim. To this end, there has been considerable research in recent years into control techniques for delaying transition from laminar to turbulent flow and into wing design methodology. This paper describes a study carried out at the Aircraft Research Association

(ARA) on transition control and its implications for the design of hybrid laminar flow wings. On swept wings, transition from laminar to turbulent flow may be caused by one of three principle mechanisms which depend mainly on streamwise pressure gradient, Reynolds number and sweep angle. These three mechanisms are attachment line contamination, crossflow (CF) instability and Tollmien-Schlichting (TS) instability. The control of these instability modes has been investigated in the form of a parametric study. The range of pressure distributions considered in the parametric studies and how they may affect the various instability modes are described in Section 2 of this paper.

Fig 1, taken from Ref 1, illustrates the application limits of laminar flow technologies in terms of sweep and Reynolds number, and where current Airbus aircraft lie relative to these parameters. For small aircraft with low wing sweep, natural laminar flow may be achieved by wing section geometry shaping to produce an appropriate type of pressure distribution. For larger aircraft with higher sweep such as the civil transport aircraft typical of the Airbus range, suppression of the boundary layer instabilities possibly by means of surface suction, at least in the leading edge region, is required in addition to geometry shaping in order to delay transition. The combination of geometry shaping and active control in the leading edge region is known as hybrid laminar flow control (HLFC). The study of ways of suppressing various instability modes in order to delay transition and their implications for HLFC design are described in Section 3. For even larger aircraft, active control, such as the use of wave cancellation devices, may be needed further downstream, in addition to suction in the leading edge region, in order to maintain laminar flow. This area is known as laminar flow control (LFC) and is beyond the scope of this paper.

In Europe, a number of research programmes have been carried out with the aim of demonstrating the viability of using surface suction for controlling transition on a full scale aircraft, for example, the A320 laminar fin programme [1]. Due to structural constraints for civil transports, it may not be feasible for the porous surface and suction system to be extended downstream aft of the wing front spar. This constraint will limit the extent of laminar flow that can be achieved. A flow control technique that may be suitable for overcoming these structural constraints is surface cooling applied aft of the front spar to control TS instability. The use of this technique in terms of the required cooling rates and distributions in combination with surface suction in the leading edge region is also described in Section 3.

It is difficult to choose an appropriate ‘rooftop’ pressure distribution for optimum aerodynamic performance in HLFC wing design. Section 4 discusses the relative merits of favourable and adverse ‘rooftop’ pressure gradients for HLFC design applications. ARA has been involved in the assessment of theoretical methods currently available in the UK aerospace industry for HLFC applications [2]. Section 5 discusses various issues in the use of these methods and design in the inner wing region where the flow is highly three-dimensional.

2 Parametric Studies and Transition Prediction

A range of pressure distributions has been constructed systematically for the parametric studies as illustrated in Fig 2. The pressure distributions consist of a range of initial gradients downstream of the attachment line followed by a range of ‘rooftop’ gradients. The initial pressure gradient is related to the size of the leading edge geometry of a section, with a steeper gradient being associated with a smaller leading edge radius. The range of initial gradients considered in the investigation encompasses both conventional civil transport wings and the Pfenninger-type wing section with its small leading edge radius and undercut lower surface (see Fig 3). The gradient of the ‘rooftop’ pressure may be favourable or adverse.

For the purpose of illustration the sketch of the pressure distributions depicted in Fig 2 is more pertinent to the outer wing study. In the parametric studies, pressure distributions with different combinations of ‘rooftop’ gradients and extents were used.

For swept wings, the occurrence of attachment line transition and CF instability is associated mainly with the initial pressure gradient, though favourable ‘rooftop’ gradients will allow CF instability to persist. TS instability generally becomes dominant further aft, particularly for adverse gradients. This division of the pressure distributions into two parts allows the different transition mechanisms to be investigated independently. This is consistent with the use of linear stability analysis for transition prediction, which also presupposes that the instability modes may be treated independently. The interactions between the different instability modes need to be treated with a non-linear method such as PSE (Parabolised Stability Equations) [3]. However, these methods are still under evaluation and are not yet ready to be used as design tools.

In the UK aerospace industry, linear stability analysis methods coupled with the ‘e^n’ criterion, are widely used for transition prediction. The theory behind such methods has been well documented elsewhere, see for example Ref 4, and therefore will not be repeated here. The method employed for the work described here is the spatial method, CoDS, due to Atkin [5]. The integration strategy chosen for the calculation of the N-factor is the constant spanwise wavenumber strategy, which is considered the most physically meaningful for infinite yawed wing flows.

3 Transition Control and Design Implications

Given that the various instability modes can be confined to different regions of the wing as already noted, a control methodology which treats each mode separately may be employed. This means that the attachment line, CF and TS instabilities may be controlled successively as described in the following sections.

3.1 Attachment Line Contamination

For swept wings, the attachment line can be contaminated by the turbulence originating from the fuselage. This gross contamination is likely to occur when the attachment line Reynolds number, $\bar{R}$, exceeds a value of around 245, based on the results of Poll and Paisley [6]. The value of $\bar{R}$ is strongly dependent on the leading edge pressure gradient and sweep angle. This can be seen in Figs 4 and 5, which show the variation of $\bar{R}$ with Reynolds number for two initial pressure gradients and two sweep angles, respectively. For all of the pressure gradients, Reynolds numbers and sweep angles considered, except the extremely high gradient ($dC_p/d(x/c) = 100$) and low Reynolds number ($Re = 25 \times 10^6$) condition, $\bar{R}$ exceeds the critical value of 245. This means that any bursts or spots of turbulence are self-sustaining and will propagate along the attachment line. Gross contamination may be controlled by surface suction or devices such as a ‘Gaster bump’, and the relative effectiveness of these control methods is discussed in Ref 7.

The attachment line boundary layer is also susceptible to TS disturbances, Ref 6 has shown that these waves first appear when $\bar{R}$ reaches a value of approximately 580. If $\bar{R}$ exceeds 580 then the waves amplify as they travel along the attachment line and ultimately reach some threshold condition beyond which the waves break down to form localised turbulent spots. The greater the value of $\bar{R}$ the more rapid the amplification of the disturbances and the shorter the distance to breakdown. If the local values of $\bar{R}$ drop below 580 then the waves will be damped and eventually die out. Although the values of $\bar{R}$ shown in Figs 4 and 5 are below 580, this critical value is sensitive to surface roughness and reduces with roughness height. However, Hall et al [8] have shown that suction is an effective means of increasing the critical value of $\bar{R}$.

The results shown in Figs 4 and 5 provide a useful indication of the relative stability of the attachment line for a range of flow conditions and initial pressure gradients. The results indicate that the area of the wing where a greater degree of flow control is required is the inner wing region, where the leading edge geometry is bluffer and the chord Reynolds number is higher.

3.2 Crossflow Instability

CF instabilities are due to the inflection point in the crossflow mean velocity profile. These instabilities are strongly dependent on wing leading edge sweep and the initial flow acceleration corresponding to a steep favourable pressure gradient. To suppress CF instability, suction is applied over the initial steep pressure gradient region with the aim of reducing the amplitude ratio below a given N-factor. Fig 6 shows the minimum suction velocity required to suppress CF for different initial pressure gradients for a range of Reynolds numbers assuming n = 10. It can be seen in Fig 6 that a higher suction velocity would be required for the inboard wing region. However, for Reynolds numbers above 80×10^6, the suction velocity required tends to become asymptotic and less dependent on the initial pressure gradient. This may be beneficial for design in terms of determining the maximum required suction velocity applicable across the wing span.

The required suction velocity is sensitive to the value of the N-factor assumed for transition onset (see Fig 7). This is particularly important for CF instability control, since an underestimate in the suction quantity required would lead to a total loss of laminar flow. Assuming n = 8 rather than 10 implies a 10% difference in the suction velocity over most of Reynolds number range. The level of suction required is also sensitive to wing sweep as would be expected. This is illustrated in the results shown in Fig 8 for wing leading edge sweep angles of 27.8° and 35.6°. These sweep angles are relevant to the Airbus civil transport range where the cruise Mach number varies between 0.78 and 0.85, resulting in a Mach number normal to leading edge of 0.69 which is more or less constant across the range of aircraft. At a Reynolds number of 40×10^6, a difference of 30% in the required suction velocities is found between the two wing sweep angles.

3.3 Tollmien-Schlichting Instability

With the assumption that CF instability has been controlled and the onset of transition delayed to aft of the minimum pressure point, then TS instability would become the dominant mode for transition. For suppressing TS instability, the level of suction required is much less than for CF, investigations carried out in Ref 2 have shown that for most cases a suction velocity of about –0.0002 would be sufficient for a range of rooftop pressure gradients. In order to achieve a greater extent of laminar flow, it is more effective to increase the suction panel length than the suction velocity (see Fig 9). This implies that a greater extent of laminar flow would not be possible due to the structural constraint of limiting suction to the region forward of the front spar. This constraint may be overcome by the use of surface cooling instead of suction downstream of the front spar for suppressing TS instability. The cooling rates required were found to be low, generally about 10% below the ambient temperature is sufficient to delay transition significantly.

The practicality of the cooling technique needs to be assessed, but there are a number of advantages with this technique compared with surface suction. Examples of problems associated with the use of suction which are not relevant to cooling are, firstly, skin stiffness of the porous surfaces and, secondly, maintenance of the porous panels to ensure that the holes are free from blockage. However, there may a risk of ice accretion with cooling but the risk may be small due to the fact that the cooling panel is applied aft on the wing surface. The proposed methodology of using suction in the leading edge region to control mainly CF instability and then to apply cooling to delay transition due to TS instability is illustrated in Fig 10. The figure shows the N-factor variation for a case for which suction is applied in the initial 8% chord region for suppressing CF instability (V_s = -0.00074) and from 15–20% (V_s = -0.0001) to delay TS transition to about 26% chord, subsequently a cooling strip is applied from 25–35% chord. This arrangement allows transition onset, assuming n = 10, to be delayed to 43% chord with relatively low suction and cooling rates (T_w/T_∞ = 0.95). Clearly a greater extent of laminar flow could be achieved by the application of a series of discrete cooling panels downstream on the wing.

Fig 11 shows the variation of the predicted transition position with pressure gradient for different Reynolds numbers, where suction has been applied in the initial 20% chord region. These results indicate that the possible extent of laminar flow becomes independent of the adverse gradient for higher Reynolds numbers. This suggests that it may be feasible to consider an adverse pressure gradient for hybrid laminar flow applications. In a parallel exercise aimed at military aircraft [9], transition due to TS instability has been shown to be independent of sweep. This implies that the same control methodology may be applied across the wing span irrespective of local sweep. The above findings may be important when considering the type of pressure distribution and transition control employed, particularly for the inner wing region.

4 Pressure Distributions

For maximising laminar flow extent, pressure distributions with a favourable or flat ‘rooftop’ gradient are usually regarded as the most appropriate. However, apart from viscous drag reduction, wave drag and lift capability are also important design considerations, therefore pressure distributions with an adverse ‘rooftop’ gradient should not be ignored in the design process.

Figs 12 and 13 show the pressure distributions of two aerofoils that may be suitable for hybrid laminar flow applications, one with a favourable and the other with an adverse ‘rooftop’ pressure gradient. The drag characteristics and performance characteristics in terms of ML/D for the aerofoils are compared in Figs 14 and 15, respectively. The aerofoils may be regarded as being equivalent to three-dimensional sections on an infinite yawed wing for which the leading edge sweep is representative of current civil transport wings. A suction velocity of –0.0007 from 0 to 5% chord and –0.0002 from 5% to 15% chord has been applied for suppressing CF and TS instabilities respectively to allow a significant extent of laminar flow. As illustrated in the above results, despite the transition position on the favourable pressure gradient aerofoil being further aft than on the adverse pressure gradient aerofoil, the adverse gradient aerofoil has a higher lift capability for a given shock strength and better drag rise characteristic than the favourable gradient aerofoil. This implies that the same type of upper surface pressure distribution can be chosen for a hybrid laminar flow wing as for a turbulent wing. This is also important for ensuring a viable wing design in terms of performance in the event of suction failure.

5 Inner Wing Region

The results in previous sections have shown that, if CF instability in the initial pressure gradient region is suppressed, transition would be caused by TS instability and its location would be determined by the ‘rooftop’ pressure gradient and the suction extent. For the inner wing, it is more difficult to achieve laminar flow due to higher chord Reynolds numbers and bluffer leading edge geometry. To suppress attachment line and CF instability a higher level of suction is required compared with that for the outer wing. However, the results have also shown that at high Reynolds numbers relevant to the inner wing, transition is independent of pressure gradient. This finding suggests that for the inner wing, performance benefits in terms of lift and wave drag may be gained with an adverse ‘rooftop’ pressure gradient design.

For an inner wing with a double shock system common to some civil transport aircraft, that is a strong forward shock follow by a weaker aft shock, the pressure distribution would not be suitable for significant laminar flow. However, for pressure distributions with a single shock, with a lower forward suction peak recompressing to a weak aft shock, the results obtained for adverse pressure gradient flows indicate that laminar flow may be possible. From the results shown in Fig 11 where suction is applied in the initial 20% chord region, a 30% chord laminar extent could be maintained. A greater extent of laminar flow could be achieved by a series of discrete cooling panels placed downstream of the front spar. Given the large surface area, the inner wing may have a high potential for performance improvement in terms of skin friction drag reduction.

The validity and accuracy of the methods used in the study to calculate the boundary layer and the associated stability characteristics have been evaluated for infinite swept-tapered wing flow conditions [2]. This is pertinent to the outer wing region where the isobars lie close to the wing generators. For the inner wing, the isobars are generally not aligned with the wing generators and the flow is highly three-dimensional. This is illustrated by the isobar pattern shown in Fig 16 for a wing with a planform geometry relevant to current civil transport aircraft. The corresponding pressure distributions at a number of spanwise stations are shown in Fig 17. These results were calculated using the three-dimensional viscous coupled method, VFP, described in Ref 10. The long 'rooftop' pressure distributions may be applicable to HLFC design. As can be seen in Fig 16, the isobars are roughly aligned with the wing generators on the outer wing but not on the inner wing. For the inboard wing, the isobar pattern is consistent with a planform geometry having inverse taper.

A possible way of assessing the adequacy of the current methods for the inner wing region is to compare the local flow directions given by the swept-tapered boundary layer method using the local isobar sweep with those predicted by the flow solver, VFP. Comparisons of the flow directions for an outboard wing station, η = 0.533 and an inner wing station, η = 0.274 are shown in Figs 18 and 19, respectively. For the outboard wing station, apart from the differences in the leading edge region, the results are in good agreement, as would be expected, which indicates the consistency of the swept-tapered assumption being applied here. For the inner wing station, there is a difference in the magnitude of the flow angles but the trend in the variation of flow direction is in good agreement.

The above results suggest that for transition prediction, at least for the TS instability mode, the swept-tapered wing assumption based on the local isobar sweep angles may be applicable for the inner wing region. The accuracy of the prediction needs to be properly assessed by using a fully three-dimensional transition prediction method and experimental data. As already noted, transition due to TS instability is independent of sweep implying that the same control methodology can be applied across the wing span irrespective of local sweep. These are encouraging conclusions for HLFC design for the inner wing region.

6 Concluding Remarks

a) A parametric study has been carried out to investigate ways of controlling the attachment line, CF and TS instabilities in order to delay transition and the implications for HLFC design. Given that these instability modes are confined to different regions of the wing, a control methodology of treating each mode separately and successively has been employed for a range of pressure distributions relevant to civil transport.

b) The stability of the attachment line for a range of flow conditions and initial pressure gradients has been assessed based on the magnitude of the attachment line Reynolds numbers, $\bar{R}$. The results indicate that the area of the wing where a greater degree of flow control is required is the inner wing region.

c) CF instabilities have been shown to be strongly dependent on wing leading edge sweep and the initial flow acceleration. To suppress CF instability, suction has been applied over the initial steep pressure gradient region. Although a higher level of suction is required for the inboard wing, for Reynolds numbers above 80×10^6, the suction velocity required tends to become asymptotic and less dependent on the initial pressure gradient. This may be beneficial for design in terms of determining a maximum required suction velocity applicable across the wing span.

d) To suppress TS instability, it is more effective to increase the suction extent than the suction velocity in order to delay transition. This implies that a greater extent of laminar flow would not be possible due to the structural constraint of limiting suction to the region forward of the front spar. The results have shown that it may be feasible to use surface cooling instead of suction downstream of the front spar for suppressing TS instability in order to achieve a greater extent of laminar flow.

e) It is important to consider the drag rise characteristics and lift capability, in addition to viscous drag reduction, for HLFC wing design. The results have shown that it is possible to obtain a significant extent of laminar flow on aerofoils with an adverse 'rooftop' pressure gradient, which suggests that the same type of upper surface pressure distribution may be chosen for a HLFC wing as for a turbulent wing. This is also important when considering performance reduction in the event of suction failure.

f) At the higher Reynolds numbers relevant to the inner wing, transition tends to become independent of the gradient of the 'rooftop' pressure. This finding suggested that for the inner wing, performance benefits in terms of lift and wave drag may be gained with an adverse 'rooftop' pressure gradient design. Combining an appropriate pressure distribution with the use of surface cooling aft of the front spar for suppressing TS instability, a significant extent of laminar flow may be achievable. This would have considerable potential benefit in terms of skin friction drag reduction given the large surface area associated with the inner wing. Results have shown that the swept-tapered wing assumption for transition prediction may also be applicable for the inner wing region, even though the flow is highly three-dimensional and the isobars are not aligned with the wing generators. The above conclusions are encouraging for HLFC wing design.

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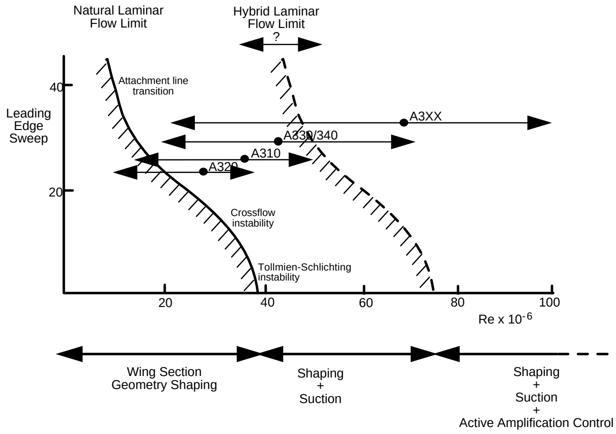

Fig 1. Limits of laminar control technologies

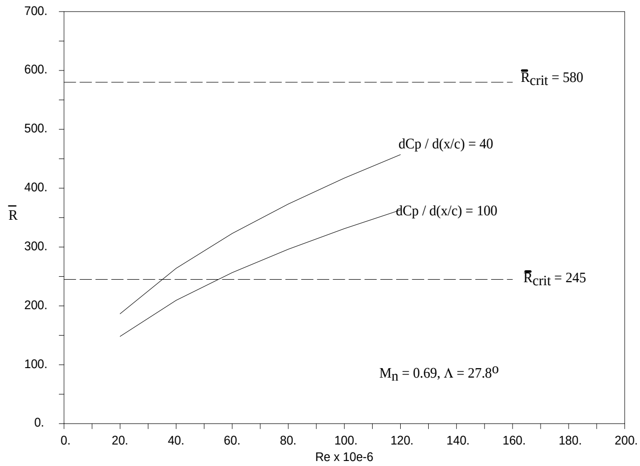

Fig 4. Effect of initial pressure gradient on $\bar{R}$

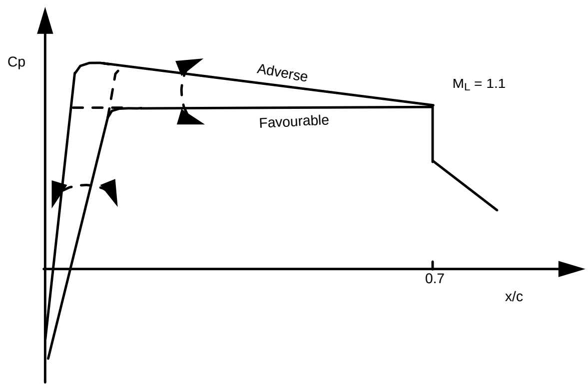

Fig 2. Sketch of pressure gradient variation

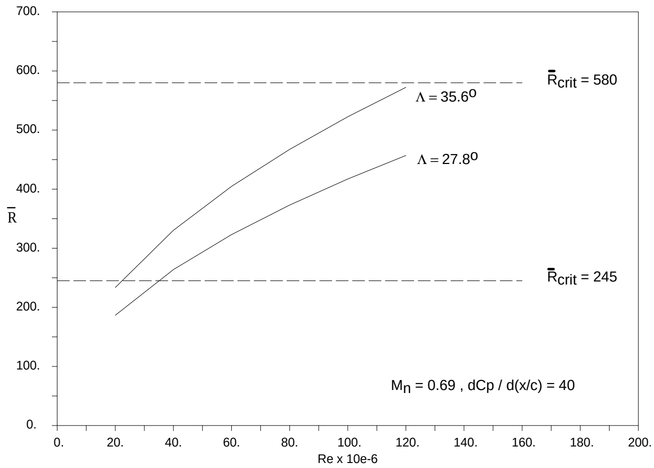

Fig 5. Effect of sweep angle on $\bar{R}$

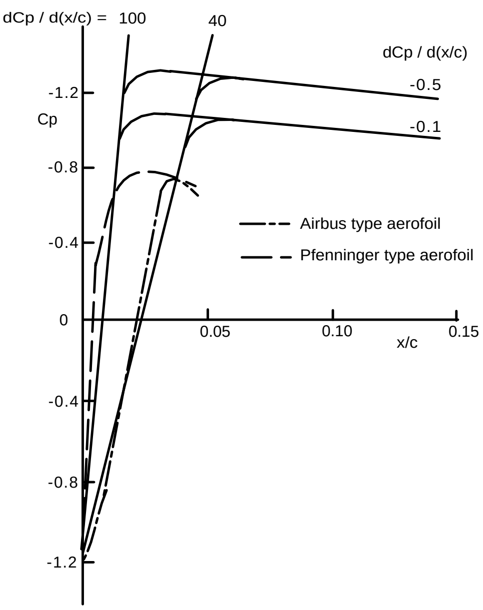

Fig 3. Range of initial pressure gradients

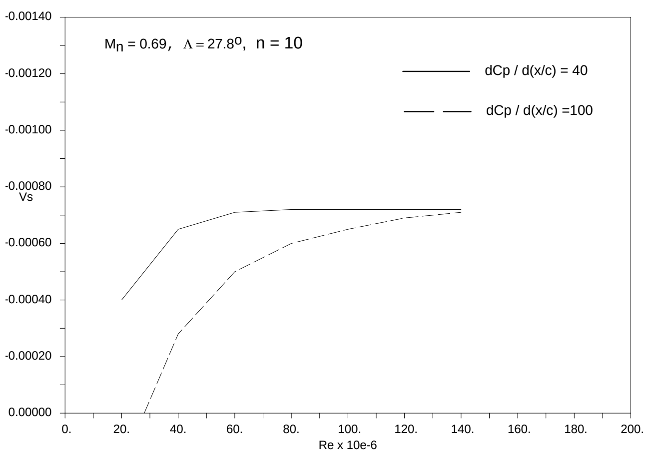

Fig 6. Effect of initial pressure gradient on suction velocity

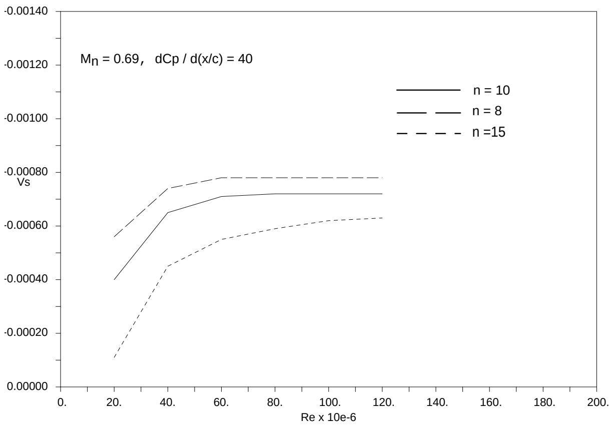

Fig 7. Effect of n-factor on suction velocity

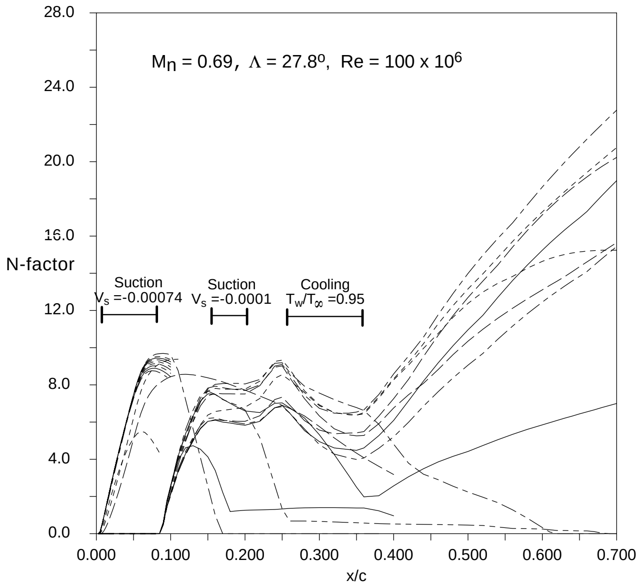

Fig 10. Illustration of control methodology

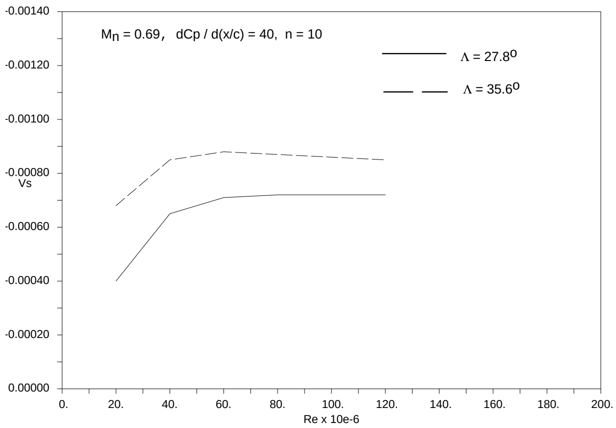

Fig 8. Effect of sweep on suction velocity

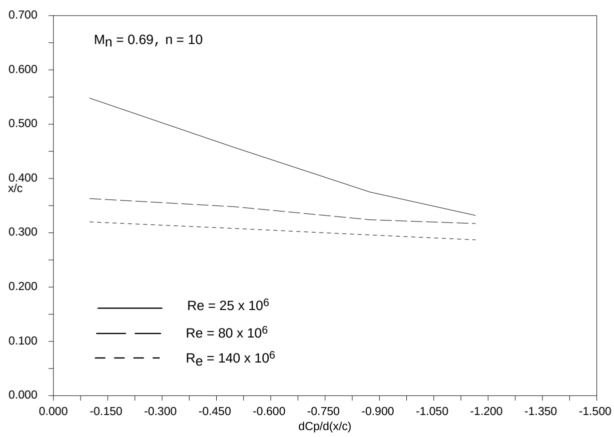

Fig 11. Effect of 'rooftop' pressure gradient on TS transition

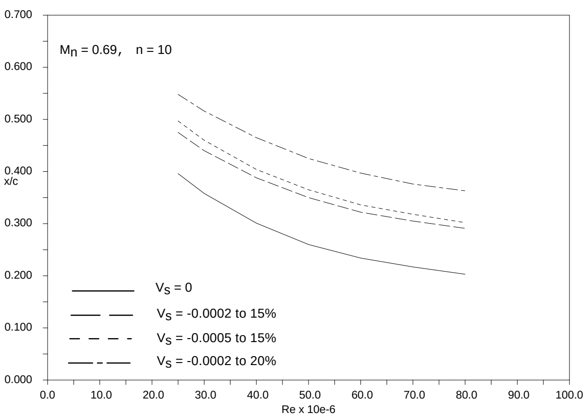

Fig 9. Effect of suction velocity and extent on TS transition

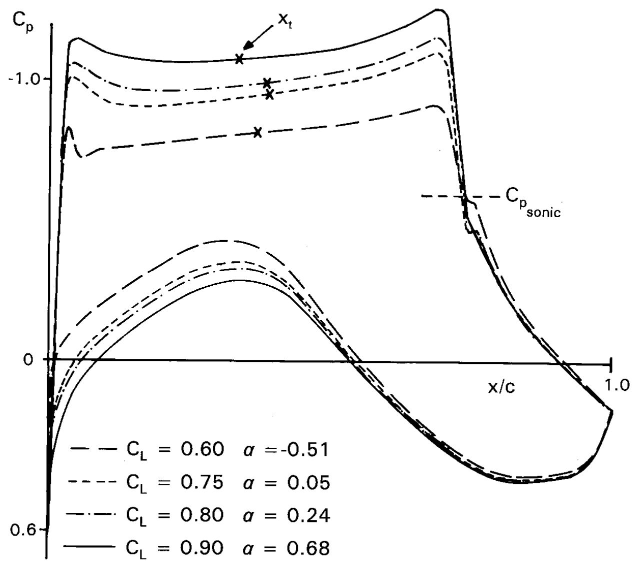

Fig 12. Favourable pressure gradient aerofoil
M = 0.75 Re = 35 x 10^6

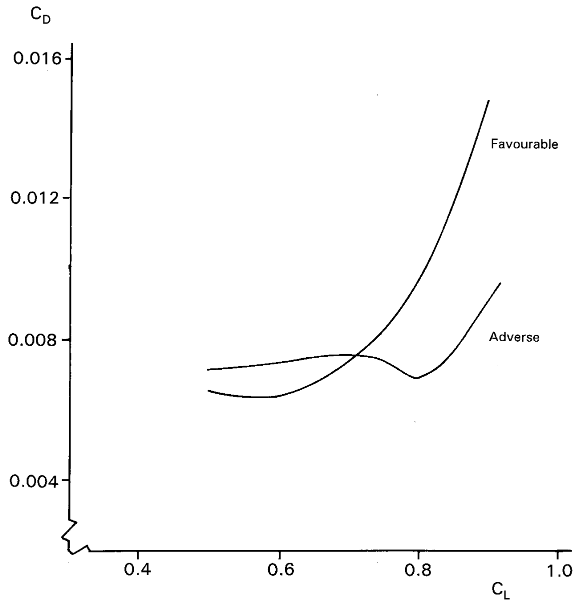

Fig 14. Drag characteristics

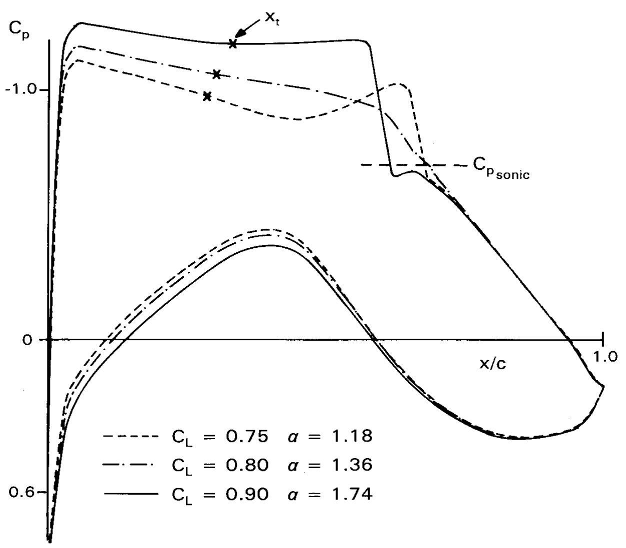

Fig 13. Adverse pressure gradient aerofoil
M = 0.72 Re = 35 x 10^6

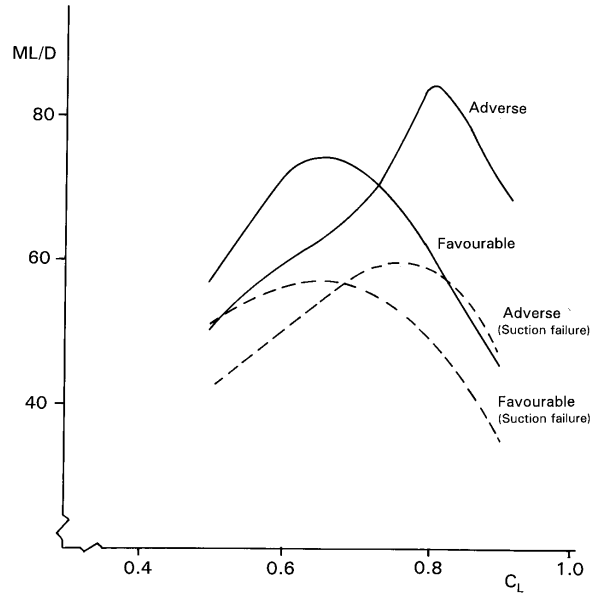

Fig 15. Performance characteristics

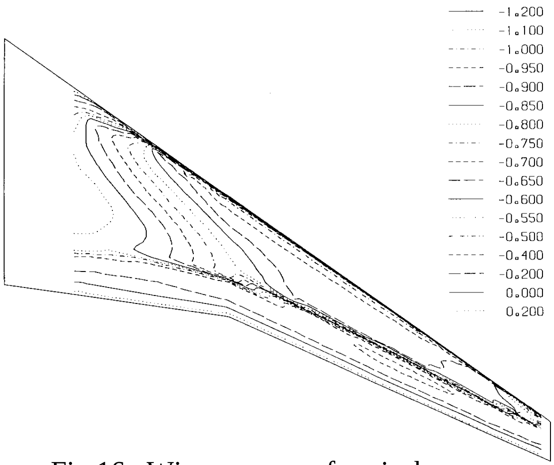

Fig 16. Wing upper surface isobars
$M_\infty = 0.85$ Re = 79 x 10^6 $\alpha = 0.5^o$

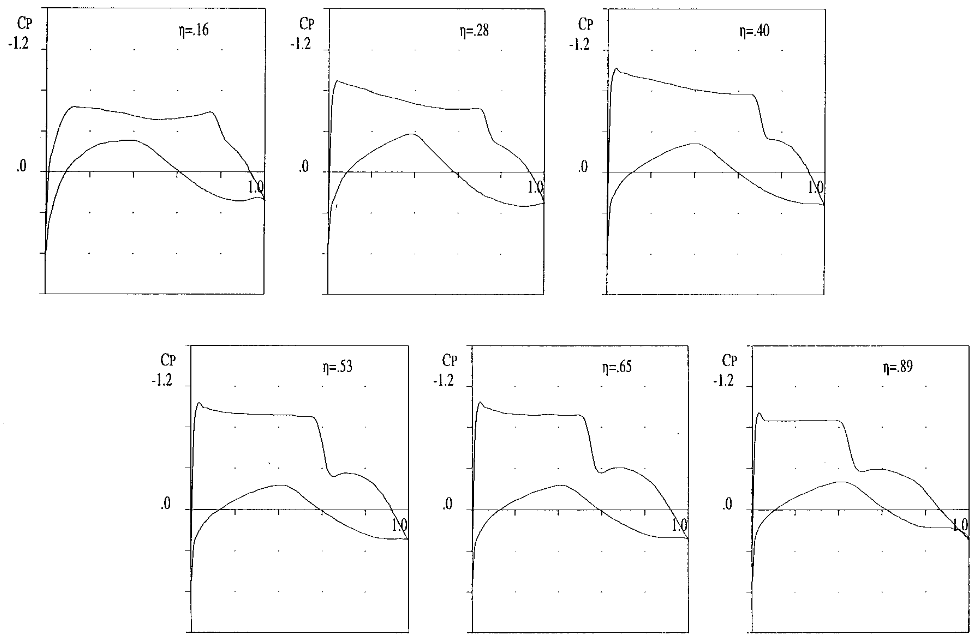

Fig 17. Wing pressure distribution
$M_\infty = 0.85$ Re = 79 x 10^6 $\alpha = 0.5^o$

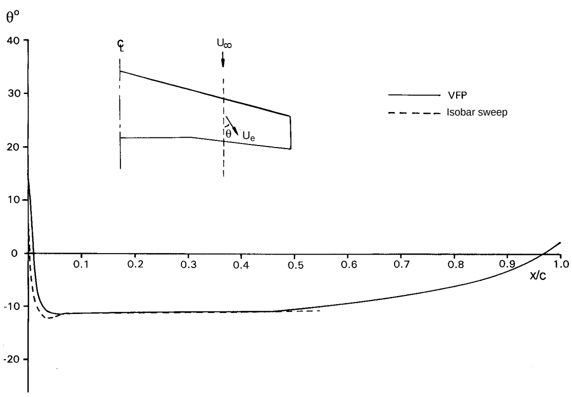

Fig 18. Flow direction at an outer wing station $\eta = 0.533$

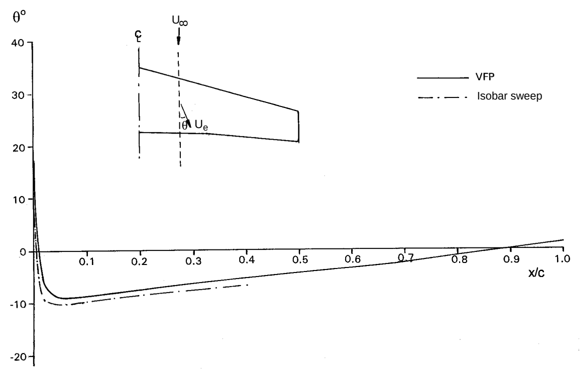

Fig 19. Flow direction at an inner wing station $\eta = 0.274$