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DEVELOPMENT AND APPLICATION OF METHODS FOR LAMINAR FLOW RESEARCH AT ARA

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Abstract

This paper describes the development and assessment of theoretical methods currently available to the U.K. aerospace industry for laminar flow aerofoil and wing design. The methods considered are for the prediction of transition onset, transition zone and laminar boundary layers with surface suction. Two different approaches for predicting transition onset are investigated, one based on linear stability theory and the other using a simple empirical criterion similar to that due to Granville. The transition zone model described here is a linear-combination model due to Narasimha and Dey and the laminar boundary layer method with surface suction is an integral method due to Thwaites. These methods are assessed by comparison with wind tunnel data where possible and the results obtained are presented. Various issues involving the use of the methods and uncertainties in their accuracy are discussed. The methods other than the linear stability analysis have been implemented into a transonic aerofoil program, BVGK, for laminar flow aerofoil calculations. An application of the enhanced BVGK program for investigating the sensitivity of aerofoil performance to some of the uncertainties in transition prediction is described.

Notation

c	Aerofoil chord
C_{DF}	Skin friction drag coefficient
C_{DP}	Pressure drag coefficient
C_{DV}	Viscous drag coefficient
C_f	Skin friction coefficient
C_L	Lift coefficient
C_P	Pressure coefficient
H	Shape factor δ^*/θ
L_T	Transition zone length
ℓ	Shear stress parameter
M	Mach number
m	Pressure gradient parameter (Thwaites' method: $m = -\lambda_\theta$)
n	Amplitude ratio
R	Reynolds number
Re	Reynolds number based on streamwise chord
s	Surface distance
U	Streamwise velocity
u	Boundary layer velocity
V_s	Suction velocity, non-dimensionalised by freestream velocity
x	Ordinate in streamwise direction
x_t	Transition onset position
x_T	Location of end of transition zone
β^*	Spanwise wave number
γ	Intermittency factor
δ^*	Displacement thickness
θ	Momentum thickness
Λ	Suction velocity parameter
λ	Effective transition zone length ($\lambda = x_{\gamma=0.75} - x_{\gamma=0.25}$)
λ_θ	Pressure gradient parameter $\lambda_\theta = \frac{\theta^2}{\nu_e}\frac{dU_e}{dx}$
μ	Viscosity
τ_w	Wall shear stress
ν	Kinematic viscosity
ψ	Wave orientation

Subscripts

av	Averaged conditions
e	Conditions at edge of boundary layer
expt	Experimental conditions
L	Laminar conditions
NS	Neutral stability
t	Conditions at transition onset
T	Turbulent conditions (or end of transition zone)
∞	Freestream conditions

1. Introduction

In recent years, there has been increased interest in applying the concept of hybrid laminar flow to civil transport aircraft, as this is seen as a promising technique for drag reduction. In Europe, a number of laminar flow research programmes have been initiated, with flight tests being carried out using various demonstrator aircraft, for example the natural and hybrid laminar flow wing gloves tested on a Falcon 50(1) and the A320 laminar fin programme (2). In the United States, similar research programmes have been carried out, most recently using a Boeing 757(3). Laminar flow research at the Aircraft Research Association (ARA) is concerned with the assessment of the suitability and accuracy of theoretical methods currently available to the UK aerospace industry for laminar flow aerofoil and wing design. Part of the work has involved the development of methods which may be used as practical tools for the design and analysis of laminar flow aerofoils and the implementation of these methods into the transonic aerofoil program BVGK$^{(4)}$. This paper describes these methods and discusses their application with particular reference to the difficulties of transition prediction and the sensitivity of aerofoil performance to uncertainties in the theoretical methods.

For laminar flow aerofoil and wing design, an acceptably accurate prediction of transition position is required. A method that is commonly used for predicting the onset of transition is linear stability theory and the 'e^n' criterion. This type of method is quite complex with a requirement for a high level of user interaction and, while valuable, may not be practical for routine design applications. An alternative would be a simple empirical criterion which can be implemented easily into either a flow solver, such as BVGK, or a boundary layer method. Such a criterion has been developed at ARA for two-dimensional, compressible flows. Section 2 describes these two approaches to transition prediction and assesses their capabilities. These methods predict the position of transition onset but the location at which the flow becomes fully turbulent may be some distance further downstream. This transition zone length may be significant for certain flow conditions and its effects on aerofoil performance cannot be ignored. The aim of the work at ARA was to investigate transition zone models which are computationally inexpensive and simple to use for routine aerofoil flow calculations. The linear-combination model due to Narasimha and Dey$^{(5)}$ has been investigated for this purpose and is described in Section 3.

In order to delay transition to turbulent flow, it may be necessary to employ boundary layer suction over some region of the wing surface. The level of suction required may be significant and the consequent thinning of the boundary layer may affect the pressure distribution. Section 4 describes a laminar boundary layer method with suction which has been implemented into BVGK to enable this problem to be investigated. The inclusion of this method in BVGK, together with the simple transition criterion and the transition zone model, has enabled the program to be used for laminar flow aerofoil studies and this application is described in Section 5.

2. Transition Prediction Methods

There are three principal sources of instability which may lead to transition on an aircraft wing. These are attachment line contamination, crossflow instability and Tollmien-Schlichting (T-S) instability. The first of these is associated with a source of gross disturbance, such as the wing-body junction, from which undamped turbulence is convected along the leading edge. This phenomenon is essentially a 'bypass' mechanism and its prediction will not be discussed here. The methods under consideration in this section address the problem of predicting transition due to crossflow and T-S instability.

The principal methods commonly used are based on linear stability theory and the 'e^n' method, in which the growth rates of amplifying small disturbances are integrated through the boundary layer until the amplification factor, n, reaches a value for which it may be assumed that transition onset would occur. This value relies on correlation with experimental data and is not universal but depends on different factors such as the freestream turbulence level and the type of disturbance causing transition. It is also dependent on the integration strategy employed. This section discusses some issues involved in the use of linear stability theory for transition prediction. Since these methods are usually computationally expensive to use, it is valuable to have simple empirical criteria based on correlations between boundary layer parameters for predicting transition. Such criteria may be readily used for routine calculations. One such criterion for two-dimensional, compressible flows, similar to the Granville incompressible criterion$^{(6)}$, has been developed at ARA and will be described here.

2.1 Stability Analysis

A number of linear stability methods are widely used in the UK aerospace industry, in particular CoDS$^{(7)}$ and COSALX$^{(8)}$. The two methods were developed for 2D and quasi-3D flows (i.e. infinitely swept or conically similar 3D flows), both incompressible and compressible, with the assumption that the flow is parallel but including streamline and surface curvature treatment. CoDS uses the compact-difference scheme of Malik to solve the spatial linear stability eigenvalue problem whereas COSALX is an enhancement of the original temporal stability analysis method developed by Malik. Since the two methods have been compared for a range of test cases and have been shown to give similar results$^{(9)}$, it is sufficient to use the results given by one of the methods to illustrate the various issues involved and CoDS is used in this paper.

Experimental and analysis work has been carried out by Ashill and Betts$^{(10)}$ to determine transition positions on a swept panel wing designed for natural laminar flow and this has provided data for extensive evaluation of linear stability analysis methods. For example, the data have been used to study different integration strategies for determining the n-factor. In order to integrate the amplification rates to arrive at a n-factor for three-dimensional flows, it is necessary that a particular property of the wave, in addition to the frequency, be fixed. Currently, it is unclear which wave property should be fixed in order to model the physics of the problem most accurately; the selection of this property is termed the 'integration strategy', (see Refs 11 and 12 for some discussion of this issue). A choice of integration strategy is provided in CoDS, with either the envelope method, constant spanwise wavenumber (β*) or constant wave orientation (ψ) methods being available.

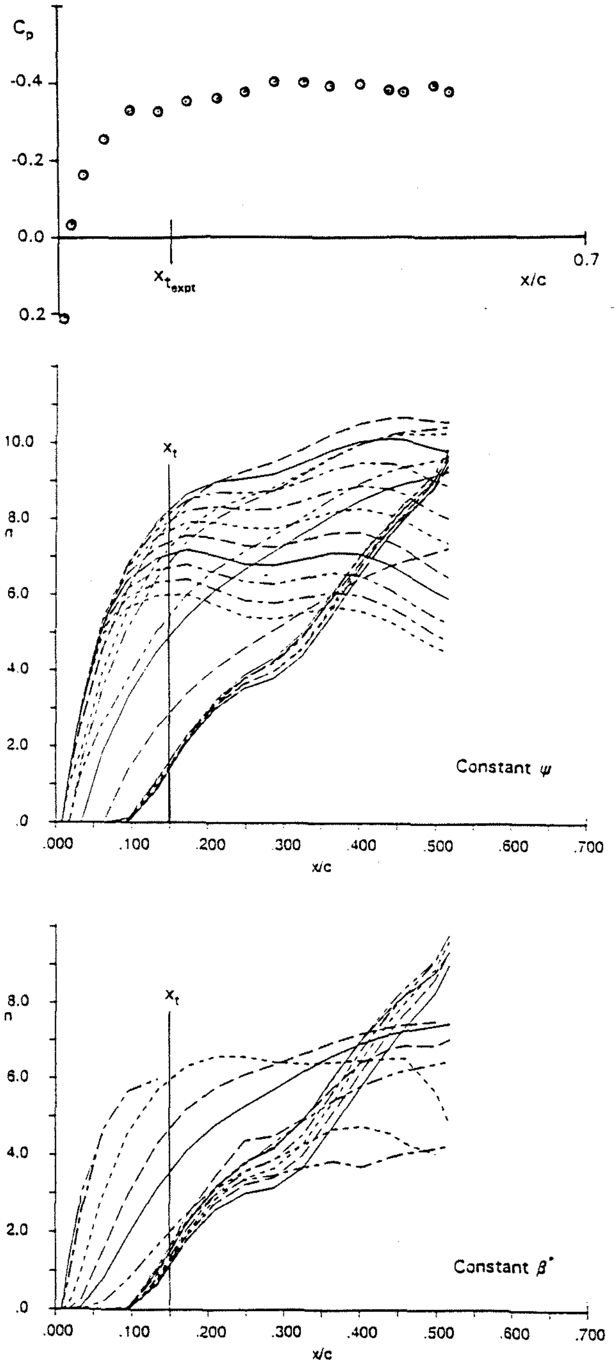

FIGURE 1 - Investigation of integration strategy for crossflow instability
$M_\infty = 0.5$ Re = 10.9×10^6 sweep = 25^0

Fig 1 shows the experimental pressure distribution and results in the form of n-factor distributions as predicted using two alternative integration strategies, constant β* and constant ψ, for a case for which crossflow instability is the dominant mechanism leading to transition. For this type of flow condition, the n-factors given by the constant β* strategy are consistently lower than those given by constant ψ, as shown in Fig 1. From kinematic wave theory it can be shown that under the infinite swept wing assumption the constant β* integration strategy has the greatest physical relevance for crossflow dominated flows(13). However, the predicted n-factor for transition onset given by both strategies is relatively low compared to other quoted results for both wind tunnel and flight tests(14),(12). As this is consistent with previous tests in this tunnel, this is likely to be caused by disturbances in the wind tunnel as discussed in Ref 15. (This problem would be addressed by the complex subject of receptivity and is beyond the scope of this paper.) For T-S dominated flows these two integration strategies give similar results; however, comparison with the envelope method shows considerable differences in n-factor. This is illustrated in Fig 2 for a different flow condition for the same model for which transition is caused by T-S instability. In this case there is also a strong crossflow component and this may call into question the linearity assumption, since there is likely to be some degree of interaction between the two instability mechanisms and it is possible that such flows may need to be treated using non-linear methods, such as PSE. It should be noted that for T-S instability the most amplified disturbance may not be in the streamwise direction but at some oblique angle, and it is important that these waves are taken into account when carrying out the n-factor integration. These results illustrate the difficulties inherent in predicting transition onset and indicate the importance of studying the sensitivity of results to n-factor integration strategy and the value assumed for transition location. The implications for aerofoil performance will be discussed in Section 5.

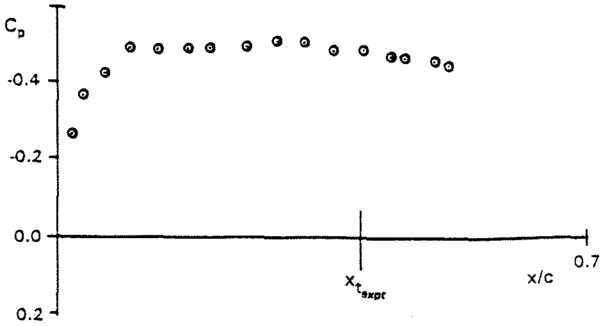

FIGURE 2 - Investigation of integration strategy for T-S instability
$M_\infty = 0.6$ Re = 7.0×10^6 sweep = 25^0

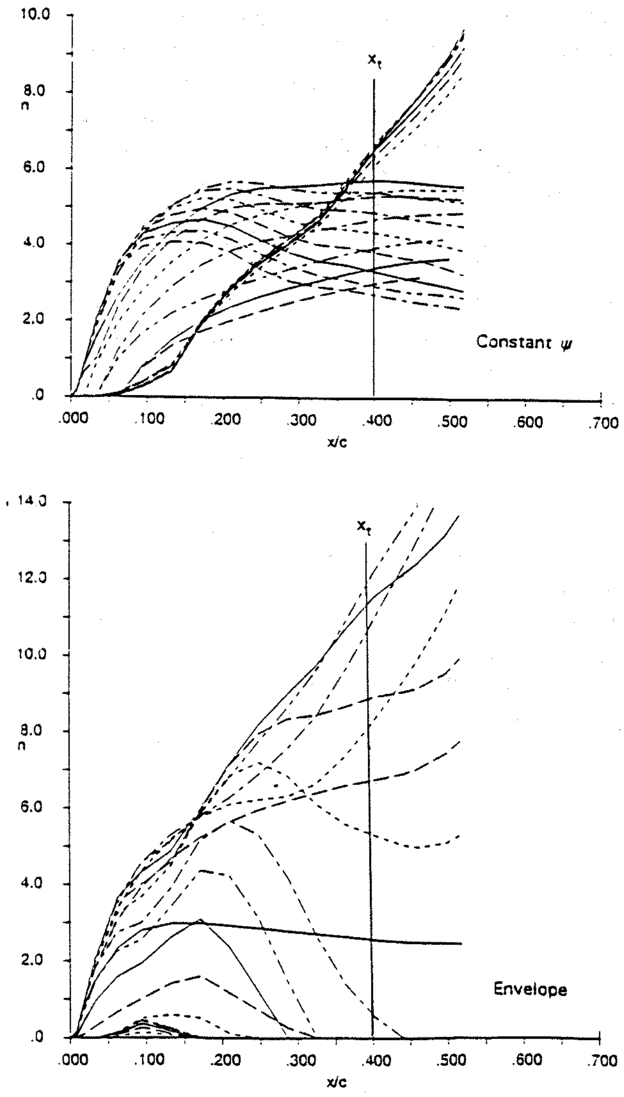

FIGURE 2 continued

For large civil transport aircraft wings the mean chord Reynolds number may be as high as 80×10^6 and laminar flow could only be maintained by means of suction over part of the wing surface, probably confined to the area ahead of the front spar, combined with suitably chosen pressure distributions. Part of the work at ARA has involved the parametric study of the combination of types of pressure and suction distributions which may be used for such hybrid laminar flow wings. The effects of varying pressure gradient and flow condition on transition position have been investigated systematically. Pressure gradient variation may be considered in two parts, first the initial gradient away from the attachment line and second the 'rooftop' gradient, see Fig 3. 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. For this exercise the range of gradients was chosen to encompass those found on civil transport wings. The occurrence of crossflow instability is associated mainly with the initial pressure gradient, though for favourable rooftop gradients it will persist. T-S instability generally becomes dominant further aft, particularly for adverse pressure gradients.

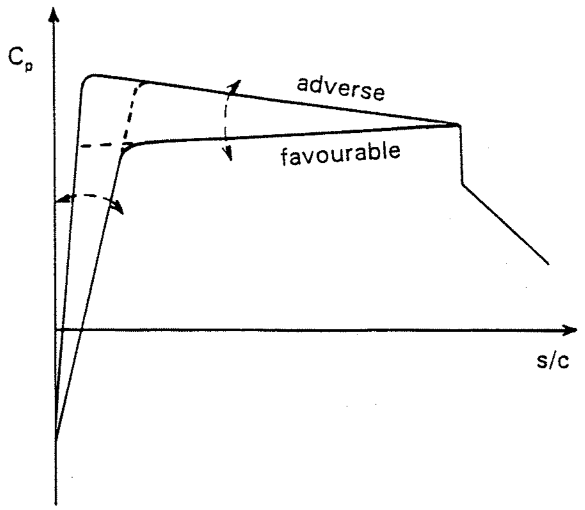

FIGURE 3 - Sketch of pressure gradient variation

It was found that the suction quantity required to suppress crossflow instability depends significantly on the choice of n-factor and integration strategy. Fig 4 shows an example of results illustrating the sensitivity of suction quantity required to suppress crossflow in the region of the steep initial pressure gradient to different values of n-factor and integration strategy for various Reynolds numbers.

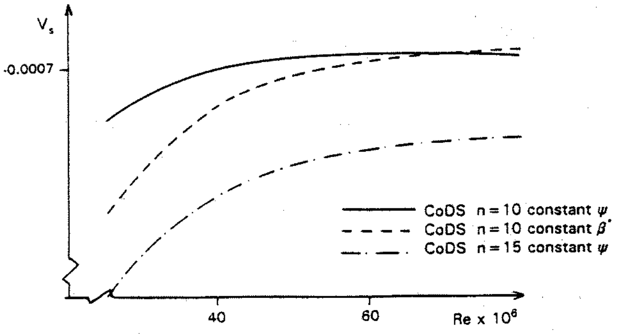

FIGURE 4 - Sensitivity of suction quantity to n-factor

For suppressing T-S instability, investigations have indicated that a suction velocity of -0.0002 would be sufficient for a range of rooftop pressure gradients. This was found to be true for all the integration strategies considered in this paper. Fig 5 illustrates the effectiveness of using a suction velocity of -0.0002 over a region of adverse rooftop pressure gradient for delaying transition due to T-S instability given by the constant ψ integration strategy.

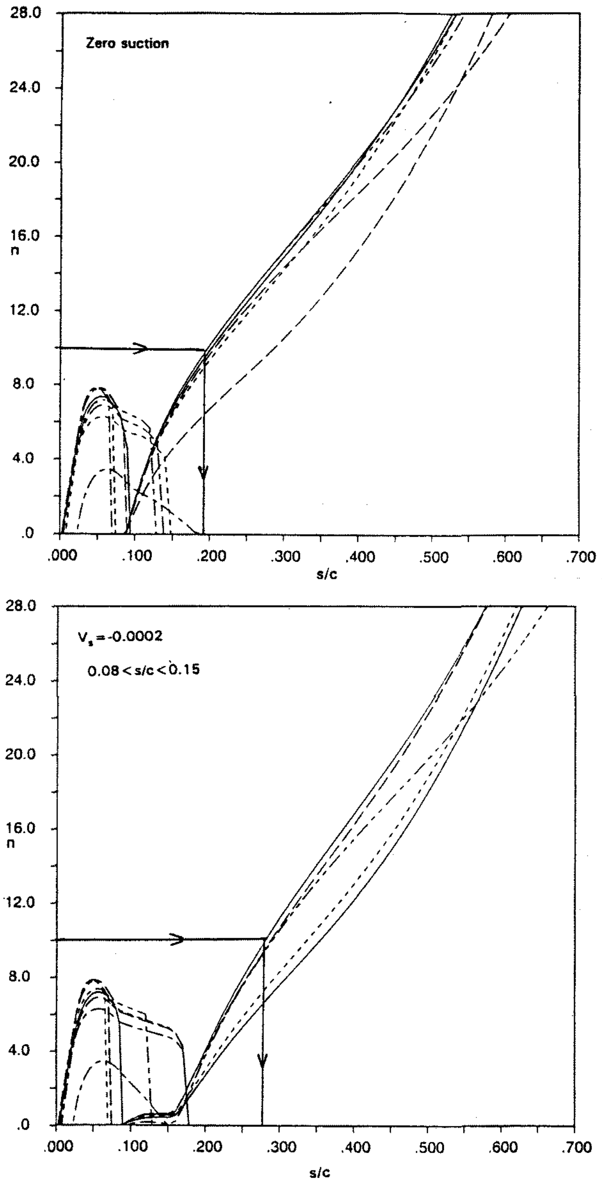

FIGURE 5 - Effect of suction on T-S instability
$M_\infty = 0.78 \quad Re = 80 \times 10^6 \quad sweep = 27.8^0$

2.2 A Two-Dimensional Empirical Transition Criterion

Simple criteria are useful alternatives to linear stability analysis for predicting transition onset due to their speed and ease of use in conjunction with any type of boundary layer method. Such a criterion commonly used for two-dimensional flows is that due to Granville$^{(6)}$, which involves a correlation of the difference in momentum thickness Reynolds number at transition, $R_{\theta t}$, and that at the neutral stability point with the pressure gradient parameter averaged over the distance from the point of neutral stability, $\lambda_{\theta av}$. The neutral stability point is predicted using a similar criterion based on the local values of R_θ and λ_θ. The original Granville instability and transition criteria were based on incompressible experimental data. However, it is well known that compressibility has a strong stabilising effect on T-S disturbances and so a similar transition criterion was derived which took account of this. Due to the lack of suitable experimental data available in the open literature upon which to base such a criterion, a correlation has been constructed using stability analysis to predict transition. Early work by Smith and Gamberoni$^{(16)}$ on using linear stability theory to study transition in incompressible flows had shown that a value of n=9 correlated well with transition onset and therefore it would be expected that this value would be consistent with the original Granville criterion. For consistency with the original criterion, the new version was derived based on the same parameters with a further dependence on local Mach number, M_e. For the zero pressure gradient case, a flat plate velocity distribution was used for the boundary layer calculations and stability analysis and pressure gradient effects were included by altering the rooftop velocity gradient. The criterion was derived for M_e up to 1.6 to cover the range of local boundary layer edge Mach numbers encountered in practical aerofoil applications. As for the original criterion, the correlation is in the form of curves relating $R_{\theta t}$ - $R_{\theta NS}$ to the pressure gradient parameter, $\lambda_{\theta av}$, averaged over the distance from the neutral stability point, which is predicted using the standard Granville criterion.

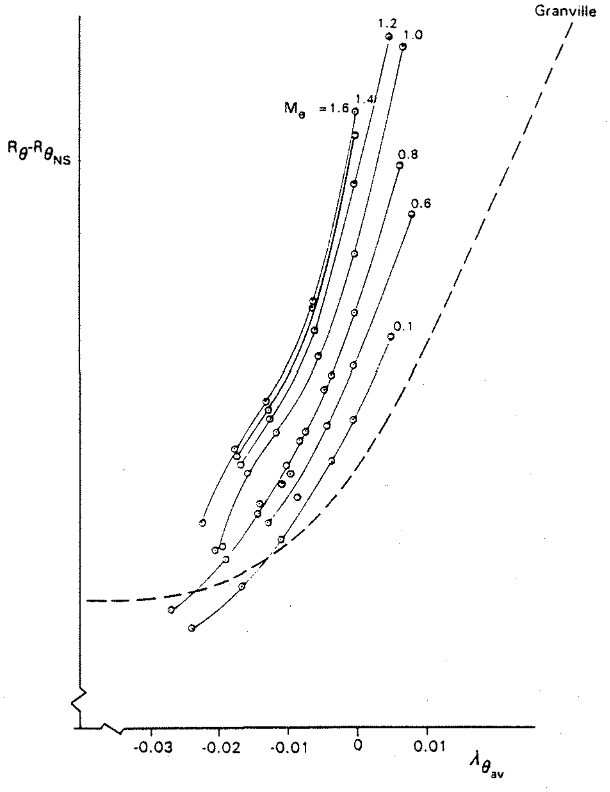

FIGURE 6 - Compressible transition criterion

The correlation is shown in Fig 6, where it can be seen that there is a clear trend with Mach number with only a small degree of scatter in the data. The original Granville criterion is shown for comparison. The trend of the correlation becomes less consistent for severe adverse pressure gradients for which laminar separation may occur and such conditions would not be considered realistic for practical laminar flow aerofoil applications.

As an example of the use of this criterion, a case for the swept panel model discussed above has been chosen. Fig 7 shows the experimental pressure distribution with predicted and measured transition positions indicated. Since the predicted n-factors for transition on the swept panel model are generally lower than 9, the transition position given by the criterion is downstream of the actual onset point, as would be expected. This result suggests that a useful extension of the criterion would be one which took into account a variation in n-factor. Also, it is envisaged that the new criterion will be extended to flows with suction.

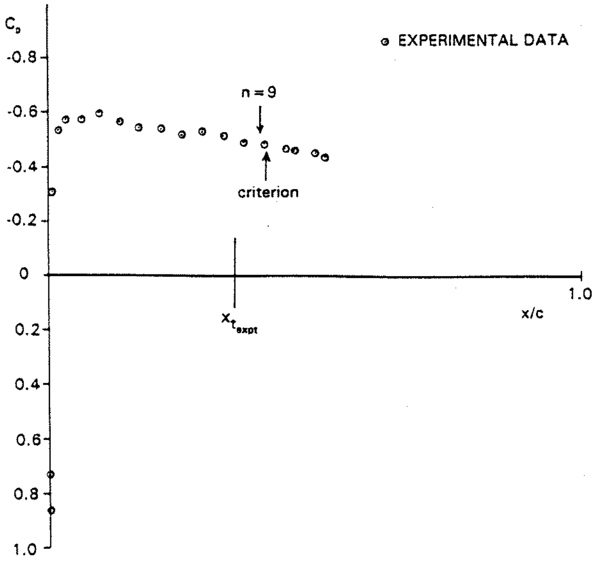

FIGURE 7 - Transition prediction using the compressible criterion
$M_\infty = 0.5$ $Re = 4.7 \times 10^6$ sweep $= 25^0$

3. Transition Zone Modelling

The methods discussed in the previous section are concerned with the prediction of transition onset but transition occurs over a region of the aerofoil or wing surface and it is equally important to be able to predict the length of this region and the development of the boundary layer through the transition zone. Various models are available for the prediction of the zone length and are categorised into three main types: differential, algebraic and linear-combination models. The first two types are designed to be incorporated into turbulence models of varying complexity and the last one may be coupled with any method of calculating the boundary layer flow. The versatility and speed of solution of the linear-combination model have led to its adoption in the work carried out at ARA.

This type of model assumes that the boundary layer in the transition zone can be taken as a linear combination of a laminar flow and a fully turbulent flow, based on the assumption that the transitional flow comprises intermittent spots of turbulence in an otherwise fully laminar flow. The linear combination is governed by the intermittency, γ, the fraction of time that the flow is turbulent, with the mean velocity profile and skin friction being determined as follows

$$u = (1-\gamma)u_L + \gamma\, u_T$$
$$C_f = (1-\gamma)C_{f_L} + \gamma\, C_{f_T}. \qquad (3.1)$$

Defining an appropriate distribution for the intermittency and determining the length of the transition zone are the two main features of this type of model. The model discussed here is that due to Narasimha and Dey(5) which was derived for zero pressure gradient flows only but has since been extended by Gostelow and Walker(17) to include adverse pressure gradient effects. However, since the model was developed for constant pressure gradient flows, the formulation is based on conditions at transition onset and no account is taken of any subsequent change in gradient.

Using experimental data, Narasimha(18) showed that the intermittency could be described by a universal distribution

$$\gamma = 1 - \exp(-0.41(x - x_t)^2 / \lambda^2) \quad , \qquad (3.2)$$

where $\lambda = x_{\gamma=0.75} - x_{\gamma=0.25}$ and can be related to the overall zone length by

$$L_T = x_T - x_t = 3.36\lambda \quad . \qquad (3.3)$$

Walker and Gostelow postulate that the transition zone length for an arbitrary pressure distribution with adverse gradient will lie between the value for zero pressure gradient and that given by a minimum transition length model. Based on experimental data, the following correlation is proposed

$$L_T / L_{T\min} = \frac{0.14 + 20\exp(100\lambda_{\theta t})}{0.33 + 3\exp(100\lambda_{\theta t})} \qquad (3.4)$$

where the minimum transition zone length is given by

$$R_{LT\min} = 2.3\, R^{1.5}_{\delta^*_t} \quad . \qquad (3.5)$$

From the relation given by equation (3.1) it follows that

$$\delta^* = (1-\gamma)\delta^*_L + \gamma\, \delta^*_T$$

$$\theta = (1-\gamma)^2\theta_L + \gamma^2\theta_T + \gamma(\gamma-1)\int_0^\delta [u_L(1-u_T) + u_T(1-u_L)]dy \qquad (3.6)$$

The model has been implemented into the BVGK aerofoil program and the swept panel model discussed in Section 2 has been used for evaluation. In the experiment both transition onset and completion locations were measured thereby giving a transition zone length. This evaluation is still in progress and, for the limited number of cases considered so far, transition completion correlates well with the point at which the zone model in BVGK predicts γ=0.75, generally considered to be the effective end of the transition zone. The results for a typical case are shown in Fig 8, where the calculated pressure distribution is compared with the experimental data and the observed and predicted transition zones are indicated. The experimental transition onset position was used in the calculation. Also included in the figure is the point at which the flow is predicted to become fully turbulent, x_T, which gives an overall zone length of 15% chord which may be significant for laminar flow aerofoil design. For laminar flow aerofoils, where transition is expected to be located relatively far aft on the chord and the overall length of the zone is long, a shock may occur in the transition zone and this may cause separation in the laminar boundary layer calculation and solution failure in the linear combination procedure.

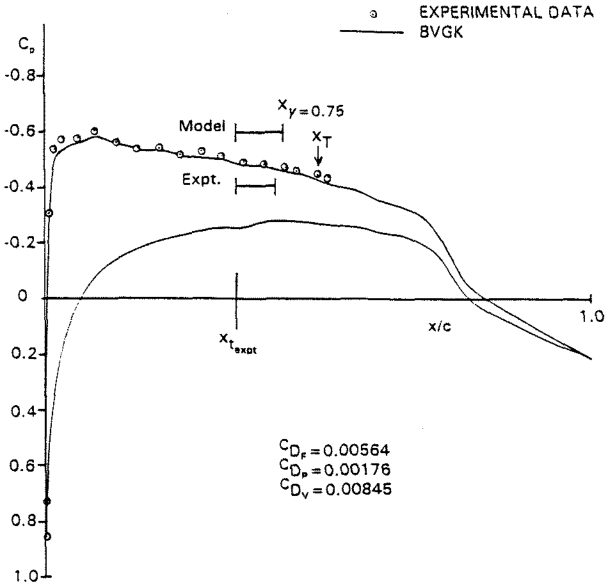

FIGURE 8 - Transition zone prediction
$M_\infty = 0.5$ Re = 4.7×10^6 sweep = 25°

There is some inconsistency inherent in this model, with, in particular, an apparent imbalance in the conservation of momentum, as noted by Green(19). This in turn would lead to discrepancies in the predicted drag. This is illustrated by the drag values given in Fig 8, where the sum of the pressure and friction drags, C_{DP} and C_{DF}, is lower than the viscous drag, C_{DV}. Clearly these inconsistencies need to be investigated further.

4. Laminar Boundary Layer with Suction

The effectiveness of surface suction for delaying transition has already been illustrated in Section 2. The suction quantities required to stabilise the boundary layer, in particular for crossflow instability, may have a significant effect on the boundary layer development and hence the pressure distribution on an aerofoil or wing. To enable this effect to be quantified, the laminar boundary layer method in the BVGK aerofoil program has been modified to include surface suction. The method used is that due to Thwaites(20) with the effects of compressibility taken into account by the Stewartson-Illingworth transformation(21),(22). The extension of the method for suction cases is also due to Thwaites(23). In the method, the streamwise momentum equation with suction may be written in the form

$$\frac{U_e}{\nu}\frac{d\theta^2}{dx} = 2[m(H+2) + \ell - \Lambda] = L(m,\Lambda) - 2\Lambda \qquad (4.1)$$

with the characteristic parameters ℓ, m and Λ defined as

$$\ell = \frac{\tau_w}{\mu}\frac{\theta}{U_e}, \; m = -\frac{dU_e}{dx}\frac{\theta^2}{\nu} \text{ and } \Lambda = -\frac{V_s\,\theta}{\nu}. \qquad (4.2)$$

From the families of similar profiles with suction, Thwaites found that the function L(m,Λ) can be approximated by the expression

$$L(m,\Lambda) = 0.45 + 6m + 0.72\Lambda + 0.76\Lambda^2 \;. \qquad (4.3)$$

Thus, combining equations (4.1) and (4.3), the momentum equation may be integrated in the form

$$\theta^2 = \frac{\nu}{U_e^{\,6}}\int_0^x U_e^{\,5}(0.45 - 1.28\Lambda + 0.76\Lambda^2)\,dx\,. \qquad (4.4)$$

The solution for θ enables the pressure gradient parameter m (equation (4.2)) to be calculated. The values of the shear stress parameter ℓ and the shape parameter H are determined as in the standard Thwaites method. In the implementation of the method into BVGK, the wall transpiration velocity has been modified to include suction.

BVGK calculations with suction have been carried out for an aerofoil having a favourable rooftop pressure gradient which might be considered for laminar flow applications. This aerofoil may be regarded as being equivalent to a three-dimensional section on an infinite yawed wing with leading edge sweep representative of current civil transport wings. Consistent with the analysis outlined in Section 2, such a wing section at a Reynolds number of 35×10^6 would require a suction velocity of -0.0007 from 0 to 5% chord in the region of the initial steep pressure gradient to suppress crossflow and a suction velocity of -0.0002 from 5% to 15% chord to suppress T-S instabilities sufficiently to allow a significant extent of laminar flow. This suction distribution may be regarded as being representative for hybrid laminar flow aerofoil applications, where suction is applied ahead of the wing front spar position. The calculated pressure distributions and the corresponding boundary layer displacement thickness for this aerofoil, with and without suction, are shown in Fig 9.

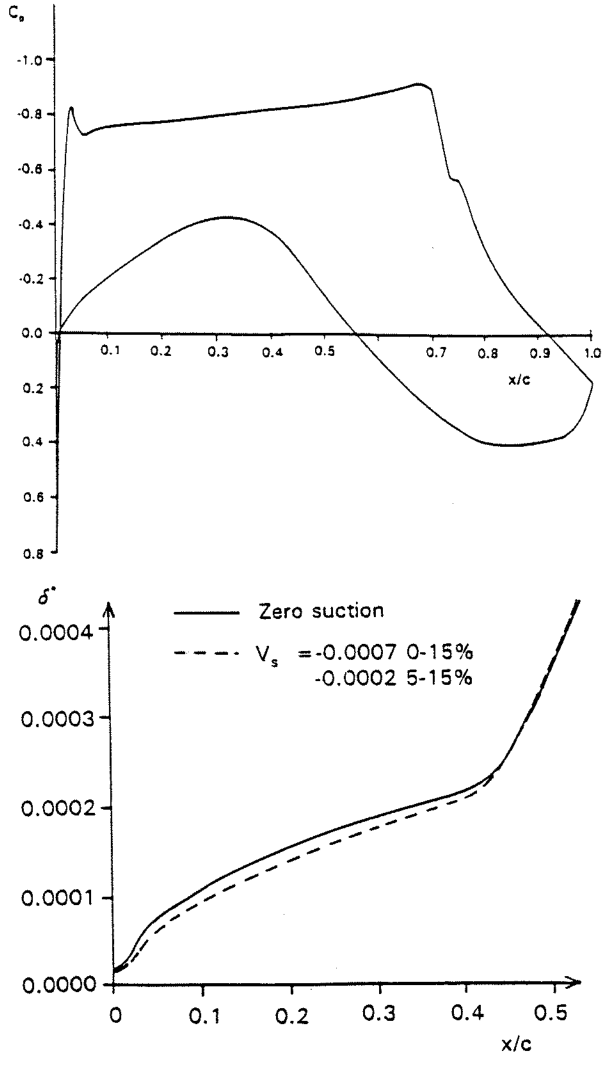

FIGURE 9 - Aerofoil pressure distribution and boundary layer displacement thickness $M=0.75 \quad R_c=35 \times 10^6 \quad \alpha=-0.5$

The results show that for this level of suction, there is no significant effect on the pressure distribution. This may be explained by the fact that the effect of suction on the wall transpiration velocity is not large enough to affect the pressure distribution directly and that the reduction in the boundary layer thickness is insufficient to influence the subsequent boundary layer development and hence the circulation. Similar results have been obtained for aerofoils with adverse rooftop pressure gradients. These results indicate that whereas suction has little direct effect on pressure distribution, its effect in delaying transition will significantly affect aerofoil performance through changes in pressure distribution and viscous drag.

5. Transonic Aerofoil Program Application

The compressible transition criterion, the transition zone model and the laminar boundary layer method with suction have been implemented into BVGK for laminar flow aerofoil applications. As discussed in Section 2, there are uncertainties in the choice of integration strategy and n-factor for predicting transition onset, which will influence the prediction of wing performance. The enhanced BVGK program can be used to investigate the sensitivity of performance of an equivalent two-dimensional section to these uncertainties. For example, Figs 10 and 11 show pressure distributions with different transition onset positions for two aerofoils, one of which being that considered in Section 4 and the other an aerofoil with an adverse rooftop pressure gradient. A rooftop pressure with an adverse gradient may be considered as an alternative type of pressure distribution for hybrid laminar flow. For an aerofoil with this type of pressure distribution, although the transition position would be further forward, the drag rise characteristics may be better and this is an important consideration for overall aerofoil performance.

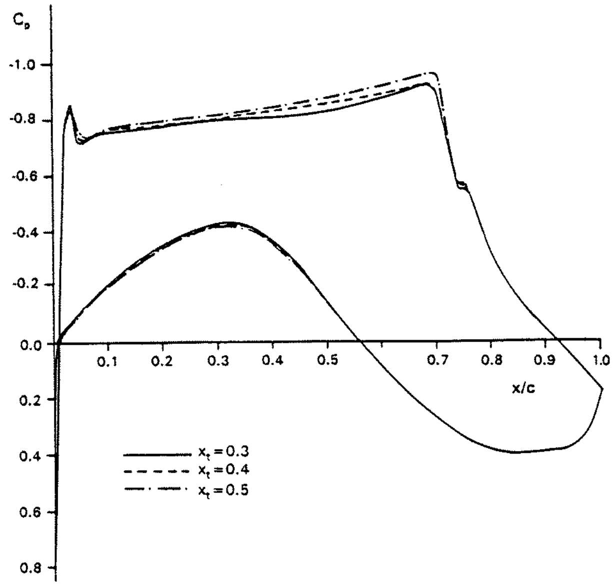

FIGURE 10 - Favourable pressure gradient aerofoil $M=0.75 \quad R_c=35 \times 10^6 \quad \alpha=-0.5$

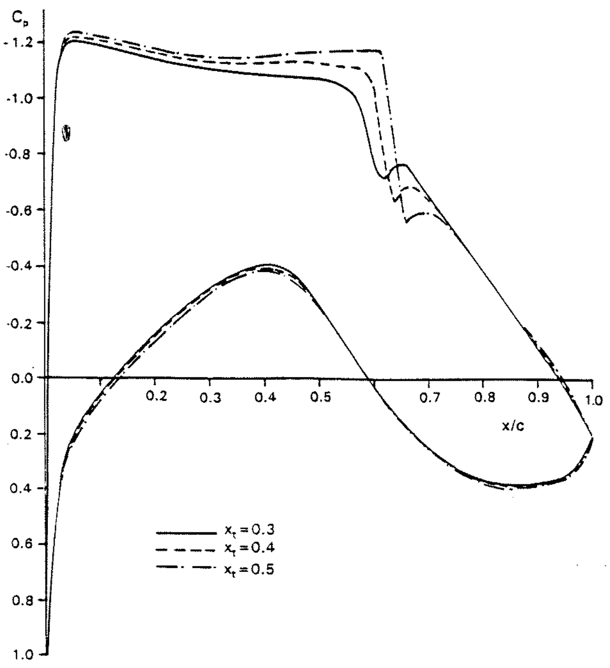

FIGURE 11 - Adverse pressure gradient aerofoil
$M=0.72$ $R_c=35 \times 10^6$ $\alpha=1.5$

Included in the BVGK solution are the suction quantities required to stabilise the boundary layer for delaying transition according to the linear stability analysis program CoDS.

The transition positions corresponding to various n-factor values were given by CoDS using the constant wave angle integration strategy and this variation is shown in Fig 12. For both aerofoils, a difference of 4% chord in the transition onset position may be obtained depending on whether an n-factor value of 9 or 10 is used.

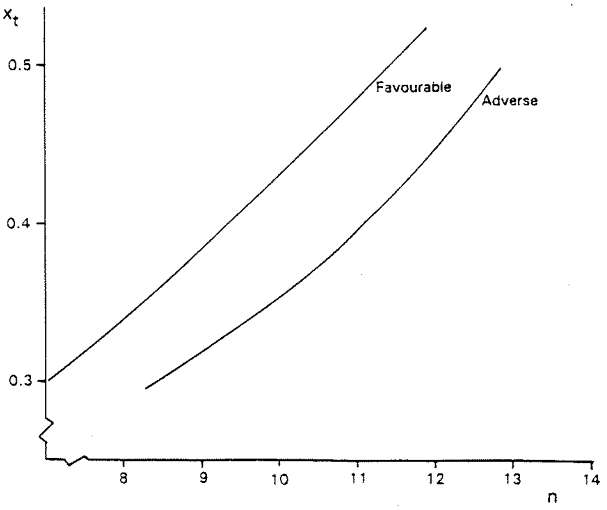

FIGURE 12 - Variation of aerofoil transition position with n-factor

The sensitivity of aerofoil performance in terms of ML/D to these changes in transition location and n-factor is shown in Fig 13. As can be seen, the predicted aerofoil performance would be significantly influenced by the choice of n-factor. The results also suggest that the performance of an aerofoil with a favourable pressure gradient may be more sensitive to the choice of n-factor than one with an adverse pressure gradient. The results presented here are for the constant wave angle integration strategy. Similar studies could be carried out using BVGK for other integration strategies.

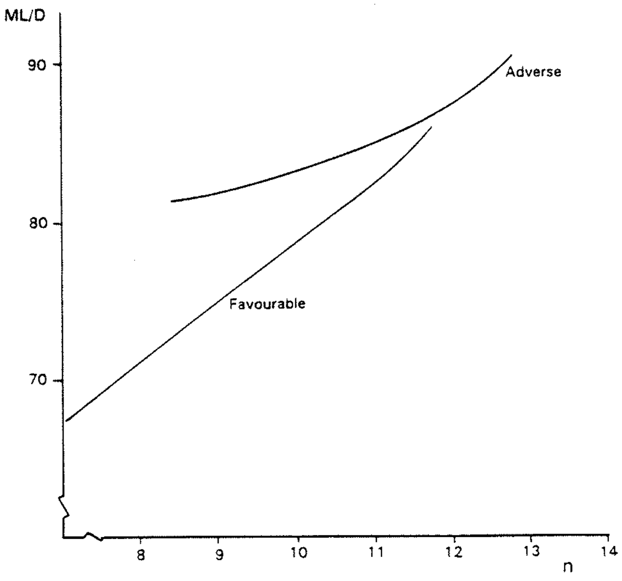

FIGURE 13 - Variation of aerofoil performance with n-factor

6. Concluding Remarks

(a) In the prediction of transition onset using linear stability analysis methods, care must be taken in the choice of n-factor and integration strategy. Comparison with experimental data has shown a sizable variation in n-factor at transition depending on the strategy employed, particularly for crossflow dominated flows. For conditions where suction would be required to suppress crossflow instability the necessary suction quantity varies significantly with chosen n-factor and strategy. In suppressing T-S instability, although the suction quantity required is less dependent on integration strategy, the predicted extent of the downstream movement of the transition onset position is influenced quite strongly.

(b) A transition criterion for two-dimensional, compressible flow has been derived using linear stability analysis and this shows a clear trend with Mach number. The criterion is therefore an improvement on the standard Granville criterion in that it reflects the stabilising effect of compressibility. Further work is required to extend the criterion to allow for suction and variation in n-factor for transition.

(c) The transition zone model due to Narasimha and Dey has been implemented into the BVGK aerofoil flow program. Preliminary comparison with experiment has shown that the predicted zone length is in fair agreement with that observed, if the predicted zone length is defined as extending to the point at which $\gamma=0.75$. The total zone length defined by the point at which the flow is fully turbulent may be long and this has implications for hybrid laminar flow aerofoils, where transition onset may be far enough aft for a shock to exist in the transition zone. In this case the method will fail due to a laminar separation in the calculation. In general, shock wave/boundary layer interaction for transitional flows is not well understood and this will cause problems when predicting aerofoil performance.

(d) The Thwaites boundary layer method in BVGK has been modified to take account of suction. For the level of suction velocity required to suppress crossflow and T-S instability sufficiently to maintain a significant extent of laminar flow, no effect on aerofoil pressures was predicted.

(e) The aerofoil program BVGK has been used to assess the sensitivity of aerofoil performance to changes in the chosen n-factor for transition. The results show that performance, as measured by ML/D, is more sensitive to n-factor for a favourable rooftop pressure gradient aerofoil than for one with an adverse pressure gradient. This is an issue which should be borne in mind when designing hybrid laminar flow aerofoils.

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