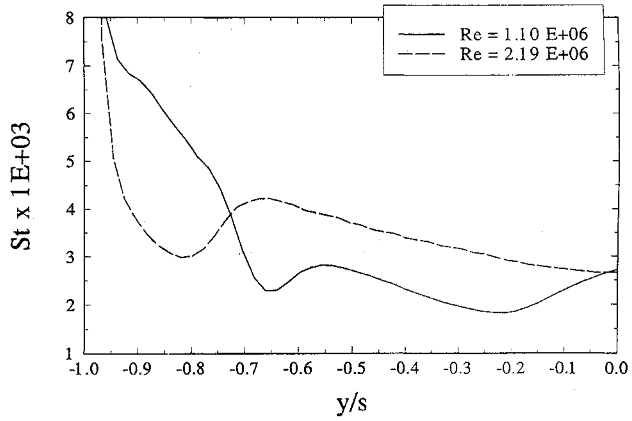

Fig. 4 Spanwise Stanton number distribution as a function of Reynolds number (α = 15 deg and x/c = 0.65).

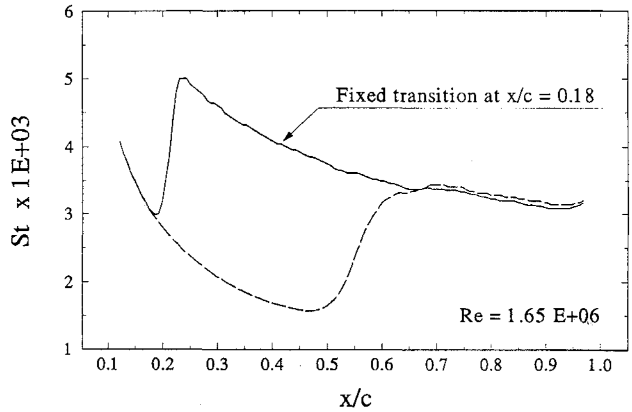

Fig. 5 Effect of induced transition on chordwise Stanton number distribution (α = 20 deg and y/s = 0.0).

if at the model apex and nearby the trailing edge the two Stanton number trends overlap.

IV. Concluding Remarks

IR thermography has been employed for heat transfer measurements and surface flow visualizations on a 65-deg delta wing model. Experimental results generally confirm the capability of the IR technique to analyze such a complex surface flowfield by means of convective heat transfer coefficient measurements.

In the central part of the wing, where nearly parallel flow conditions are established, a laminar core is present, followed by a transitional region, after which the boundary layer becomes turbulent. Data obtained by increasing angle of attack and Reynolds number have proved that the behavior of this portion of surface flow can be correctly explained with current boundary-layer theories.

In the region influenced by crossflow, a significant effect of Reynolds number is confirmed: the secondary separation line is deflected outboard in the x/c location where transition occurs.

The effectiveness of a strip in triggering transition has been found to be very remarkable.

Acknowledgment

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Prediction of Separation Bubbles Using Improved Transition Criterion with Two-Equation Turbulence Model

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Introduction

THE transitional separation bubble developed on the airfoil surface, that comprises the laminar separation, transition, and reattachment as a turbulent boundary layer, has been studied extensively due to its importance in many engineering applications. Among various analytic procedures in the literature,[1–4] one more successful and rigorous than the others is the Navier–Stokes approach developed recently by Choi and Kang.[4] The use of the Navier–Stokes equations in place of the reduced equations of boundary-layer type improved the results significantly, especially for the leading-edge bubbles.

A key ingredient in the analysis is knowing where to trigger the onset of transition. As the precise location of transition is not available experimentally, it needs to be deduced from the numerical calculation in order to devise a transition criterion. Here, the calculation is performed with the transition point prescribed; the point is varied continuously to find the one that gives the best results compared with the measured data, i.e., velocity profiles, pressure, etc. The transition is assumed to occur at that point. The criterion used in Ref. 4, which relates the Reynolds number at transition to that at separation, as was similarly used in Kwon and Pletcher,[1] was satisfactory in predicting the pressure distribution. It was also noted then, however, that since the nature of the flow was so sensitive a

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slight deviation in the transition point could result in big changes in the bubble size and the velocity profiles.

The focus of this investigation is to improve this transition criterion by considering additional parameters. It will be described in this Note how this can be achieved. Since the numerically deduced transition point is only as good as the calculation method being employed, a two-equation turbulence model, rather than the Baldwin–Lomax model used in the earlier study, is adopted to better simulate the turbulent flow in the reattachment region.

Solution Procedure

The equations solved are the continuity and Reynolds-averaged Navier–Stokes equations written in body-fitted orthogonal coordinates (ξ, η). These are exact in the sense that all of the higher order terms are retained including the streamwise (ξ) diffusion terms. The finite difference scheme for these equations is similar to that used in Choi and Kang[4] and the details will not be given here.

The main difference between the present method and the earlier one lies in the turbulence model. Since the performance of an algebraic eddy-viscosity model is known to be degrading in the separation or reattachment region, the two-layer k–ε model of Chen and Patel[5] is chosen for the present analysis after an extensive comparative study of various two-equation models. This model combines the one-equation model of Wolfstein for the near-wall region with the standard k–ε model for the outer region. This eliminates the need for a low-Reynolds-number-effect correction in the ε equation and yet the model is superior to the wall-function approach in handling the reversed-flow region.

The turbulence transport equations are solved alternately with the continuity and momentum equations at each streamwise station until convergence. Usually two or three local iterations were necessary for optimum overall performance. It needs to be pointed out that the streamwise diffusion terms in the momentum and turbulence-model equations were found to be inconsequential and could be neglected.

To carry the calculation into the turbulent-flow region, the k and ε distributions at the transition location need to be prescribed. Since the transition in the present problem occurs in the numerically most sensitive region, i.e., inside the separation bubble, the simulation of it calls for careful treatment; the errors in the initial profiles may take a few steps to be smoothed out and could severely affect the solution downstream. In order to minimize the effects of this uncertainty and to ensure smooth transition, the concept of intermittency is employed. The transport equations for k and ε are solved for the entire domain, but the eddy viscosity is artificially set equal to zero in the laminar region. The intermittency factor is then made to vary gradually from zero to one through the intermittent region as was done in the previous studies.[1,4] As for the boundary conditions, k is given a very small value (say, 10^{-6}), which amounts to the freestream turbulence level, at the inlet and outer boundaries whereas ε at the inlet boundary is specified by the inner-layer relationship of the two-layer model and $\partial\varepsilon/\partial\eta = 0$ along the outer boundary. The diffusive derivatives in the ξ direction are again assumed to be zero at the exit boundary.

Transition Model and Results

The performance of the procedure is verified thoroughly against the experimental data[6,7] for three different NACA airfoil sections, NACA 63-009, modified NACA 0010, and NACA 66_3-018, at various angles of attack and Reynolds numbers. The computational domain is fitted by a nonuniformly distributed 100×80 grid with the first point from the surface placed inside $y^+ \doteq 1$. It needs to be mentioned that the domain and the grid density were checked to be sufficiently large and fine enough for the results to be independent of these factors. With the transition point ideally prescribed, the method performs quite satisfactorily and gives much better results than the earlier one[4] with the Baldwin–Lomax model, especially in the reattachment region closer to the wall.

The improved performance of the present method allows us to look more closely at the transition criterion. From the series of calculations for the cited airfoils, a new correlation between the Reynolds numbers at transition ($Re_{tr} = U_\infty s_{tr}/\nu$) and at separation ($Re_s = U_\infty s_s/\nu$), where s denotes the arc length, may be drawn

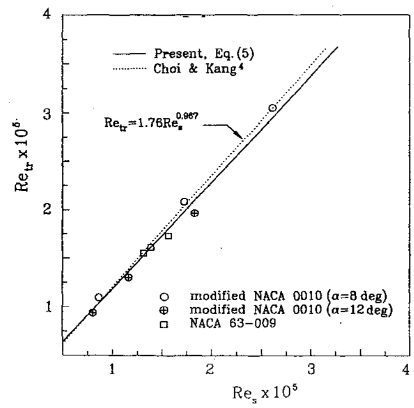

Fig. 1 Comparison of the present results with the previous transition correlation.

(see Fig. 1). The transition point used here is not a measured one but the one that gives the best results, as mentioned previously. The linear expression

$$Re_{tr} = A \cdot Re_s + B \tag{1}$$

with $A = 1.093$ and $B = 9350$ appears to fit the points well as seen in the figure. Here, the coefficients A and B were obtained to minimize the error in the mean-square sense. The formula, however, seems to be little different from the earlier criterion used in Choi and Kang,[4] which is also shown in the figure for reference. The fact that the resulting correlations are similar and not so dependent upon the associated turbulence models is encouraging as it implies that the correlation may be used with other turbulence models. What is of concern, though, is that it is doubtful from the past experience that Eq. (1) by itself would be particularly more successful than the old one.

This suggests that additional parameters may be needed to make the transition model more effective. Among several plausible quantities, the Thwaites parameter, $\lambda = (\theta^2/\nu)(\mathrm{d}U/\mathrm{d}s)$, which is a measure of the pressure gradient, appears most appropriate. Rather than trying to devise a completely new form, only the coefficients A and B in Eq. (1) are adjusted to account for the pressure gradient effects.

Define the mean Thwaites parameter λ_m between the points of suction peak and separation as

$$\lambda_m = \frac{1}{s_s - s_p} \int_{s_p}^{s_s} \lambda \, \mathrm{d}s \tag{2}$$

where the subscripts s and p denote the points of separation and suction peak. The correction formulas for the coefficients A and B are obtained as follows. First, assuming that B is correct, substitute Re_s and corresponding Re_{tr}, which are the data points in Fig. 1, into Eq. (1) and get the coefficient of Re_s. This value would be different from A (= 1.093). If we plot the difference between these two values against λ_m for each case, the resulting curve looks to be linear in λ_m as shown in Fig. 2,

$$\Delta A = 4.079\lambda_m + 0.2101 \tag{3}$$

The process can be repeated for B by holding A constant (1.093) and the variation ΔB is also found to be linear in λ_m as is seen in the same figure:

$$\Delta B = (6.278\lambda_m + 0.3271) \times 10^5 \tag{4}$$

The final correlation for Re_{tr} may then be written as

$$Re_{tr} = \left(A + \frac{\Delta A}{2}\right) Re_s + B + \frac{\Delta B}{2} \tag{5}$$

Compared to Eq. (1), this modified criterion moves the transition point upstream (downstream) when $-\lambda_m$ becomes larger (smaller) than 0.05. This is in accordance with the fact that the transition is enhanced as the pressure gradient becomes more adverse. The

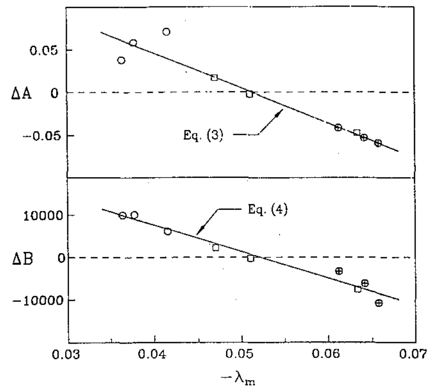

Fig. 2 Variation of A and B against the mean Thwaites parameter; see Fig. 1 for legend.

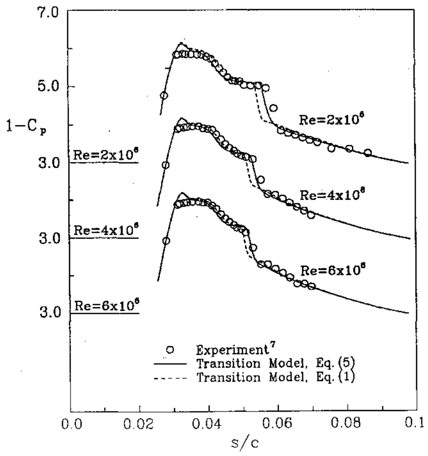

Fig. 3 Pressure distributions on the modified NACA 0010 section at α = 8 deg for various Reynolds numbers.

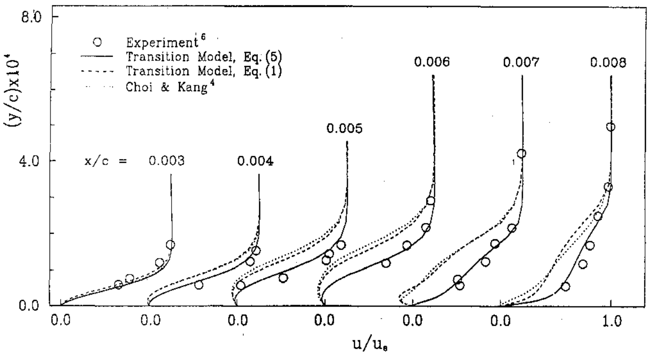

Fig. 4 Comparison of velocity profiles on the NACA 63-009 section for Re = 5.8 × 10^6 at α = 7 deg.

procedure resembles the two-step transition prediction of Granville for the attached flow.

To verify this new transition model, the calculations have been repeated for the modified NACA 0010 and the NACA 63-009 sections. Figure 3 compares the pressure distributions for the modified NACA 0010 section at $\alpha = 8$ deg for various Reynolds numbers. The results using the new transition model, Eq. (5), are seen to be in good agreement, whereas those using the correlation without the coefficient correction, i.e., Eq. (1), exhibit considerable departure from the data in the pressure recovery region. The discrepancy is attributable to the difference in transition locations. For $\alpha = 12$ deg, the pressure distributions (not shown) using Eq. (5) were found to be in similarly good agreement with the data whereas the calculation with Eq. (1) failed to yield a converged solution. What has been shown is that the corrections made to the coefficients improved the performance substantially, although Eqs. (3) and (4) do not exactly fit the ΔA and ΔB data as seen in Fig. 2 (open circles).

The velocity profiles at various sections for $Re = 5.8 \times 10^6$ and $\alpha = 7$ deg are compared in Fig. 4. The figure, which shows the results by Eqs. (1) and (5) and the earlier results by Choi and Kang,[4] emphasizes the importance of the correct transition location for the successful analysis of the transitional separation bubble. Even when the pressure distributions seem to be in reasonable agreement, the velocity profiles could be entirely different. Among many correlations, only Eq. (5) gives a correct prediction whereas the other formulas grossly overpredict the bubble.

Summary

The two-layer k–ε turbulence models has been incorporated successfully in the Navier–Stokes procedure developed earlier to solve the transitional separation bubble on an airfoil. On the basis of the transition points deduced from a series of calculations with this improved procedure, a new transition criterion for leading-edge separation bubbles that correlates the transition Reynolds number with the Reynolds number at separation and the Thwaites parameter is established. Sample calculations demonstrate that this correlation performs excellently for all of the cases examined.

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Two-Equation Model for Turbulent Wall Flow

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Introduction

THE trouble with the k-ε turbulence model is that neither of the equations is well adapted to integration through the viscous layers to the wall. The purpose of the present paper is to show how some of the difficulties may be alleviated by the choice of alternative variables.

In the usual form of the k-ε model the eddy viscosity is defined by

$$\nu_t = C_\mu f_\mu (k^2/\varepsilon) \tag{1}$$

with k the turbulent kinetic energy and ε its dissipation rate obtained from the equations

$$U_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_j}\left\{\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right\} + P - \varepsilon \tag{2}$$

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