TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

11D-2

SIMILARITY REPRESENTATION OF TRANSITIONAL BOUNDARY LAYERS UNDER POSITIVE PRESSURE GRADIENTS

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ABSTRACT

Boundary layer transition has been investigated experimentally under low and high free-stream turbulence levels and varying positive pressure gradients. Under high turbulence levels and positive pressure gradients a pronounced subtransition was present. A strong degree of similarity in intermittency distributions was observed, for all conditions, when the Narasimha procedure for determination of transition inception was used.

Under positive pressure gradients transition occurs much more rapidly than was previously appreciated. Lag effects on the velocity profile are strong and the starting turbulent layer velocity profile may not attain the equilibrium condition usually assumed in integral calculation methods. The velocity profile responds sufficiently slowly to the perturbation imposed by transition that by transition completion much of the expected drop in form factor may not have occurred. This calls into question both experimental techniques which rely on measured form factor to characterise transition and boundary layer calculations using conventional integral methods in the vicinity of transition.

INTRODUCTION

Boundary layer transition is not yet fully understood and attempts to predict it theoretically have not hitherto been entirely successful. Designers have tended to rely on correlations of experimental data for determining the beginning and end of the transition region. These correlations have generally been derived from zero streamwise pressure gradient flows, reflecting the considerable body of experimental data available for this condition, due to the paucity of available data for the diffusing flow situation.

Under positive (adverse) pressure gradients existing correlations have predicted excessive transition lengths for both attached flows and separated shear layers. In the latter case the use of existing transition length correlations has led to the prediction of a completely separated shear layer where observations indicate the existence of a laminar separation bubble.

Walker (1987) proposed a new physical model which explained the qualitative differences in transition under zero and positive pressure gradient conditions in terms of the influence of pressure gradient on the breakdown mechanism for turbulent spots. The model was confirmed experimentally by Walker and Gostelow (1989). The model predicts that instead of the "breakdown in sets" regime experienced in the absence of a streamwise pressure gradient, transition under positive pressure gradients is rather characterised by the continuous development and breakdown of Tollmien-Schlichting waves. This was demonstrated by examining appropriate velocity traces and the corresponding spectra.

Progression from the zero pressure gradient model to one appropriate to positive pressure gradients is evolutionary in nature. This progression results in a marked reduction in transition length as even a mild positive pressure gradient is imposed. The new model is expressed in transition length correlations which can be readily incorporated into existing design procedures.

Measurements by Gostelow and Blunden (1988) indicated a similar trend for transition length in a moderately turbulent free stream, as did measurements under a higher turbulence level reported by Gostelow (1989). Because the introduction of significantfree-stream turbulence results in changed transition behaviour the lowest and highest turbulence levels tested are compared in this paper. The range of turbulence levels and pressure gradients tested is wide and it is therefore pertinent to consider whether the data revealed any degree of similarity. In introducing his universal intermittency distribution for transitional boundary layers Narasimha (1957) raised questions about its validity under strong pressure gradients. It was therefore planned to scrutinise the current data for any discrepancies in intermittency distribution; it was additionally proposed to investigate streamwise variations in integral properties from a similar perspective.

INTERMITTENCY DISTRIBUTIONS

All measurements were made in the low-speed wind tunnel described by Gostelow and Blunden. The high-turbulence measurements were performed with a bi-planar grid mounted upstream, giving a nominal turbulence level of 5.3%; with no grid present the turbulence level was 0.3%. The boundary layer grew on the surface of a flat plate having a width of 600 mm. The plate had a smooth surface finish and the nose was of a slender elliptical section. Care was taken to avoid any possibility of leading edge separation. Measurements of turbulence level in the free stream and of intermittency in the boundary layer were made using a single hot wire probe. Boundary layer traverses used a pitot tube with a 1.2 mm x 0.72 mm flattened head. Intermittency measurements were facilitated by the use of an on-line intermittency meter designed by Alt (1987) and all data were logged by computer.

Positive pressure gradients of varying strength were imposed by using a fairing mounted above the plate. This could be rotated incrementally about an axis located 20 mm upstream of the leading edge of the plate. Streamwise pressure gradients were measured using centre-line static tappings with free-stream velocity measurements for confirmation.

The measurements undertaken with a turbulence grid (Grid 4) covered ten different positive pressure gradient cases, designated DP0-DP9. A further series recorded with no turbulence grid present consisted of eight different positive pressure gradients designated DP0-DP7. In each case DP0 approximates a pressure gradient of zero with higher designations approaching the highest sustainable pressure gradients for attached laminar layers.

Figure 1 presents results of the 5.3% turbulence level Grid 4 intermittency measurements and values of $F(\gamma)$ as a function of dimensionless distance, η. Consistency of transition inception, intermittency distributions, and of the representation of the transition region as a whole, was maximised when the Narasimha (1957) procedure for determination of inception was adopted. Essentially, that portion of the $F(\gamma)$ curve between 25% and 75% intermittency was fitted with a straight line, the zero $F(\gamma)$ intercept of which provided a location for transition inception, η_t. This procedure also conveniently provided values of transition length, λ. As can be seen from Figure 2, incorporation of the values of η_t and λ obtained from the $F(\gamma)$ curves into a new dimensionless distance ξ resulted in distributions which compared well with the universal intermittency distribution of Narasimha. This applies to the extreme turbulence levels, of 0.3% and 5.3%, presented in Figure 2 and also to intermediate turbulence levels.

A simpler procedure is to define transition onset, s, as 1% intermittency. For convenience this definition has been adopted in normalising the form factor since defining Hs rather than Ht as the transition inception form factor had little effect on the results. Transition completion, e, was represented by the 99% intermittency value.

Testing without a grid present was less comprehensive than for Grid 4 and this is reflected in the relatively sparse data set at low turbulence levels. In Grid 4 testing measurement difficulties were experienced for the higher intermittency levels of DP0 and DP1 which resulted in highest intermittency levels a little lower than the usual 99% completion value. This affected the quality of results for transition completion for those two cases.

If no pressure gradient is present the $F(\gamma)$ plot may be expected to be approximately linear; Narasimha (1985), however, has shown that when a pressure gradient is applied the $F(\gamma)$ plot may experience a sudden change in slope from a subcritical level to a supercritical level at a "subtransition" point. Figure 1 demonstrates this behaviour clearly. The subtransition has the effect of providing an ambiguous and erroneous transition inception location if the 1% intermittency definition is chosen (Gostelow, 1989). Fortunately these difficulties are avoided if the procedure of extrapolating the $F(\gamma)$ line back from 25% intermittency is adopted since this neglects the subcritical region entirely.

Subtransition behaviour is influenced by high levels of both turbulence and positive pressure gradient. If the free-stream turbulence level is high intermittent events may be observed well upstream of transition inception.

The diffusion of free-stream turbulence into the outer portion of the boundary layer may have a significant effect on the perceived intermittency. Figure 3 presents

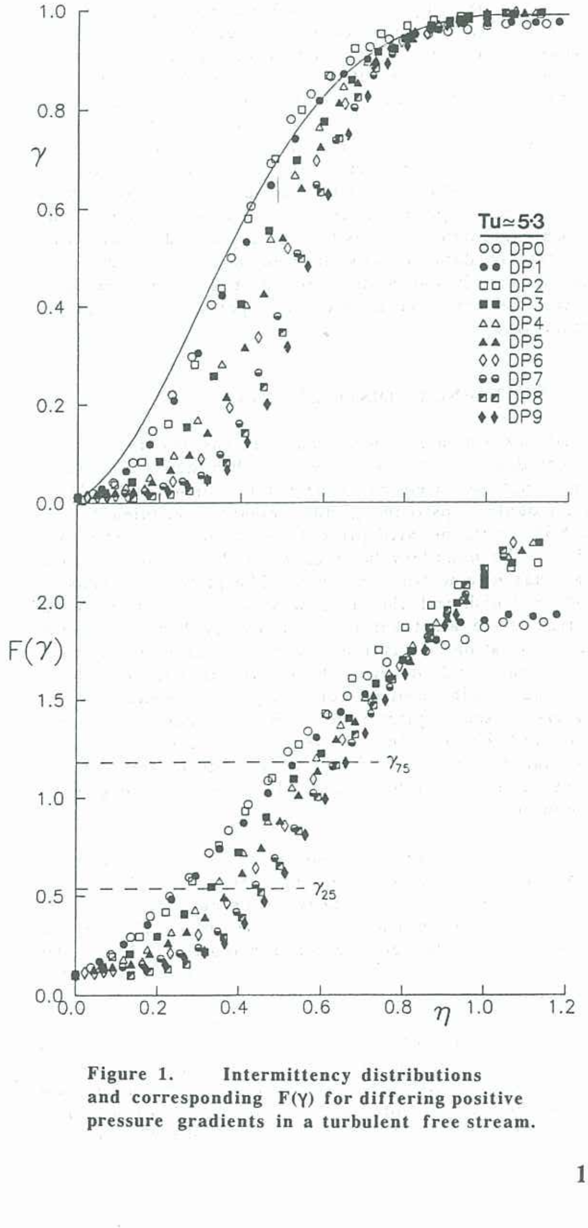

Figure 1. Intermittency distributions and corresponding F(γ) for differing positive pressure gradients in a turbulent free stream.

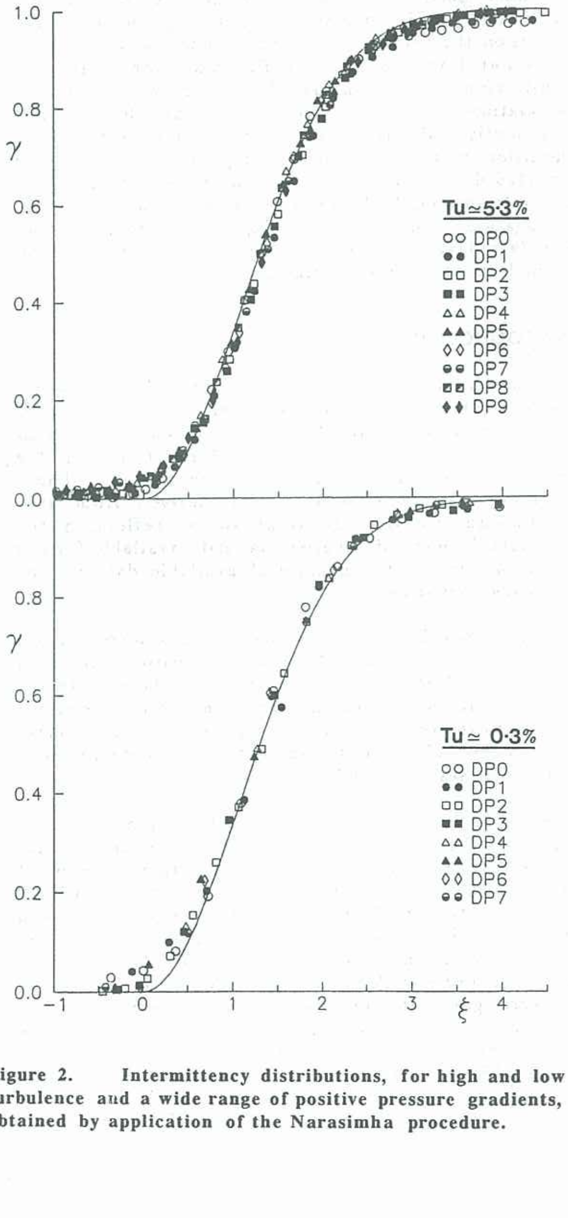

Figure 2. Intermittency distributions, for high and low turbulence and a wide range of positive pressure gradients, obtained by application of the Narasimha procedure.

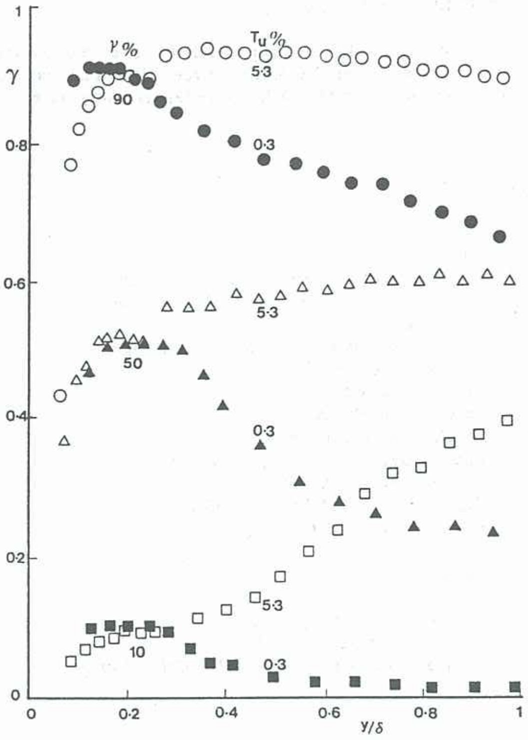

Figure 3. Intermittency traverses for high and low free-stream turbulence for nominal intermittency levels of 10%, 50% and 90%.

intermittency traverses through the boundary layer for a moderate positive pressure gradient (DP3) at the two turbulence levels and nominal intermittency levels of 10%, 50% and 90%. The approximate location for measurement of nominal intermittency was a y/δ of 0.2, around the outer edge of the intermittency plateau in the incipient turbulent wall region. Although diffusion effects from the turbulent free stream had little effect on the intermittency readings inboard of this location, further out the effects were strong.

VARIATION IN FORM FACTOR

All velocity traverses were integrated to give information on the variation of integral parameters through the transition region. The variation of form factor, H, through this region is presented for the high turbulence level results of Grid 4 in Figure 4. This shows that simply plotting the form factor does not give a universal distribution on the basis of dimensionless distance, ξ. The discrepancies are, to some extent, a result of the differences in laminar layer form factor prior to transition, resulting from the increasing pressure gradient. Also plotted in Figure 4 are normalised variations in form factor which account for the different starting conditions and fall in H through transition. This shows that there is some degree of similarity in the distribution of H between transition inception and completion.

Under strong positive pressure gradients it appears that the form factor is still falling at transition completion. A possible explanation is that the measured extent of transition was of the order of thirty absolute thicknesses; this is well within the range of ten to fifty absolute thicknesses which was suggested by the experiments of Clauser (1956) as the streamwise distance needed for a

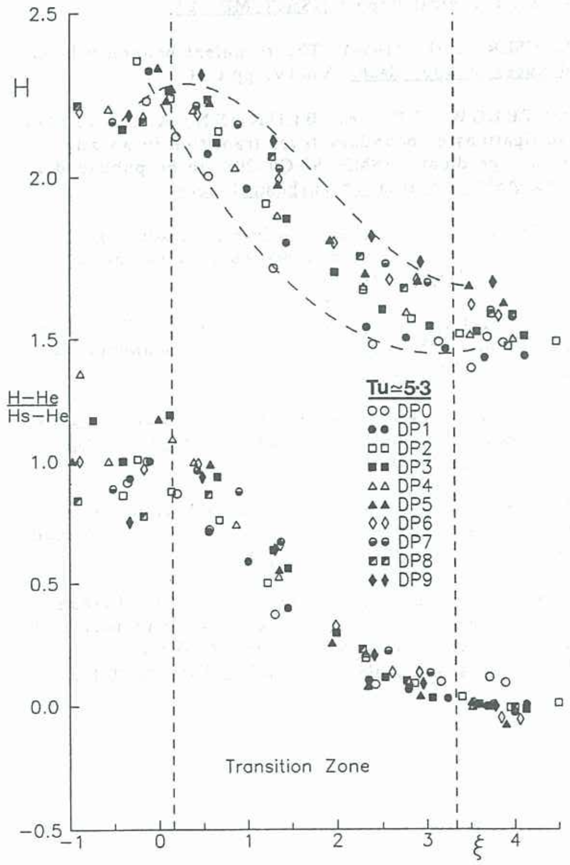

Figure 4. Raw and normalised distributions of form factor through transition for high free-stream turbulence.

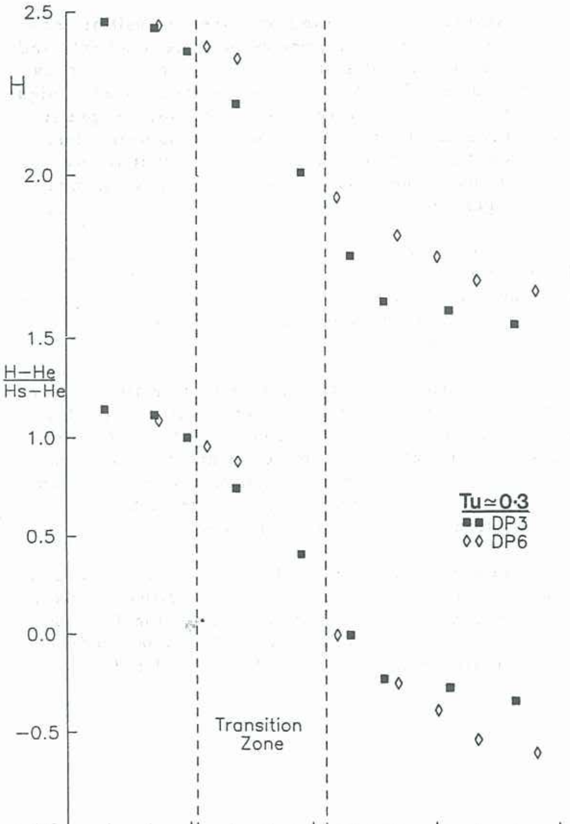

Figure 5. Raw and normalised distributions of form factor through transition for low free-stream turbulence.

turbulent layer to regain equilibrium after a disturbance. The trends established in Figure 4 are sufficiently systematic to provide information on the lag in the response of a transitional boundary layer.

Despite the sparseness of the recorded data without a turbulence grid present the lag effects were clearly observed in the tests undertaken under these conditions. For the shorter transition length results under a positive pressure gradient the boundary layer mean velocity profile, which has been perturbed by the transition process, is unable to regain equilibrium prior to the completion of transition.

Additional readings were taken upstream and downstream of the transition zone with no turbulence grid installed. These data are plotted over an extended range of ξ in Figure 5 and show that H continues to fall after intermittency readings indicate transition completion. For strong positive pressure gradients the distance between transition inception and velocity profile equilibrium is more than double the transition length. About one half of the drop in form factor takes place after the completion of transition. It appears that the distance required, relative to the transition length, to establish equilibrium is rather greater for low turbulence levels than for high turbulence levels.

Changes in measured form factor are often used by experimentalists as a variable for defining the extent of transition. The present study indicates that such a practice is questionable. The use of conventional integral methods for calculations in the transition region and the emerging turbulent layer should also be questioned. In particular the practice of linearly combining the laminar and turbulent properties is unlikely to provide a representative solution.

CONCLUSIONS

Measurements of boundary layer transition have covered a wide range of positive pressure gradients and turbulence levels. Results are presented for the two extreme values of turbulence level tested. Under high levels of free-stream turbulence and positive pressure gradient the results exhibit a pronounced subtransition. It is shown that, when intermittency distributions are presented using the procedure outlined by Narasimha, a strong degree of similarity is observed for all conditions.

The intermittency measurements represented the plateau extending to about 20% of the absolute thickness from the wall. Further out than this the flow is more strongly affected by variations in turbulence level and pressure gradient.

Under positive pressure gradients transition occurs much more rapidly than has been appreciated. Lag effects on the velocity profile are strong and the form factor responds sufficiently slowly to the perturbation imposed by transition that, in the short transition regions prevalent, much of the expected reduction in form factor may not have occurred prior to the end of transition.

This raises questions about the use of form factor as an indicator of the extent of transition in experimental work. For boundary layer calculations conventional integral methods will not be appropriate under these conditions and alternative approaches should be considered.

ACKNOWLEDGEMENTS

The work has been supported by the Australian Research Council and by Rolls-Royce plc. The careful experimental work of Mr. A.R. Blunden is appreciated.

NOTATION

$F(\gamma)$	$[-\ln(1-\gamma)]^{1/2}$
H	form factor, δ^*/θ
Re_{δ^*}	displacement thickness Reynolds Number
Re_θ	momentum thickness Reynolds Number
Tu	turbulence level, %
x	streamwise distance from leading edge
y	distance from wall
γ	intermittency factor
δ	absolute thickness
δ^*	displacement thickness
η	dimensionless distance, $(x - x_s)/(x_e - x_s)$
θ	momentum thickness
λ	distance from $\gamma=0.25$ to $\gamma=0.75$
ξ	dimensionless distance, $(x - x_t)/\lambda$

Subscripts

s	start of transition ($\gamma = 0.01$)
e	end of transition ($\gamma = 0.99$)
t	start of transition (Narasimha definition)

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