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THE EVOLUTION OF A TURBULENT SPOT UNDER AN ADVERSE PRESSURE GRADIENT

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ABSTRACT

A turbulent spot was initiated in a flat plate boundary layer under a moderately strong adverse pressure gradient. The spot was traversed at four streamwise locations. The hot-wire probe could be moved in streamwise and normal directions but was restricted to the tunnel centre line. The sharp edge of the pulse driving the triggering jet was adopted as a phase reference and velocity data were sampled at a rate of 5 kHz. Phase-averaged velocity traces, integral properties and contours of velocity perturbation and disturbance level are presented.

NOTATION

D_j	voltage disturbance level at j'th sample point
H	shape factor, δ^*/θ
N	total number of realisations
q	turbulence level, %
t	time
U	free-stream velocity
u	local velocity
v_i	instantaneous voltage for one of N realisations
$\bar{v}(j)$	ensemble-averaged voltage at j'th sample point
x	streamwise distance from leading edge
y	normal distance from plate surface
δ^*	displacement thickness
θ	momentum thickness

INTRODUCTION

The aim of recent experiments has been to address inadequacies in existing boundary layer transition predictions by providing turbomachinery designers with reliable transition data. Correlations for transition length, as a function of adverse pressure gradient and free-stream turbulence level, have been provided by Gostelow et al (1992a). Under adverse pressure gradients transition occurs rapidly; the time required for the velocity profile to adjust from laminar to turbulent may be greater than the transition length, resulting in a violation of similarity (Gostelow and Walker, 1991).

Existing linear computations of the transition region, such as the integral method of Dey and Narasimha (1988), are predicated on correlations for transition inception and a spatial division of the boundary layer into laminar and turbulent regions which are combined on the basis of intermittency.

An assumption of linear combination methods is that transition occurs in discrete turbulent spots extending beyond the thickness of the laminar layer. The overall purpose of this programme of work is to obtain three-dimensional mappings of developing spots in order to model their growth and spreading rates, with especial reference to the rapid natural transitions which occur under adverse pressure gradients.

APPARATUS AND DATA REDUCTION

The experiments were performed in the 608 mm x 608 mm octagonal open circuit tunnel at UTS. The free stream velocity in the traverse region was 8 m/s with a turbulence level of 0.3%. An aluminium flat plate was mounted horizontally in the test section and a perspex fairing could be set at a suitable angle for establishing the desired pressure gradient. Static pressure tappings were located every 50 mm along the plate. The approximately linear adverse pressure gradient was close to the condition identified as DP3 (Gostelow et al, 1992a).

Wave packets and spots were triggered by jets of air injected at a station 205 mm downstream of the leading edge. The jets were produced by a speaker driven by a 1 Hz sharp-edged pulse which also served to trigger data acquisition. The resulting signal was monitored by a small pressure transducer at the plate. Spot growth by natural amplification of instabilities was achieved using a low amplitude jet of 0.4 ms duration.

Injection ports were available at 20 spanwise locations on either side of the centre line. These were used for triggering off-centre spots, thus facilitating a complete three-dimensional mapping which will be reported subsequently.

Streamwise velocities were measured using a Dantec 55M10 anemometer with a 5 µm single wire probe. The probe was traversed in streamwise and normal directions, its normal position being monitored by a dial gauge having a least count of 0.01 mm. The reflection in the surface of the probe tip, under a concentrated light source, was used for acccurate probe positioning. Streamwise traverse locations, designated A, B, C and D were 391, 426, 461 and 496 mm downstream of the leading edge respectively.

Each trace, comprising 1000 readings, was digitised with 12 bit accuracy at 5 kHz using a Yokogawa DL3120 digital recording oscilloscope. To obtain consistent velocity data a phase-lock averaging procedure was adopted using the sharp edge of the triggering pulse as a reference. The velocity was formed by averaging 128 realisations and applying the hot wire calibration. The Wills (1962) correction for wall proximity was applied to the two traces closest to the wall. Averaged velocity profiles were plotted in the region surrounding the spot and integral properties were derived throughout the

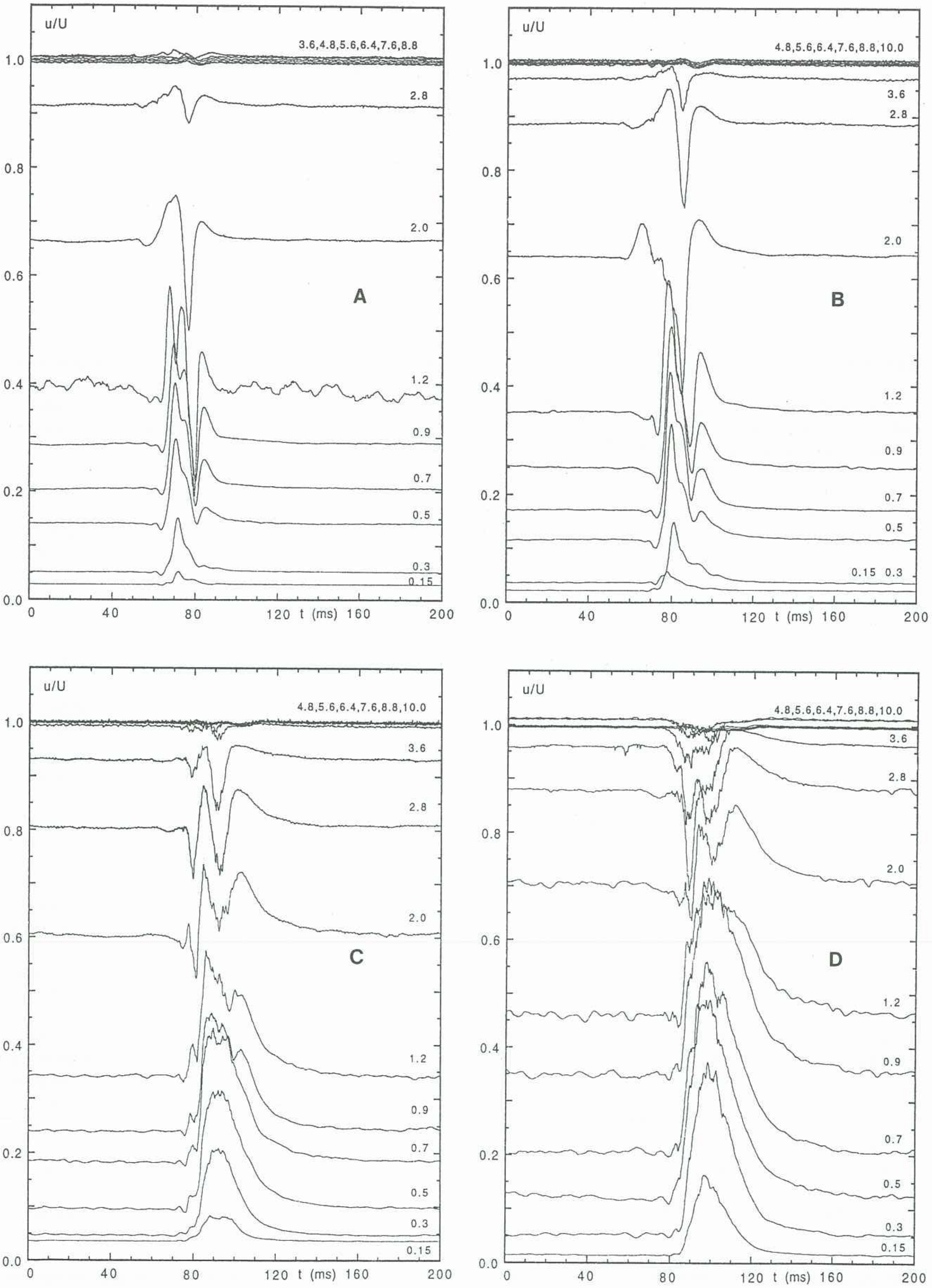

Fig. 1. *Phase-averaged normalised velocity traces for different heights through the boundary layer and at four streamwise locations.*

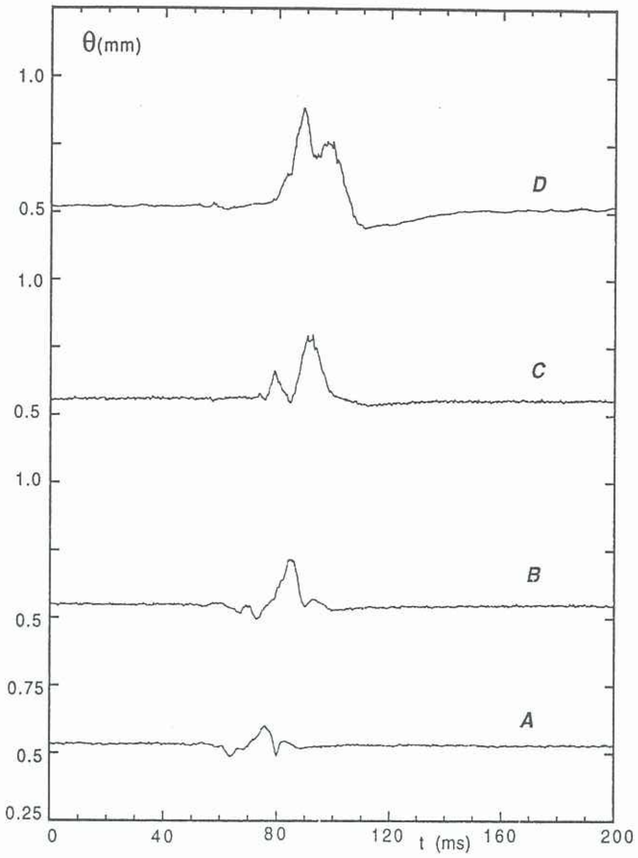

Fig. 2. Momentum thickness variation through spots.

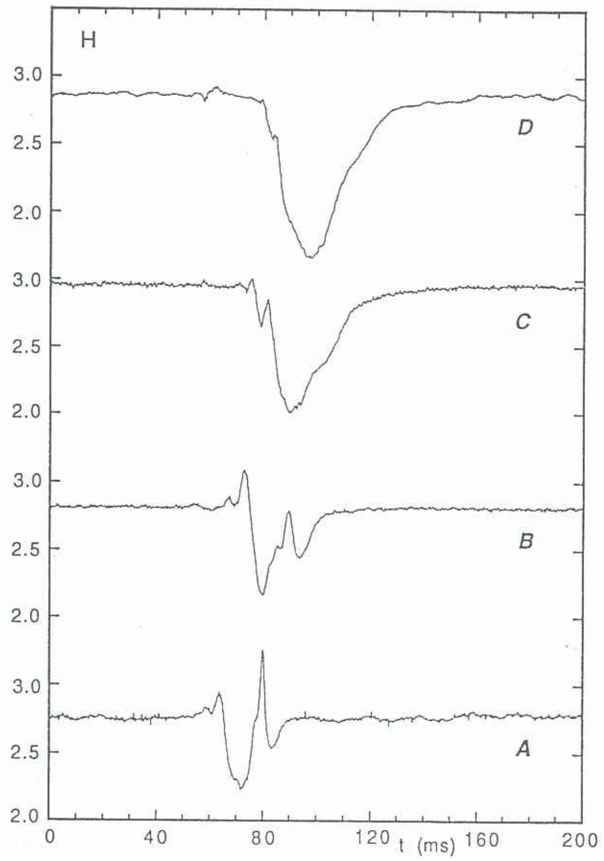

Fig. 3. Shape factor variation through spots.

region. The variation between raw traces was separately analysed in a procedure which evaluated the fluctuation level of 16 individual traces.

RESULTS

Phase-lock averaged normalised velocity traces, on the tunnel centre-line, are presented in Figure 1. Each trace is marked with the value of y (mm). Averaging has resulted in traces which reveal consistent structural features of the spot whilst smoothing out most of the variability between realisations. On the centre line the differences between an adverse pressure gradient spot and classical zero pressure gradient spot measurements are subtle. The relaxation time for velocity profile adjustment from laminar to turbulent and back becomes a consideration for transition in an adverse pressure gradient (Gostelow and Walker, 1991). Spot D has velocity traces which are relaxing for a high proportion of its duration.

Boundary layer profiles throughout the spot were assembled by interrogating the y-t arrays of averaged velocity data, for each recorded time. From these were derived integral properties throughout the spot region; the results for momentum thickness and shape factor are presented in Figures 2 and 3. These plots have a common phase reference and show how the spot evolves in the streamwise direction. Displacement thicknesses are considerably less immediately after the spot than at its leading edge.

Although the results presented were obtained on the geometrical centre-line of the spot this was not strictly the plane of symmetry. By the D location the spot appeared to have acquired a sideways drift of a few percent of its width.

Velocity perturbation contours for the A, B and D spots are given in Figure 4. An interesting comparison is with the work on wave packet development of Breuer et al (1991) who related the onset of turbulent breakdown to a kink in the velocity traces at a height of y/δ^* of 0.75. This corresponds most closely with a y of 1.2 mm in the present results. The kink is quite strong at the A location but appears to have attenuated somewhat upon the onset of turbulence at the B location. The contours for spot A appear to be similar to Breuer's but there is insufficient evidence to confirm his hypothesis for the initial breakdown.

The traces were analysed for disturbance level variations in order to map the geometry of the spot and of any attendant disorderly activity. Plotting the disturbance level variation throughout the spot was intended to assist physical understanding.

Data from sixteen individual traces were acquired for calculating the disturbance level of the spots. The disturbance levels presented are based on voltage rather than velocity and should only be treated as indicative. For each instant of time, the voltage disturbance level is defined as:

$$D_j = \frac{1}{N}\sum_{i=1}^{N}[v(i,j)-\bar{v}(j)]^2. \qquad (1)$$

The resulting contour representations of disturbance level are given in Figure 5 for streamwise locations A, B and D. The contours show consistent development from the late wave packet phase, through the subharmonic phase, to the developed spot (cf. Cohen et al, 1991). The D spot disturbance contours reveal periodic structure at a height of $0.3\delta^*$, much as was the case for the zero pressure gradient spot of Gostelow et al

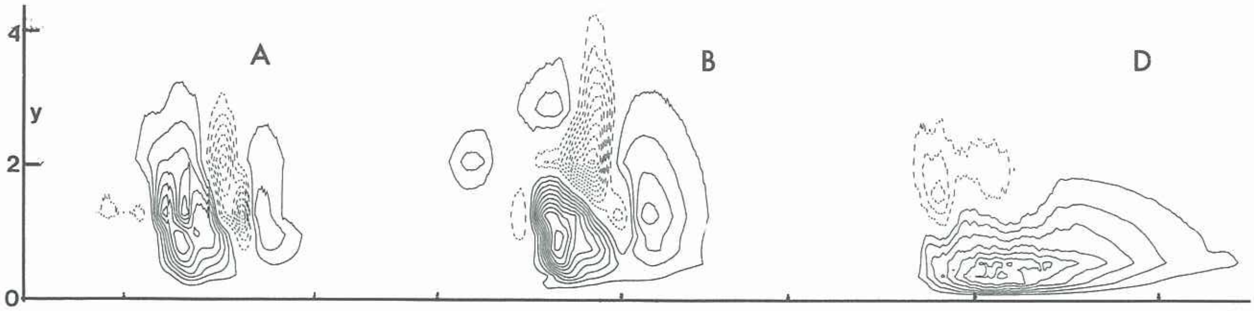

Fig. 4. Velocity perturbation contours through A, B and D spots. Intervals of 0.025U.

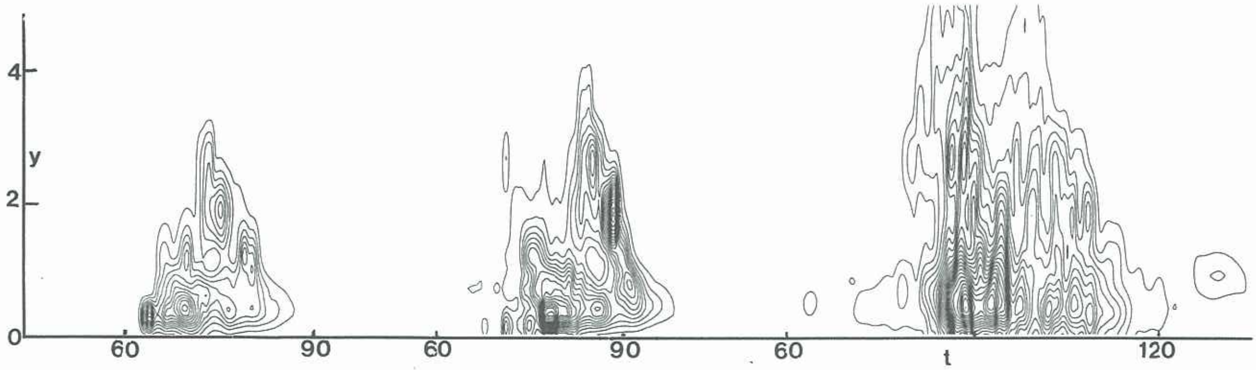

Fig. 5. Disturbance level contours through A, B and D spots. Intervals of 0.01.

(1992b). The disturbance peak spacing, normalised by laminar layer thickness, has a typical value of 5.4. This was identical with that from the zero pressure gradient spot and compares with a range of 2.8 to 5.95 given by Sankaran et al (1988). The Tollmien-Schlichting frequencies for this condition were identified in the same manner as Walker and Gostelow (1990) resulting in a T-S wavelength of approximately 10 ms.

CONCLUSIONS

Measurements of an evolving turbulent spot were made under an adverse pressure gradient. The principal objective was to obtain sufficient information to give a more accurate modelling of the spot and its environment in predictions of transitional boundary layers for turbomachinery design.

Phase-lock averaging was used; velocity profiles were plotted and integral properties derived throughout the spot and its surrounding region. Variations in disturbance level were analysed in order to map the turbulent fluctuations within the spot. Periodic variations in disturbance level were observed in the developed spot.

The information provided is part of a larger body of data which should improve the modelling of spots in transitional boundary layers. Information is needed on the behaviour of spots and their surrounding region under all pressure gradients for progress to be made in transition predictions.

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