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EVOLUTION OF COHERENT STRUCTURES IN THE REATTACHMENT REGION OF A SEPARATED FLOW

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ABSTRACT

An experimental investigation of the evolution of coherent structures in a turbulent flow over a backward facing step has been made. Downstream of reattachment the large scale structures do not return rapidly to equilibrium boundary layer conditions and their coherent contribution to the Reynolds stresses continue to increase for some distance.

INTRODUCTION

There have been a number of excellent reviews of backward facing step experiments. See in particular, Eaton and Johnston (1981), Adams et al. (1984) and Westphal et al. (1984). Recent publications with extensive references are Adams and Johnston (1988a and 1988b). Our work, on the large-scale structures upstream of the step and from the step to the reattachment region, has been given in detail elsewhere (Jovic and Browne, 1989). Here we are concerned to present some of the results obtained for the region near and downstream from the region of reattachment.

EXPERIMENTAL SET-UP

A suction fan provided a free stream velocity of 10.0 m/s in a rectangular duct section, 406 mm wide (= W) × 203 mm high, upstream of a 38 mm (=H) step. The aspect ratio of the step (W/H) was thus 10.7 while the duct area expansion ratio (X-section downstream/X-section upstream) was 1.19. The boundary layer was tripped 1690 mm upstream of the step; 200 mm upstream of the step the flow was close to full development with Re_θ = 2000. The width of the tunnel increased slightly in the flow direction to maintain a zero pressure gradient. Just before the step the boundary layer thickness was 30 mm. A schematic of the set-up is shown in Figure 1.

Temperature was used as a passive contaminant of the flow, for structure detection purposes, by heating the aluminium plates of the tunnel floor, both upstream and downstream of the step, uniformly to about 10°C above ambient. For structure detection, near and downstream of the reattachment region, a vertical rake (y direction) of six temperature sensors (0.63 μm diameter cold wires) was used with a spacing of approximately 7 mm between each sensor. This rake was fixed at each measuring station with the sensor closest to the wall at about 10 mm from the wall. A movable probe, consisting of a miniature X-wire (sensors 1.25 μm diameter, 0.4 mm long and separated by 0.3 mm) and temperature sensor (0.63 μm diameter, 0.5 mm long) was traversed normal to the wall and as close to the vertical rake as possible at each measuring station. The X-wire was used to determine the u and v components of the turbulence. Data was taken at 25 to 30 positions at each measuring station. Four stations downstream of reattachment have been used so far. These were at X/H = 9.2, 10.5, 13.2 and 16.8, where X is the distance from the step in the flow direction. The mean reattachment point was at X/H = 6.5.

The usual yaw and velocity calibrations were carried out. Data from each channel was sampled at 6000 Hz for a total of 20 seconds using a 16 bit A/D simultaneous sample and hold unit.

STRUCTURE DETECTION PROCEDURE

A large scale structure was assumed to have been detected when a sudden temperature drop was observed, more or less simultaneously, on all seven temperature sensors (six in the rake and one associated with the X-probe). To determine the "suddenness" of the temperature drop the Window Average Gradient or WAG detection was used (Antonia et al., 1987; Antonia and Fulachier, 1989). In this, a

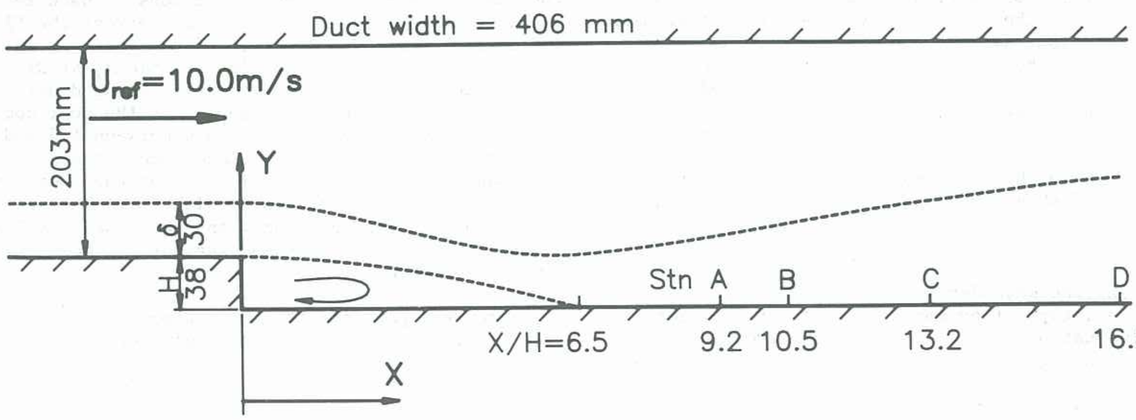

Figure 1 Schematic of the experimental set-up

window of length 2W data points (in our case W = 9 was used) is moved progressively, data point by data point, through the data (in our case the temperature data from the cold wire associated with the X-wire). The gradient of the data in the window is taken to be the mean of the data in the "front" half of the window (data points 10 to 18 in our case) minus the mean of the data in the "rear" half of the window (data points 1 to 9 in our case), divided by half the window length (9 in our case), i.e.

$$\mathrm{WAG} = \frac{\frac{1}{W}\left(\sum_{i=W+1}^{2W} \theta_i\right) - \frac{1}{W}\left(\sum_{i=1}^{W} \theta_i\right)}{W}$$

where θ_i are the temperature fluctuation data.

If ABS(WAG) > k θ_{rms}, where k is a factor to be determined by trial (in our case k = 0.6 was used) and θ_{rms} is the root mean square of all the temperature fluctuation data, and if WAG < 0, then a possible detection region has been found. The window movement is continued until WAG > 0. The position during that movement where the absolute value of WAG was a maximum, is then a possible detection point - PDP. The same WAG criteria were then applied to each of the six temperature fluctuation signals, obtained from the vertical rake of probes, by searching near the PDP point (we allowed a time offset of δ/U_∞ which amounted to ±9 data points). If such a search resulted in the WAG criteria being satisfied by each signal then the PDP became an actual detection point.

This detection procedure resulted in a primary group of large scale structures. This group of structures was used for determining the pdf of time between detections, the mean frequency distributions and for the coherent contributions to the Reynolds stresses. Typically 300 to 400 structures were obtained.

For presentation of ensemble averages and topology, a secondary group of structures was selected from the primary group by applying two further criteria :

(i) A structure was accepted if it occurred between two detection points separated, on a time basis, in the range

$$\bar{t} - 0.9t_{rms} \leq t \leq \bar{t} + 0.15t_{rms}$$

where $\bar{t}$ is the average time spacing between detections. The range selected was arbitrary but it did allow for the highly skewed nature of the pdf of the time between detections.

(ii) An ensemble average of the temperature signal from the primary group of structures was firstly determined. The temperature signal at each detection point was then compared with this ensemble averaged signal. If it did not compare reasonably in shape then the detection point associated with that signal was rejected. The comparison was made by determining the correlation, R_i, between the two signals. The phase between the two signals was then changed slightly and the correlation again calculated. This process was repeated until $R_{i,max}$ was obtained. If $R_{i,max}$ < 0.6, then the detection point was rejected.

Typically this secondary group of structures consisted of about half the original primary group.

RESULTS

Using the secondary, more selective, group of structures, typical ensemble averages of the temperature fluctuation signal, θ, and the u and v velocity fluctuation signals are shown in Figure 2.

It is apparent that all three signals might have been used for detection purposes, but tempera-

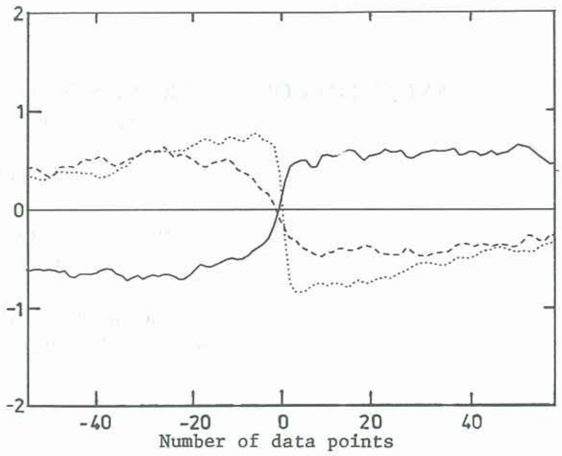

Figure 2 Ensemble average of the temperature and velocity fluctuation signals. •••, <θ> * 10; ——, <u>; - -, <v>.

ture change has the steepest slope and was recorded at a number of positions across the flow.

The $\overline{u^2}^{\frac{1}{2}}$, $\overline{v^2}^{\frac{1}{2}}$ and $\overline{uv}$ curves at X/H = 9.2 and 16.8 are shown in Figure 3. There is reasonable

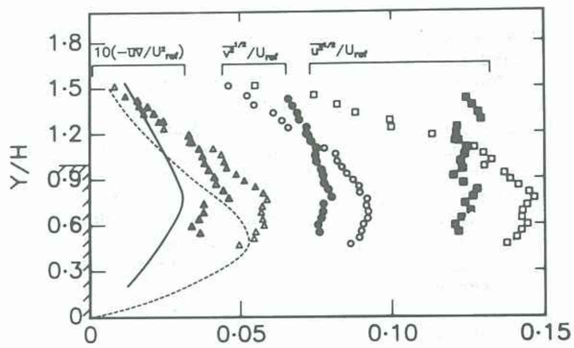

Figure 3 Distribution of $\overline{u^2}^{\frac{1}{2}}$, $\overline{v^2}^{\frac{1}{2}}$ and $\overline{uv}$. Driver and Seegmiller (1985): - -, X/H = 10; ——, X/H = 16. Open symbols : X/H = 9.2; closed symbols : X/H = 16.8.

agreement of the $\overline{uv}$ curves with the LDA results of Driver and Seegmiller (1985) although their Re_θ was 2.5 times ours. The $\overline{u^2}^{\frac{1}{2}}$ and $\overline{v^2}^{\frac{1}{2}}$ curves flatten significantly as X/H increases.

Pdf distributions of "time between detections" for the primary group of structures, normalised by the rms of the time between detections, showed remarkable similarity at all positions across the flow and at each station. The mean of the results, obtained from the across the flow positions, at X/H = 9.2 and 16.8 are shown in Figure 4. These distributions are highly skewed and show that the most common time between detections occurs between 1.5 and 2.0 times as often as the average time between detections. The structures selected for the secondary group of structures were those with "time between detections" in the range between the dashed vertical lines shown in the figure and include the most common time between detection.

From the pdf data, the mean frequency of the passing of the structures was determined (mean frequency = 1/mean time between detections). These have been normalised by H and U_{ref} (= free-stream velocity upstream of the step, i.e. 10.0 m/s) and are shown in Figure 5.

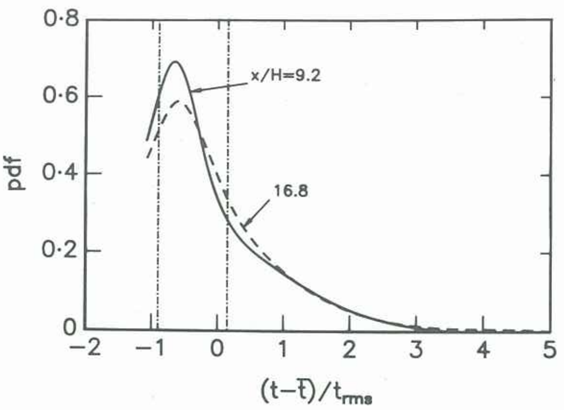

Figure 4 Pdf of time between detections.

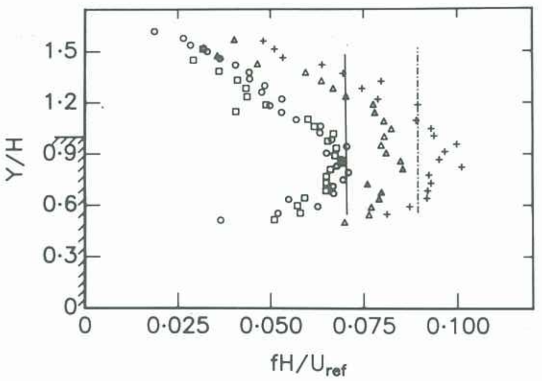

Figure 5 Distribution of the mean frequency of the passage of the large scale coherent structures. □, X/H = 9.2; ○, 10.5; Δ, 13.2; +, 16.8. ——, equilibrium boundary layer; — · —, reattachment region (Driver et al., 1987 and Kiya and Sasaki, 1983).

The mean frequency increases in the flow direction reaching values similar to those obtained by Driver et al. (1987) for the reattachment region. It would appear that, on this basis, a return to the equilibrium boundary layer conditions only occurs at very large X/H.

Using the secondary group of structures, the conditional velocity vectors, relative to the detection points, at each station were determined and the results for two stations are shown in Figure 6. A convection velocity of $0.7U_{ref}$ was used in both cases. This is about $0.8U_\infty$ in the downstream section, a convection velocity often used in boundary layer studies. The relative position of each line of vectors was determined from the maximum correlations between the temperature signals of the vertical rake. The structures at the largest X/H appear to have developed considerably in size.

The coherent contributions to the Reynolds stress values at each of the stations are shown in Figure 7. The increase in the contributions as X/H increases is consistent with the topology changes that can be seen in Figure 6.

It was most interesting to note that the peak in the coherent contributions continued to increase from X/H = 9.2 to X/H = 16.8. It has yet to be determined where these values start to fall and where they finally approach the equilibrium boundary layer values of around 0.25 to 0.35 (see Jovic and Browne, 1989 and Antonia et al., 1988).

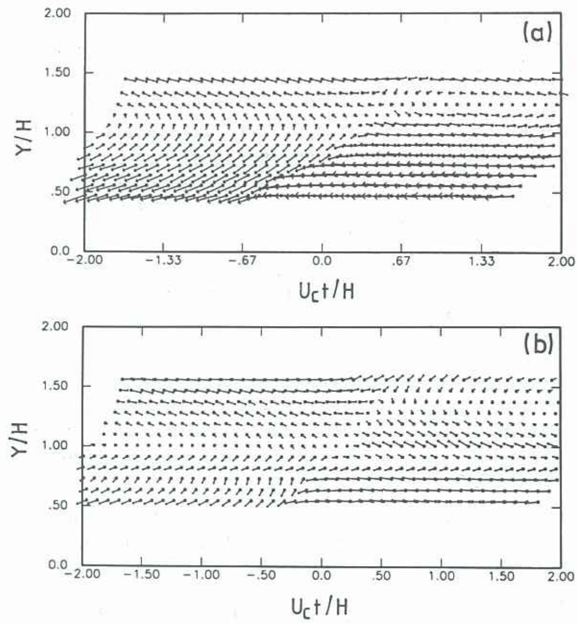

Figure 6 Ensemble averaged velocity vector plots (topology) at (a) X/H = 9.2; (b) 16.8. Convection velocity = $0.7U_{ref}$ in both cases.

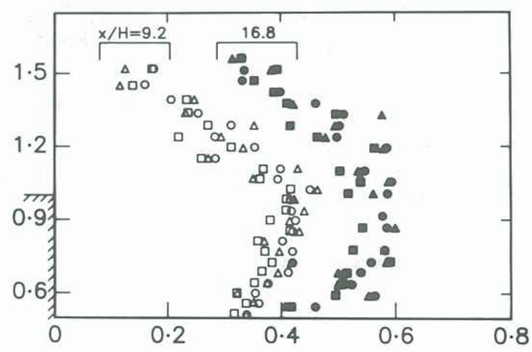

Figure 7 Contribution of the coherent motion to the Reynolds stresses. Symbols same as for Figure 5.

CONCLUSIONS

All results indicate that there is not a rapid return to equilibrium boundary layer conditions after reattachment. The structures appear to increase in size for some distance, at least up to X/H = 16.8, and correspondingly the coherent contributions to the Reynolds stresses continue to increase.

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