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ORGANISED MOTION IN A FULLY DEVELOPED TURBULENT DUCT FLOW

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ABSTRACT

Data from an array of X-probes in a fully developed turbulent duct flow indicates the existence of an organised motion antisymmetrical about the centreline, with an average wavelength of about 3.2h where h is the duct half-width. The organised motion associated with either shear layer intrudes across the centreline into the region occupied by the opposite shear layer. This interaction seems consistent with the finding that the contribution from quadrant 2 to the Reynolds shear stress is smaller in the duct than in the boundary layer.

INTRODUCTION

Significant attention is currently being given to the study of the organised motion in different turbulent shear flows, using a variety of experimental and computational approaches.

The approach adopted in our laboratory consists of using as many as 16 velocity sensors simultaneously deployed in the flow, usually, though not always, in the plane of mean shear. From the velocity signals, instantaneous velocity vectors and sectional streamlines can be calculated and then viewed in a frame of reference which translates in the main flow direction with a suitable convection velocity. Once a suitable method of detecting the organised motion is chosen, an ensemble averaged topology of this motion can be obtained.

Whereas flow visualisation using tracers such as smoke or dye is effective only at small Reynolds numbers, the above approach applies over a larger Reynolds number range. Information from this approach has been obtained in a self-preserving turbulent wake, a turbulent boundary layer and a turbulent spot which develops within a laminar boundary layer. The approach has now been applied to a fully developed turbulent duct flow, distinguishable from the previous three flows by the absence of a turbulent/non-turbulent interface. The simplifications that can be made to the equations of motion which govern the fully developed duct flow make its study particularly attractive.

The present study was motivated by the following questions :

i) Given that the topology of the near-wall flow is about the same for the duct as the boundary layer, how does the outer region topology differ between these two flows?
ii) How is the organised motion on one side of the centreline related to that on the other?
iii) What is the influence of the Reynolds number on the organised motion?

EXPERIMENTAL CONDITIONS

The experiments were made in an air duct with an aspect ratio of 18 : 1 at a distance of $x/2h = 160$ from the entrance (h is 21 mm). This location is much greater than the recommended distance from the inlet for the establishment of a fully developed flow (Comte-Bellot, 1965; Dean, 1974).

Initially, measurements were made with one X-probe at two different Reynolds numbers, Re = 11500 and Re = 21500 ($Re = hU_c/\nu$, where U_c is the centreline velocity). The probe was traversed across the duct over the range $0.1 \le y/h \le 1.25$ for u,w measurements and $0.25 \le y/h \le 1.25$ for u,v measurements. An array of approximately equi-spaced X-probes was then used, the majority of the measurements taken with the array in the (x,y) plane at Re = 5000, 11500 and 21500. In the design of the array, care was taken to minimise the possibility of flow obstruction. Both, the single X-probe and the X-probe array were calibrated for velocity and yaw at the centre of the duct, with the plane of the probe(s) aligned in the spanwise direction.

All X-probes were built using 5 μm Wollaston Pt-10% Rh wires (length ≃ 1 mm). The hot wires were operated at an overheat of 0.5 with constant temperature anemometers. D.C. offset voltages were applied to the signals from the anemometers before amplification and low-pass filtering at a cut-off frequency of 1200 Hz/channel. They were then digitised on a PDP 11/34 computer using a 16 channel 12-bit A/D data acquisition system at a sampling frequency of 2404 Hz/channel. A VAX 780 computer was used to process the data.

RESULTS AND DISCUSSION

Using the X-probe array data, instantaneous velocity vectors were calculated at eight positions across the duct. For ease of viewing these vectors, two extra rows of data were interpolated between each pair of existing rows giving a total of 22 rows. Both the original and interpolated data were then used to calculate sectional streamlines in a frame of reference moving at a velocity $U_r = 7$ m/sec in the direction of the flow. The streamlines in Figure 1 show evidence of the existence of an organised motion having a scale of the half-width of the duct on either side of the centreline. This motion appears to be antisymmetrical about the centreline.

To estimate the wavelength of the organised motion in turbulent free shear flows, the spectrum ϕ_v has been preferred (Bevilaqua and Lykoudis, 1977; Cimbala, 1984; Antonia et al., 1987) to ϕ_u because ϕ_v exhibits a discernible peak at the average frequency of the organised motion. Spectra of u and v at $y/h = 0.93$ are shown in Figure 2. While no peak can be seen in ϕ_u, a significant peak exists in ϕ_v at a frequency $f_c h/U_c = 0.32$. This peak is observed only near the centreline. The v-spectra obtained by Laufer (1953) and Comte-Bellot (1965) show a similar behaviour. The small range of y/h in which f_c

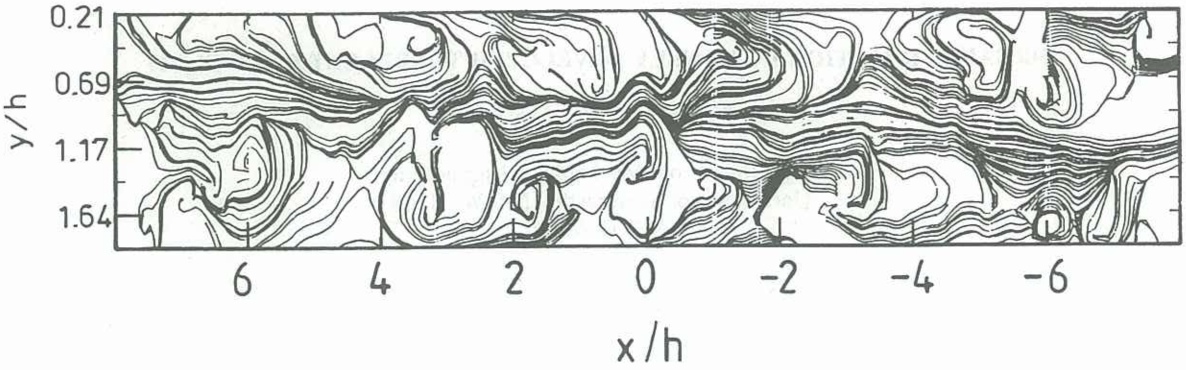

Figure 1 Sectional streamlines observed in a frame of reference moving at a velocity $U_r \simeq 0.9U_c$.

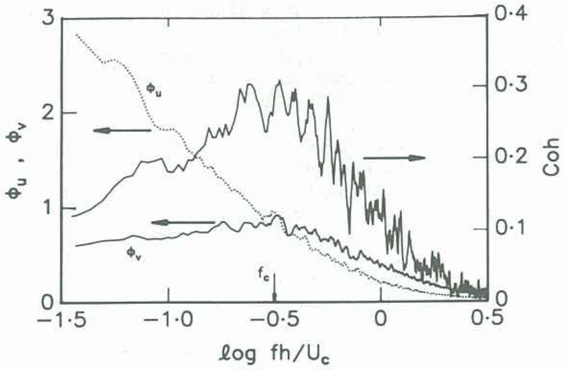

Figure 2 Spectra of u and v at y/h = 0.93; and spectral coherence between v signals at y/h = 0.93 and y/h = 1.17.

exists may be the result of the existence of different scales of motion in wall-bounded flows, making the detection of a single characteristic scale more difficult as the distance from the centreline increases. As noted by Antonia et al. (1987) the peak in ϕ_v is not a consequence of isotropy and an inflectional shape in the u-spectrum since the isotropic relation $\phi_v = \frac{1}{2}(\phi_u - k_1 \partial\phi_v/\partial k_1)$, where k_1 is the one-dimensional wavenumber, is valid only for frequencies greater than about $5f_c$.

The coherence between v signals measured on opposite sides of the centreline at y/h = 0.93 and y/h = 1.17 (Figure 2) has a significant peak at approximately f_c. The phase difference between the Fourier components of the two v signals is $\pi/2$, supporting the antisymmetry of the organised motion. Correlation contours of u and v obtained with the reference probe located at y/h = 0.69, are shown in Figures 3(a) and 3(b). The u correlations change sign across the centreline but the v correlations remain positive across the flow. This behaviour is consistent with the co-existence in the central flow region of organised motion characterising the opposite shear layers. An estimate of the organised motion wavelength λ can be inferred from the distance between successive local maxima in the v correlations on the same side of the centreline or from f_c via the relation $\lambda \equiv U_c/f_c$. Both approaches yielded the same result ($\lambda \simeq 6.7$ cm) corresponding to $\lambda/h = 3.2$. For comparison, the spectra of Laufer (pipe) and Comte-Bellot (duct) indicate values of 3.6 and 3.4 respectively. The reasonable agreement in the previous values of λ/h suggests

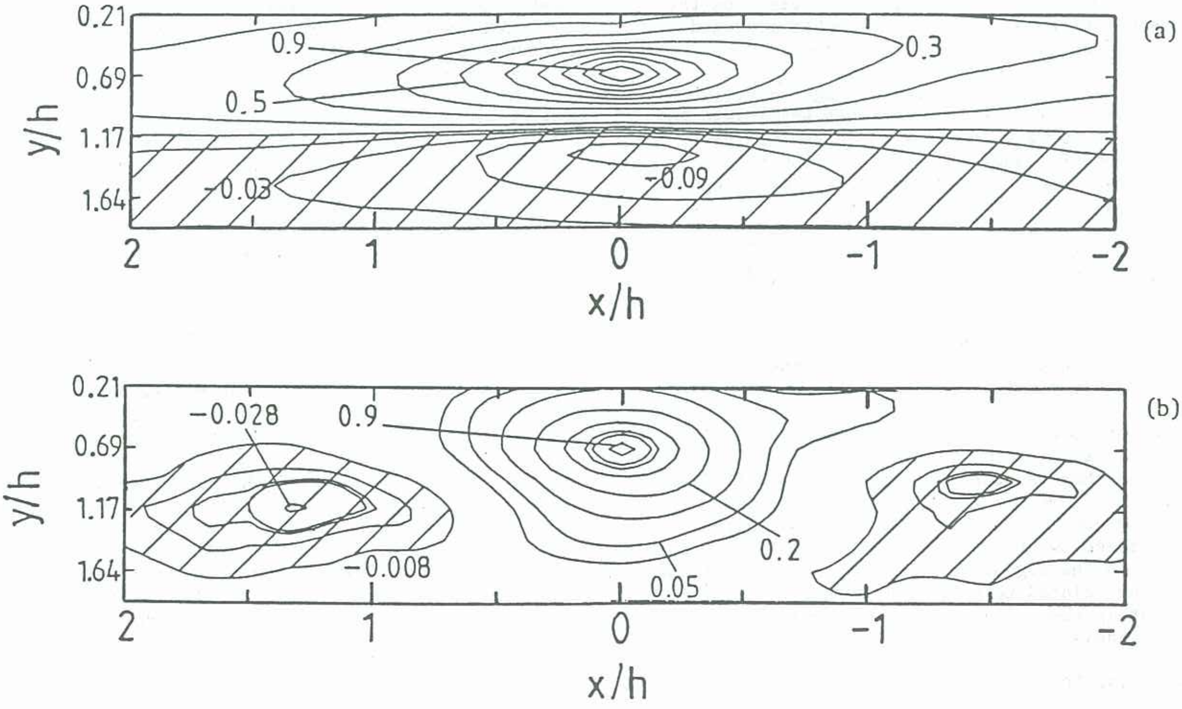

Figure 3 Correlation contours of u and v. Cross-hatched contours are negative. (a) u; (b) v.

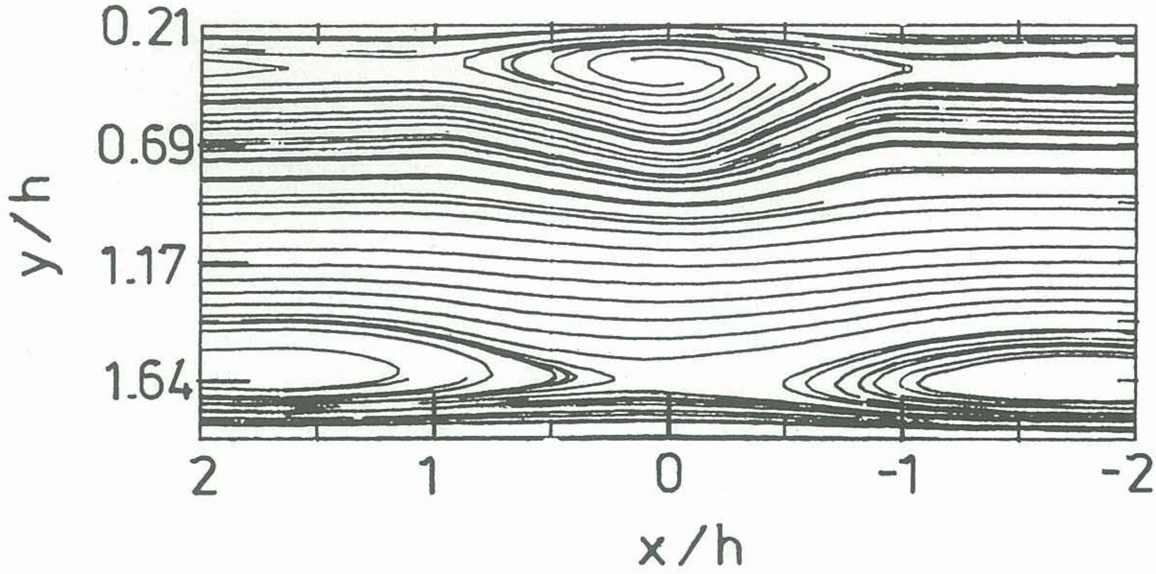

Figure 4 Conditionally averaged sectional streamlines observed in a frame of reference moving at a velocity $U_r \simeq 0.9U_c$.

that this ratio does not significantly depend on the Reynolds number and that the organised motion scales with the duct width or pipe diameter.

An ensemble averaged picture of the organised motion was obtained using a detection method based on v signals at y/h = 0.69 and y/h = 1.4. A window average gradient (WAG; a description is given in Bisset et al., 1989) was calculated by moving a computational window point by point through the digital time series for v. Whenever the WAG magnitude exceeded a threshold value (0.3v', where v' is the rms value of v) a detection was made. Because of the antisymmetry, the gradient of v was required to be positive at y/h = 0.69 and negative at y/h = 1.4. Detections from opposite sides of the centreline were then compared. Detections which matched (within a tolerance of x/h = ±0.8) were ignored while all others (a total of 800) were retained. Using the latter detection set, ensemble averaged sectional streamlines were plotted (Figure 4). The good agreement between Figures 3(b) and 4, showing approximately the same length scale for the organised motion, suggests that v correlation contours give a fairly good indication of the spatial organisation of the flow.

Although the near-wall topology is about the same in a boundary layer and in a duct, the intrusion of structures from either side of the centreline into the other side (e.g. Figure 1) must

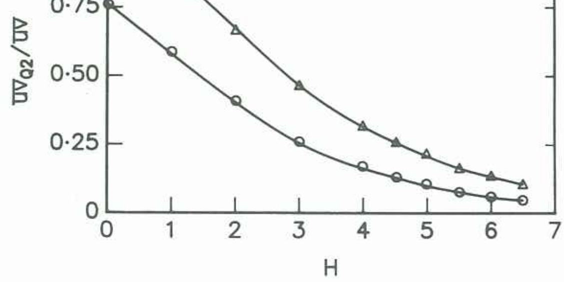

Figure 5 Fractional contribution to $\overline{uv}$ from Q2 events. ○, duct; Δ, boundary layer.

affect the outer flow topology (see Wei and Willmarth, 1989). The application of a quadrant-hole analysis on uv indicates that the contribution from quadrant 2 (Q2) to the Reynolds shear stress is smaller in the duct than in the boundary layer (Figure 5) reflecting the mutually inhibiting effect of organised motions associated with the opposite shear layers.

CONCLUSIONS

The flow in a duct consists of organised motions associated with the opposite shear layers. The organisation is antisymmetrical about the centreline with a characteristic wavelength, as estimated from the peak frequency of the v spectrum and v correlation contours, equal to about 3.2h. This estimate appears to be independent of Reynolds number. Comparison with the boundary layer indicates that quadrant 2 events are less intense in the duct, reflecting the mutually inhibiting influences of the opposite shear layers.

ACKNOWLEDGEMENT

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