DETACHED COHERENT STRUCTURES IN CHANNEL REVISITED: COMPARISON WITH HOMOGENEOUS SHEAR TURBULENCE

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Abstract Coherent structures in statistically-stationary homogeneous shear turbulence (HST) are compared with those of the detached family in channels. Similarly to attached ones, detached Qs in channels form streamwise trains of side-by-side groups of a Q2 and a Q4. This is also true in HST. Contrary to attached structures, but similarly to those in HST, detached Q4s in channels are comparable in size to their related high-streamwise velocity streaks. Vortex clusters tend to associate with Q2s and Q4s, equally distributed between them in HST but more closely with Q2s in channels. The results strongly suggest that coherent structures in channels are not particularly associated with the wall, or even with a given shear profile.

INTRODUCTION

It is known that the statistics of channel turbulence with off-wall boundary condition agree reasonably well with those of classical channels [1], and that bursting in channel turbulence is well approximated by Orr bursts similar to those in homogeneous shear turbulence (HST) [2]. Similarities between HST and the logarithmic layer of channels have also been observed in the shear parameter, spectra of the vertical velocity, self-regeneration process, etc. [3], raising the question of how similar are different shear-induced turbulent flows. We aim to contribute to the answer by comparing the characteristics of coherent structures in HST with those of the wall-detached family in channels.

The two kinds of structures that we study are: Qs, based on the quadrant analysis of the Reynolds stress, and vortex clusters defined by the second invariant (II) of the velocity gradient tensor. As in channels [4, 5], individual structures in HST are defined by thresholds: $|u(\boldsymbol{x})v(\boldsymbol{x})| > Hu'v'$, where $(')$ stands for the root-mean-square, for Qs, with $H = 1.75$, and $\mathrm{II}(\boldsymbol{x}) > \alpha\mathrm{II}'$ for clusters, with $\alpha = 1.5$. In channels, structures separate into families according to whether their minimal distance to the closest wall is $y_{min} < 20$ (attached) or $y_{min} > 20$ (detached). The former have been intensely investigated [4, 5], but less attention has been paid to the latter due to their smaller contribution to the total Reynolds stress or enstrophy. However, there are reasons for not neglecting them. Firstly, structures that are attached at a given moment are often detached earlier or later in their history, with no discontinuous variation in their properties [6]. Secondly, the fractional contribution to the total Reynolds stress of detached Q2s and Q4s above $y \approx 0.4h$ is actually higher than that of attached ones, although it tends to be cancelled by that of detached Q1s and Q3s [5]. Lastly, although the mean shear profile is different in both flows, detached channel structures resemble those of HST in that they interact with the mean shear while being relatively free from the influence of the wall. Both have sizes up to integral scale.

RESULTS

We study the spatial organization of detached coherent structures in channels by computing the p.d.f.s of relative positions of all detached structures in one half of the channel with respect to to those in the band $y_{min} > 0.2$ and $y_{max} < 0.4$. Repeating the analysis for the band $y_{min} > 0.3, y_{max} < 0.5$ gave similar results. Position is defined by

$$\delta_x = 2\frac{x_c^{(j)} - x_c^{(i)}}{d^{(j)} + d^{(i)}}, \delta_y = 2\frac{y_c^{(j)} - y_c^{(i)}}{d^{(j)} + d^{(i)}} \text{ and } \delta_z = 2\frac{z_c^{(j)} - z_c^{(i)}}{d^{(j)} + d^{(i)}} \tag{1}$$

where $\boldsymbol{x_c}^{(i)}$ and $d^{(i)}$ are respectively the centre and diagonal length of the rectangular box containing each structure. Only structures with volumes that differ by less than a factor of two are considered. Figure 1a shows the streamwise cross-section of the p.d.f. of the relative positions of detached Q4s. It agrees very well with that in HST. Detached Q2s behave similarly. The clockwise tilt of the two maxima is intriguing because it suggests a streamwise inhomogeneity of the groups of Q4, but it requires further statistical confirmation. Figure 1b also shows good agreement in the relative position of Q4s with respect to Q2s. The more compact contours of the HST are probably due to the constricting effect of the computational box, which is always minimal for that flow, particularly in the spanwise direction [3]. The results in figure 1a and 1b are qualitatively consistent with those of attached Qs [5]. It is not unexpected that detached (or attached) Q2 and Q4 are paired in the spanwise direction, since they are associated with adjacent longitudinal low- and high-velocity streaks [6]. It is more surprising that detached structures are so close together in the streamwise direction ($|\delta_x| < 1.0$), because the streaks are supposed to be mostly filled by larger attached structures that should separate the detached ones. Probably, the latter lie within the folds of the former, which are 'sponges of flakes' with fractal dimension $D \approx 2$ [5]. The results do not depend on the Reynolds number for either channels or HST. The above results strongly suggest that neither the presence of the wall nor the different mean shear profiles are important in determining the formation or the spatial organization of detached Qs in channels or in HST.

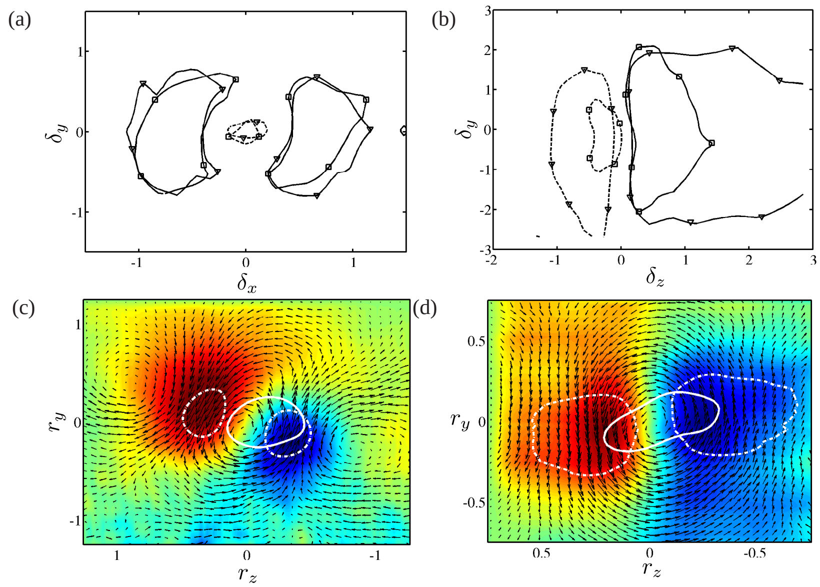

Figure 1. (a) Joint p.d.f. of the relative position of neighbouring Q4s in the $(x - y)$ plane in HST with $Re_\lambda = 100$ (□) and of detached Q4s in a channel with $Re_\tau = 2000$ (▽). Solid: p^{44}/p^{44}_∞=2.1; dashed: 0.8. p_∞ is the mean probability for $\delta_x^2 + \delta_y^2 + \delta_z^2 > 4$. (b) Joint p.d.f. of relative position of Q4s with respect to Q2s in the $(x - y)$ plane in HST with $Re_\lambda = 100$ (□) and of detached ones in a channel with $Re_\tau = 2000$ (▽). Solid: p^{42}/p^{42}_∞=1.6; dashed: 0.6. p_∞ is the mean probability for $\delta_x^2 + \delta_y^2 + \delta_z^2 > 9$. (c) Cross-flow section of the conditional average through the centre of detached Q2–Q4 pairs for which with $|\delta_x| < 1.0$, $|\delta_y| < 0.5$ and $|\delta_z| < 0.5$, in a channel with $Re_\tau = 950$. The shaded contours are the streamwise velocity (blue: $u < 0$; red: $u > 0$). The arrows are $(v - w)$. The dash lines are 0.75 of the maximum probability of points belonging to the Q2–Q4 pair. The solid line is 0.85 of the maximum probability of points belonging to vortex cluster. (d) As in (c), for Q2–Q4 pair in HST with $Re_\lambda = 104$. The dashed lines are 0.70 of the maximum probability of points belonging to the Q2–Q4 pair. The solid line is 0.95 of the maximum probability of points belonging to vortex cluster.

The mean flow conditioned to a close pair of detached Q2–Q4 was computed using the method in [5]. Figure 1c shows the two-dimensional section of the conditional flow field in a cross-flow plane through the centre of the pair. The conditional Q2s and Q4s are of similar size, but the high-streamwise velocity region associated with the Q4 is larger than the low-velocity one, and also larger than the Q4 itself. This is similar to, although less marked than, the flow around attached pairs [5]. However, the points used to compile figure 1c do not exclude the attached Q2s or Q4s that might lie in the neighbourhood of the detached pair. When that contribution is removed, the high-speed region shrinks considerably, and so does the high-speed bulge overhanging the Q2. The Q2 changes little, and the result is to make the Q2–Q4 pair more symmetric. The HST pair in figure 1d is symmetric, as required by the homogeneity of the flow. This results should not be interpreted to mean that attached and detached pairs in channels are intrinsically different. They rather form a continuum in which structures become more symmetric, and more similar to the structures of HST, as they move farther from the wall. The wall itself does not appear to be required for the generation of the Q2s or Q4s. The conditional vortex cluster in figure 1c, which includes contributions from attached and detached structures, tends to be associated with the Q2. This is also the case for attached pairs [5]. In the HST in figure 1d, it is equally distributed between the Q2 and the Q4. The simplest interpretation is that the channel Q2s carry vorticity from the higher-shear region near the wall [4], while both directions are equivalent in HST.

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