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A New Wall-Dependent Identification Method for Coherent Streamwise Streaks in Turbulent Channel Flows

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Abstract

A wall-dependent identification method for low-speed streamwise streaks in turbulent channel flows is presented to overcome a key limitation of uniform thresholds, which tend to produce either an excess of detected structures near the wall or an apparent lack of streaks farther from it. The method is constructed following wall-dependent threshold requirements established in the literature and is applied to DNS data of Couette–Poiseuille flows at $Re_\tau \approx 250$ using percolation analysis and clustering to extract three-dimensional objects. In addition, a percolation study at a significantly higher Reynolds number is included to assess the effect and robustness of the filter beyond the reference case. Although some global trends remain consistent with previous results obtained using uniform thresholds, the present work provides a direct comparison between both approaches and shows more clearly how the threshold definition affects the identification of streaks away from the wall. The detected structures are classified into wall-attached and wall-detached families, separated by a transition region at $y_{\min}^+ = 20$, and both exhibit self-similar geometric trends. Their spatial distribution is also analysed, showing differences mainly associated with the alignment of attached streaks in pure Poiseuille and pure Couette flows.

Keywords: DNS; turbulence; Couette flows; Poiseuille flows; coherent structures; streaks

1. Introduction

Since the classical observations of Kline et al. [1], wall-bounded turbulence has been known to display a significant degree of organization, with recurrent coherent motions playing a central role in its dynamics [2]. Among the most prominent of these motions are streamwise vortices and the alternating low- and high-speed streaks found in the spanwise direction [3,4]. These structures are part of the regeneration cycle that sustains turbulence [5]. From this viewpoint, coherent structures are not simply geometric features of the flow, but dynamically relevant regions that may extract energy from the mean shear, dissipate it, or retain it long enough to influence the overall energy balance [6].

Away from the near-wall region, however, the organization of turbulence changes and requires a different description. In the logarithmic layer, Townsend’s attached-eddy framework [7] provides such a description by modeling the flow in terms of self-similar energy-containing motions attached to the wall, with a size that scales with the distance to the nearest wall. This framework has been widely used to interpret the logarithmic mean profile and the scaling of Reynolds stresses. For a long time, coherent structures in this region were mostly considered from a statistical perspective [8]. More recently, attention has shifted towards instantaneous structures identified directly in velocity fields



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through specific filters and extraction procedures [6]. Recent studies have also examined the distinction between wall-attached and wall-detached motions, together with their hierarchical arrangement [9,10]. Within this context, three-dimensional clustering of thresholded fields has become a common tool for identifying vortex clusters [11], wall-shear-stress structures [12], intense Reynolds-stress events [13–17], and streamwise streaks [17–21].

A well-known difficulty in this type of identification is the choice of threshold. In wall-bounded turbulence, the flow is strongly inhomogeneous in the wall-normal direction, so uniform thresholds are often problematic. As pointed out by Nagaosa and Handler [22] and later by Del Álamo et al. [11], a threshold that captures near-wall structures appropriately tends to leave very few detectable objects farther from the wall. On the other hand, reducing the threshold for visualizing outer-layer motions results in an excessive concentration of structures near the wall.

The present work revisits the streak-identification method proposed by Bae and Lee [21] and explores whether it can be reformulated using a wall-dependent criterion consistent with the requirements discussed by Nagaosa and Handler [22]. We focus on streamwise streaks because of their key role in the regeneration cycle and in the self-sustaining process of wall turbulence [5]. To determine a suitable threshold, we perform a percolation analysis [11,13–15,17] in a turbulent Couette–Poiseuille channel, extending the recent analysis of Gandía-Barberá et al. [17]. We then study the topology and spatial organization of the extracted three-dimensional structures.

The paper is organized as follows. Sections 2.1 and 2.2 describe the numerical methodology and the Couette–Poiseuille dataset. The wall-dependent filter and the percolation analysis are presented in Sections 2.3 and 2.4. The resulting statistics of the identified three-dimensional structures are discussed in Section 3, including their geometry and topology in Section 3.1 and their spatial organization in Section 3.2. Finally, Section 4 summarises the main findings. This study relates to the United Nations Sustainable Development Goals 7 and 9, as improving our understanding of turbulence may contribute to more efficient energy use and technological innovation [23].

2. Methodology and Numerical Simulations

2.1. Couette–Poiseuille Simulation Dataset

In this study, a new dataset of direct numerical simulations of turbulent Couette–Poiseuille (C-P) channels at $Re_\tau \approx 250$ is generated. The dataset comprises six C-P cases, ranging from pure Couette flow (i.e., C10P00) [24–27] to pure Poiseuille flow (i.e., C00P10) [28–30]. The viscosity and bulk velocity are kept constant in all cases; see Table 1. The governing parameter of the C-P dataset is the ratio between the shear stresses at the two walls (i.e., the moving and the static wall), $\gamma = \tau_M / \tau_S$, which is restricted by definition to the range $-1 \leq \gamma \leq 1$ [31]. Based on the shape of the mean streamwise velocity profile, cases with $\gamma > 0$ are classified as Couette-like, whereas cases with $\gamma < 0$ are classified as Poiseuille-like. Pure Couette and pure Poiseuille flows correspond to $\gamma = 1$ and $\gamma = -1$, respectively. A particularly relevant case is C06P04, for which $\gamma \approx 0$. This case exhibits nearly zero mean shear at the moving wall and can therefore be used as a model for studying turbulent flows near separation [31]. Under these conditions, the wall affects the core flow mainly through the impermeability condition; that is, the wall-parallel velocity components are only weakly influenced by the presence of the upper wall.

Table 1. Description of the C-P dataset. Two different Reynolds numbers are given depending on the local Re_τ at the moving (fourth column) over the stationary (third) wall. $\gamma = \tau_M/\tau_S$ is the ratio of shear stress at the two walls [31]. The next two columns denote the computational time span while statistics were taken in wash-outs (U_b/L_x) and eddy turn-overs (u_τ/h). T is the computational time spanned by those fields. The last column lists the percolation indexes used for streaks identification acc. to Equation (4). Line shapes given in the second column are used to identify the cases throughout all the figures in this paper.

Case	Line	Re_τ^s	Re_τ^m	γ	TU_b/L_x	Tu_τ/h	α
C10P00	—●—	250	250	1.00	28.2	38.6	1.60
C08P02	—	252	97	0.38	32.1	44.3	1.60
C06P04	—	254	6	0.02	24.0	33.4	1.60
C04P06	—	256	54	−0.21	20.4	28.7	1.60
C02P08	—	263	139	−0.53	25.9	37.3	1.60
C00P10	—■—	275	275	−1.00	36.4	54.9	1.60

2.2. Numerical Methodology

The simulations have been performed in a computational box of sizes $L_x = 8\pi h$, $L_y = 2h$, and $L_z = 6\pi h$, where h is the half-channel height. The streamwise, wall-normal, and spanwise coordinates are denoted by x , y , and z , and the corresponding velocity components are U , V , and W . Statistically averaged quantities are denoted by an overbar, whereas fluctuating quantities are denoted by lowercase letters, i.e., $U = \bar{U} + u$. Primes are reserved for intensities, $u' = (\overline{uu})^{1/2}$. Quantities averaged in time or along any particular direction are denoted using angle brackets; that is, $\langle U \rangle_{xzt}$ is the streamwise velocity averaged in the homogeneous directions and time.

The C-P flows can be described through the mass balance and momentum equations:

$$\partial_j U_j = 0, \quad (1)$$

$$\partial_t U_i + U_j \partial_j U_i = -\partial_i P + \frac{1}{Re_\tau} \partial_{jj} U_i, \quad (2)$$

where repeated subscripts indicate summation over 1, 2, and 3 and $(U_1, U_2, U_3) = (U, V, W)$. The pressure term includes the constant density ρ . The previous equations are transformed into an equation for the wall-normal vorticity ω_y and for the Laplacian of the wall-normal velocity $\phi = \nabla^2 v$. The spatial discretization uses dealiased Fourier expansions in x and z , and seven-point compact finite differences in y , with fourth-order consistency and extended spectral-like resolution [32]. The temporal discretization is a third-order semi-implicit Runge–Kutta scheme [33]. The algorithm is described in [34]. This code exhibits significant parallelizability, encompassing I/O operations, facilitating computations demanding substantial computational power [35]. Results from this code have been used largely by the community [36–39], so we consider the code and its results validated.

The mesh has a size of (768, 251, 1152) points, which provides a resolution of 8.2 and 4.1 wall units in x and z , respectively. The wall-normal grid spacing is adjusted to keep the resolution at $\Delta y = 1.5\eta$, i.e., approximately constant in terms of the local isotropic Kolmogorov scale $\eta = (v^3/\varepsilon)^{1/4}$. In wall units, Δy^+ varies from 0.37 at the wall to $\Delta y^+ \simeq 2.68$ at the centreline. This grid size is similar to that commonly used in DNS of Poiseuille and Couette channel flows [35,40]. The simulations were run for at least 25 ETT in order to obtain accurate statistical information [41].

In addition to the $Re_\tau \approx 250$ dataset used throughout the main analysis, we also considered a higher-Reynolds-number case in order to assess the percolation behaviour and the corresponding threshold indices beyond the reference configuration. For this purpose, we used one of the datasets generated in the study of Hoyas et al. [41], corresponding to a sim-

ulation at $Re_\tau = 1000$ in a computational box of size $16\pi h \times 2h \times 3\pi h$. The computational cost of this case is approximately 100 times larger than that of the $Re_\tau \approx 250$ simulation, which explains why, within the scope of the present work, this higher-Reynolds-number dataset has been used specifically for the percolation study.

2.3. Wall-Dependent Identification of Low-Speed Streamwise Streaks

The pointwise identification relies on applying a specified filter to the instantaneous velocity fields of the Couette–Poiseuille dataset (Table 1). The choice of filter depends on the type of coherent structure to be identified, being, in this study, low-speed streamwise streaks.

The initial proposal by Bae and Lee [21] states that the points belonging to a low-speed streak must fulfil the following conditions:

$$u(x, y, z) < 0, \quad (3)$$

$$\sqrt{u^2(x, y, z) + w^2(x, y, z)} > \alpha u_\tau, \quad (4)$$

where u_τ is the friction velocity and α is the percolation index for the identification of low-speed streamwise streaks.

The condition in Equation (4) employs a constant threshold defined by the friction velocity. However, as stated in the Introduction (Section 1), wall-dependent thresholds are preferable for the identification of coherent structures in wall-bounded flows. In this sense, Nagaosa and Handler [22] defined at least two conditions that a wall-dependent threshold shall accomplish:

1. The rms-average of the filtered quantity shall have a strong variation along the wall-normal direction. This fact suggests that the use of a constant threshold cannot simultaneously capture the dynamics of both the near-wall and outer areas.
2. After redefining the threshold condition as $\chi(x, y, z)/\chi'(y) > \beta$, the probability density function of $\chi(x, y, z)/\chi'(y)$ shall collapse when evaluated at diverse wall-normal distances. Here, χ can be any kind of magnitude, such as the wall-parallel velocity magnitude defined in Equation (4).

The streak identification condition (Equation (4)) was evaluated against the requirements presented by Nagaosa and Handler [22]. The first condition is depicted in Figure 1a. Here, the rms of the quantity $\chi = \sqrt{u^2(x, y, z) + w^2(x, y, z)}$ is plotted along the wall-normal direction. Peaks on the rms-average are observed in the near-wall area in all cases. A strong decay is observed in the channel centre for the pure Poiseuille case (pink), while the pure Couette case (black) defines a plateau along the outer area. Figure 1b,c depict the second condition for the pure Poiseuille and Couette cases, respectively. In both figures, the probability density function of $\chi(x, y, z)/\chi'(y)$ collapses very well at $y^+ \geq 50$. The deviation of the curves near the wall (here at $y^+ < 50$) was also observed by Nagaosa and Handler [22] in their study.

Based on the results plotted in Figure 1, the identification of low-speed streaks can be redefined using a wall-dependent threshold as

$$u(x, y, z) < 0, \quad (5)$$

$$\chi(x, y, z) > \alpha \chi'(y), \quad (6)$$

with $\chi = \sqrt{u^2(x, y, z) + w^2(x, y, z)}$ being the wall-parallel velocity magnitude.

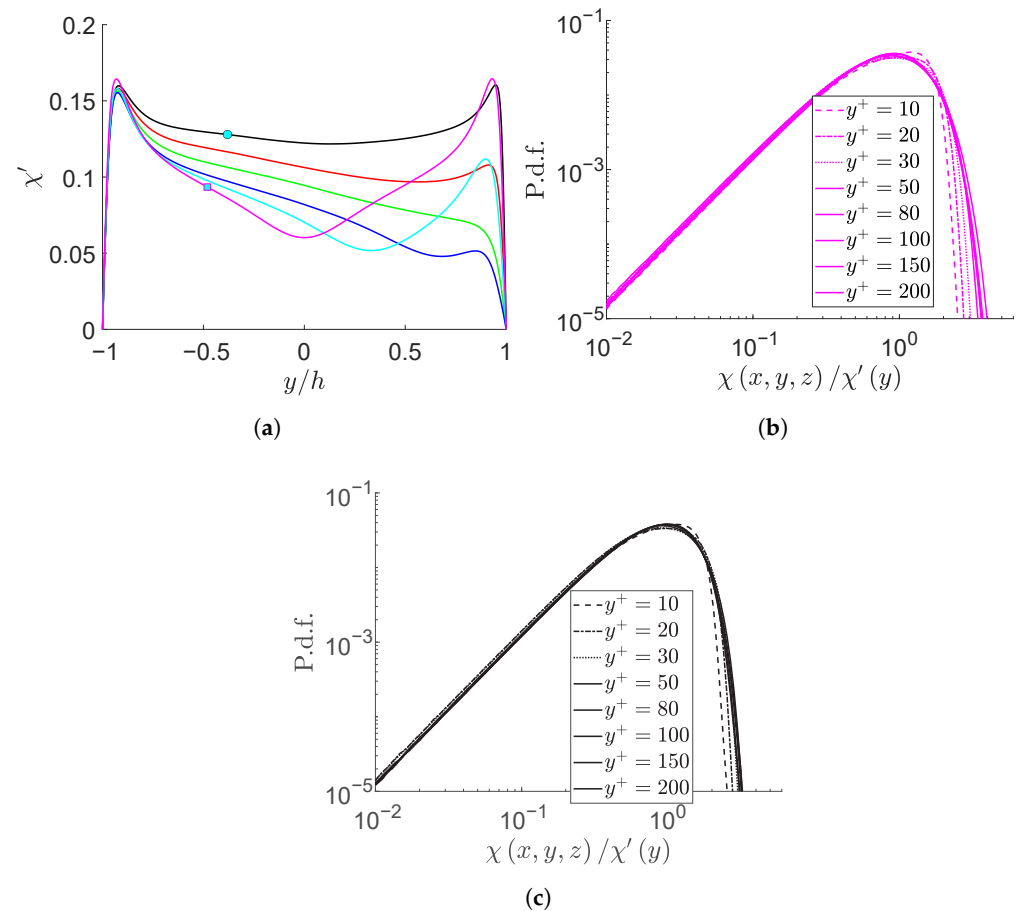


Figure 1. Lines as in Table 1. (a) Root-mean-square of the wall-parallel velocity magnitude χ' as defined in Equation (6) along the wall-normal direction y/h . (b) Probability density function of χ/χ' at diverse wall-normal distances for a pure Poiseuille channel flow at $Re_\tau \simeq 250$. (c) Probability density function of χ/χ' at diverse wall-normal distances for a pure Couette channel flow at $Re_\tau \simeq 250$.

2.4. Percolation Analysis and Clustering

The percolation index for streaks (6) is estimated through percolation analysis [11,13,15,21]. In this analysis, a set of potential percolation indexes is selected, and the conditions (Equations (3) and (6)) are evaluated for each index in the selected interval. For each index, a volume ratio $V_{\max}/V_{\text{tot}}$ and a ratio of identified objects $N/\max(N)$ are calculated. The former compares the maximum volume of a single streak ($V_{\max}$) against the whole identified volume (V_{tot}). The latter compares the number of identified streaks at each index ($N(\alpha)$) against the maximum number of streaks among all indices ($\max(N(\alpha))$).

Figure 2 shows the results of the percolation analysis for low-speed streamwise streaks. In the figure, the volume ratio $V_{\max}/V_{\text{tot}}$ tends to unity at low percolation values. Here, the scenario comprises a very large coherent structure that merges most identified points and several small structures without a relevant volume proportion. On the other hand, at high percolation ratios, both the volume ratio and the ratio of identified objects $N/\max(N)$ become small, resulting in very few but very intense structures. The percolation index is selected where the ratio of identified objects reaches unity, enabling the identification of the maximum number of structures. Additionally, the volume ratio shall fall from unity and undergo a percolation crisis [11], which in Figure 2 occurs at $1 \leq \alpha \leq 1.5$. Using this criterion, the percolation index (α) for all cases is selected at 1.6 (Table 1). Small variations in the indices do not alter the qualitative or quantitative results of the analysis,

as this was tested at $\alpha = 1.9$. In our case, all reported results remain essentially unchanged under reasonable perturbations of α in the range after the percolation crisis.

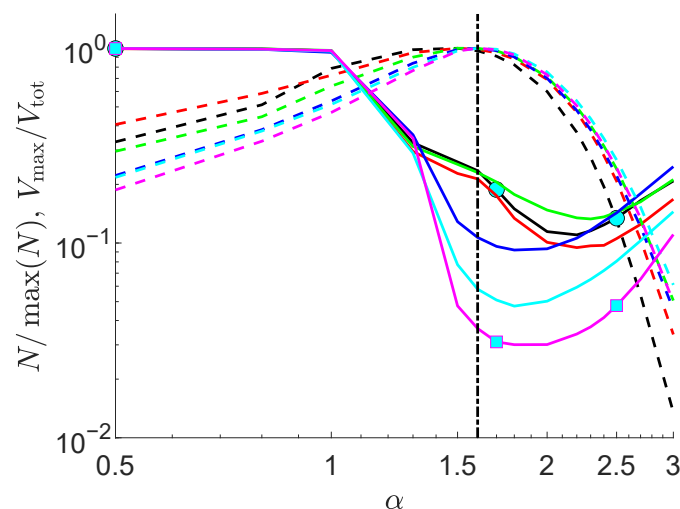


Figure 2. Lines as in Table 1. Percolation study for identifying low-speed streamwise streaks. At each percolation index, the curves depict the ratio of the volume of the largest identified object against the volume of all identified objects $V_{\max}/V_{\text{tot}}$ (solid lines) and the ratio of the number of identified objects against the maximum number of objects $N/\max(N)$ (dashed lines). To avoid the inclusion of many small structures, those with a volume $V^+ \leq 30^3$ were excluded from the study. The vertical dotted-dashed line at $\alpha = 1.6$ denotes the selected percolation index.

Once the percolation index is selected, coherent structures are defined by connecting identified points in the six orthogonal directions of the direct numerical simulation Cartesian mesh. This algorithm is detailed by Gandía-Barberá et al. [42]. Once the clusters satisfying the threshold are built, three-dimensional coherent structures with a volume less than 30^3 wall units are discarded to reduce noise in identifying structure interactions [11].

Each identified streak is contained within a Cartesian box aligned with the simulation domain axes [21]. The box's length, width, and height are defined by the parameters Δx , Δz , and Δy , respectively. Streaks tend to be meandering objects with complex geometries; therefore, streak volume cannot be measured as the volume of the containing box. Indeed, each streak's volume is measured as the sum of the volume of the individual structure voxels, defined as in Lozano-Durán et al. [43].

2.5. Percolation Analysis at Higher Reynolds Number

In order to assess the behavior of the identification criterion at higher Reynolds numbers, we first carried out the percolation analysis for the $Re_\tau = 1000$ case [41]. The resulting curves are shown in Figure 3. In both definitions, the behavior is consistent with expectations from the percolation framework, and the percolation crisis remains abrupt. This indicates that the threshold-selection procedure is still well defined at higher Reynolds numbers and that the transition between disconnected and percolating structures can be identified clearly in both cases, with similar values.

To better understand the physical implications of the two criteria, Figure 4 presents a direct comparison between streaks identified with the classical u_τ -based threshold (in red) and with the wall-dependent threshold (in blue). The three-dimensional visualization (Figure 4a,b) shows that the classical definition is strongly conditioned by the near-wall region, whereas the wall-dependent criterion remains approximately uniform in relative intensity along the wall-normal direction, as it measures the intensity of the fluctuations with respect to the local wall distance [22].

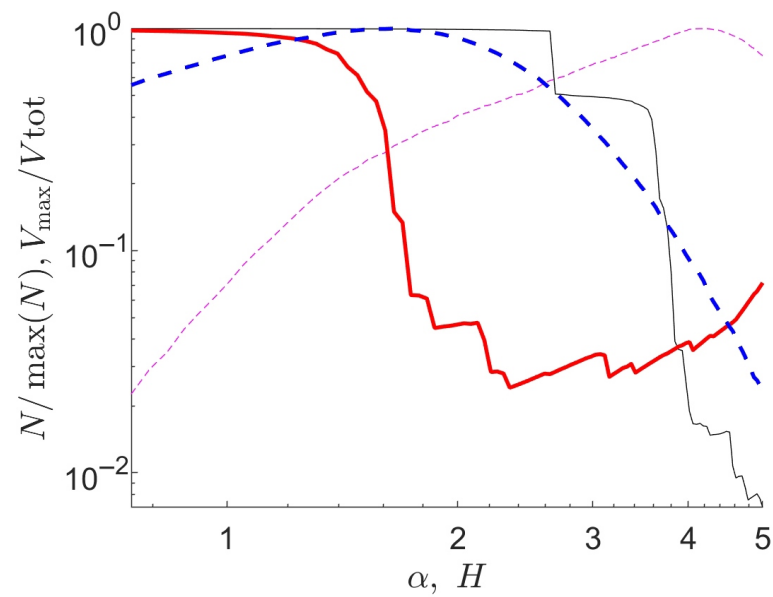


Figure 3. Percolation study for the classical criterion (thin lines) and the wall-dependent criterion (thick lines). Solid lines represent the volume ratio (red, black), whereas dashed lines represent the ratio $N/N_{\max}$ (blue, cyan).

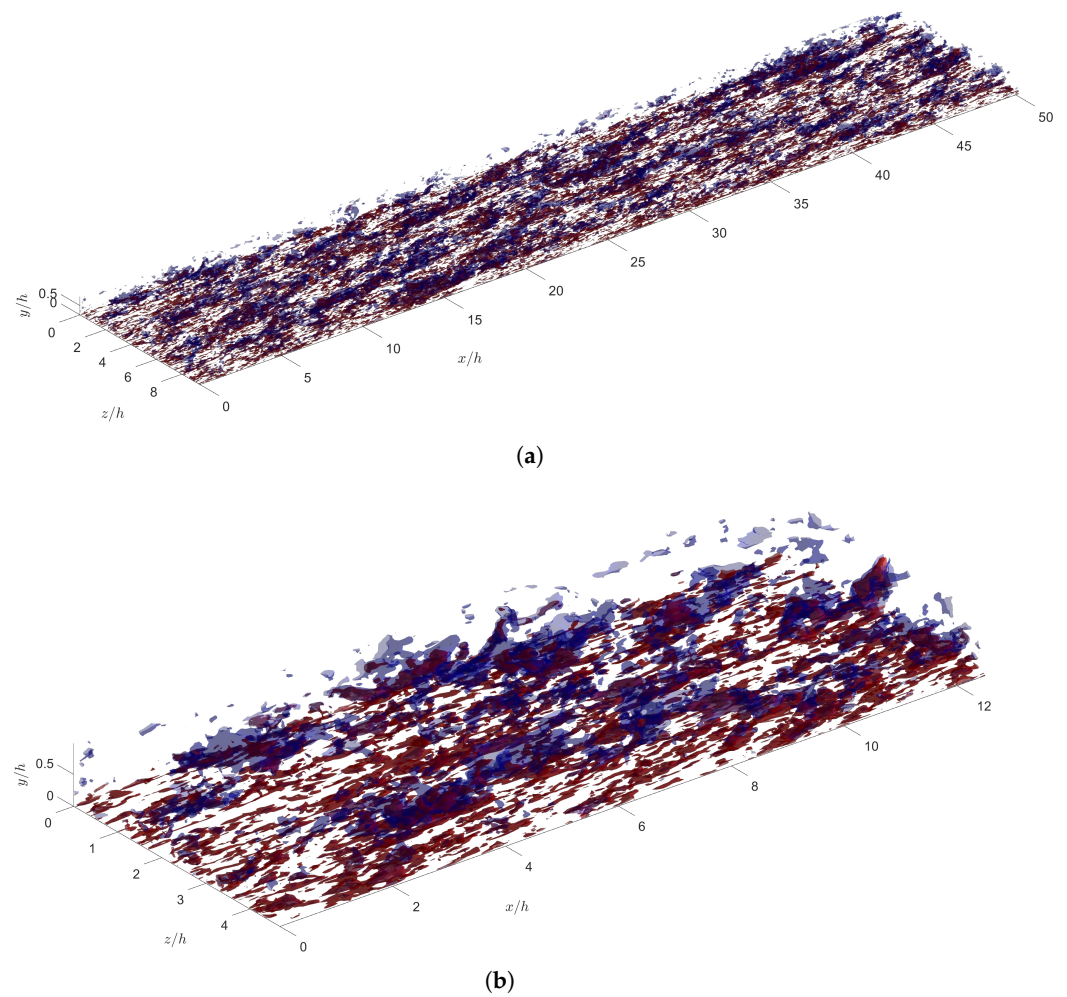


Figure 4. Cont.

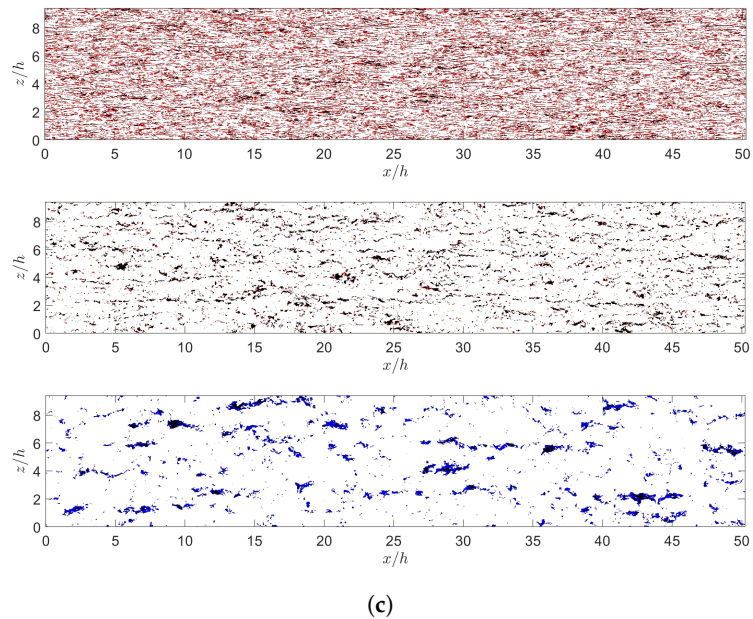


Figure 4. Instantaneous streaks identified in the turbulent flow field. Red corresponds to streaks obtained with the classical u_τ -based criterion, whereas blue denotes streaks identified with the wall-dependent criterion. (a) Three-dimensional view of the streaks in the $Re_\tau = 1000$ case, in a domain of size $16\pi h \times 2h \times 3\pi h$. (b) Zoomed view of the upper-left corner of panel (a). (c) Cross-sectional distribution of the identified points in planes at $y^+ = 15$ (top), $y^+ = 170$ (middle), and $y^+ = 700$ (bottom).

This behavior is illustrated in Figure 4c, where points identified only by the classical criterion are shown in red, those identified only by the wall-dependent criterion in blue, and the common points in black for three different heights. This situation is also shown in Figure 5. At both the end of the viscous sublayer and the beginning of the outer region, the overlap between the two criteria reaches its highest values, with almost 100%. However, farther from the wall, the classical u_τ -based streaks almost disappear Figure 4c (bottom), while the wall-dependent ones remain detectable.

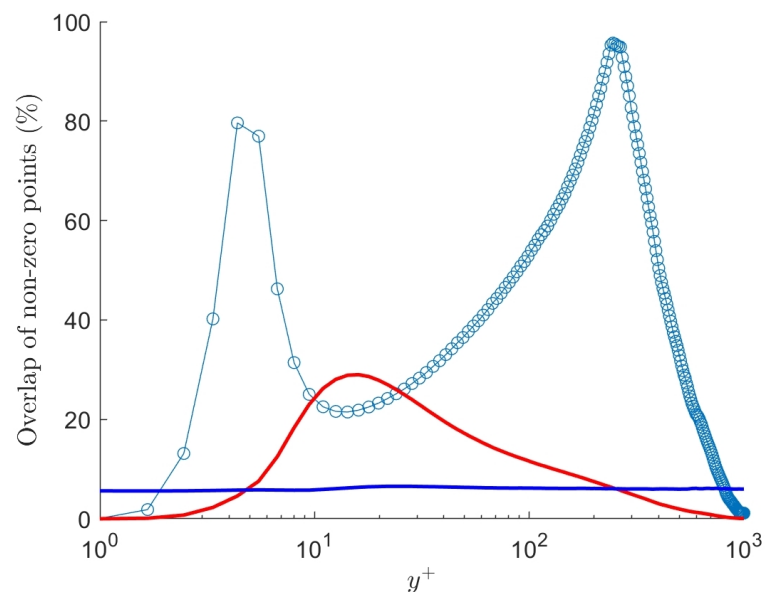


Figure 5. Comparison between the two identification criteria. Red denotes the percentage of points attributed to streaks using the classical u_τ -based definition. Dark blue denotes the corresponding percentage obtained with the wall-dependent criterion. Blue circles represent the overlap between both identifications.

3. Results

This section presents the main statistical trends of the identified streamwise streaks in the form of probability density functions (PDFs). The definitions of the heading and elevation angles, as well as the classification into attached and detached families, are introduced in Section 3.1. The relative distance between streaks is defined in Section 3.2.

3.1. Geometry and Topology of Individual Streaks

Streaks and other coherent structures in wall-bounded turbulence are often classified according to their distance from the nearest wall [9,13,21]. Figure 6 shows the joint probability density function (PDF) of the wall-normal distances from the bottom ($y_{\min}^+$) and top ($y_{\max}^+$) of each streak to the closest wall for the cases listed in Table 1. In all cases, two regions contain at least 50% of the total probability. These regions are separated by a transition zone of lower density around $y_{\min}^+ = 20$. This value therefore provides a natural criterion to distinguish two types of streaks: wall-attached and wall-detached [13,15,17,21]. The former, hereafter referred to as attached streaks, satisfy $y_{\min}^+ \leq 20$, whereas the latter, detached streaks, satisfy $y_{\min}^+ > 20$.

Attached streaks lie too close to the wall to show a clear scaling trend in this representation. By contrast, detached streaks follow a well-defined relation, $y_{\max}^+ \propto (y_{\min}^+)^{0.73}$, in all cases. This suggests that the height of detached streaks is less sensitive to the specific forcing mechanism of each Couette–Poiseuille configuration. This behaviour is consistent with the fact that detached streaks are more isotropic than attached ones [21] and are typically associated with smaller-scale motions, often of the order of the Kolmogorov scale [13]. As a result, detached streaks interact less directly with the mean shear and display a more similar growth across all Couette–Poiseuille cases.

The analysis of the circumscribing-box dimensions of the identified streamwise streaks provides information on how these structures grow along each Cartesian direction. Their self-similarity can be assessed from the probability density functions (PDFs) of the dimensional ratios derived from the box dimensions, shown in Figure 7 [44]. In all cases, a good collapse of the distributions is observed for both attached and detached streaks, indicating that the two families retain well-defined geometric trends across the different Couette–Poiseuille configurations.

Attached streaks tend to cluster around a streamwise ratio $\Delta x / \Delta y = 3.3$ and a spanwise ratio $\Delta z / \Delta y = 0.73$. They therefore form a self-similar family with characteristic aspect ratios

$$\Delta x \approx 3.3 \Delta y \approx 4.52 \Delta z, \quad (7)$$

whereas detached streaks tend to exhibit $\Delta x / \Delta y = 1$ and $\Delta z / \Delta y = 0.82$, yielding

$$\Delta x \approx \Delta y \approx 1.22 \Delta z. \quad (8)$$

These results show that the distinction between attached and detached families remains robust under the new wall-dependent criterion. This is in itself an important result, since it indicates that the main geometrical separation between the two families is not an artefact of the identification procedure. At the same time, the comparison with Gandía-Barberá et al. [17], who used the constant threshold of Equation (4), reveals a clear and physically relevant difference. While most of the dimensional trends remain qualitatively unchanged, the ratio $\Delta x / \Delta y$ of attached streaks is systematically reduced when the wall-dependent threshold of Equation (6) is used. In other words, the new criterion identifies attached streaks that are consistently shorter in the streamwise direction in all cases listed in Table 1. This indicates that the constant-threshold approach tends to overestimate the streamwise extent of attached streaks, whereas the wall-dependent criterion provides

a more balanced identification across the wall-normal direction, in agreement with the behaviour shown in Figure 1b,c. The new result is therefore not simply a repetition of the previous analysis, but a quantitative indication of which geometric properties are robust and which are sensitive to the threshold definition.

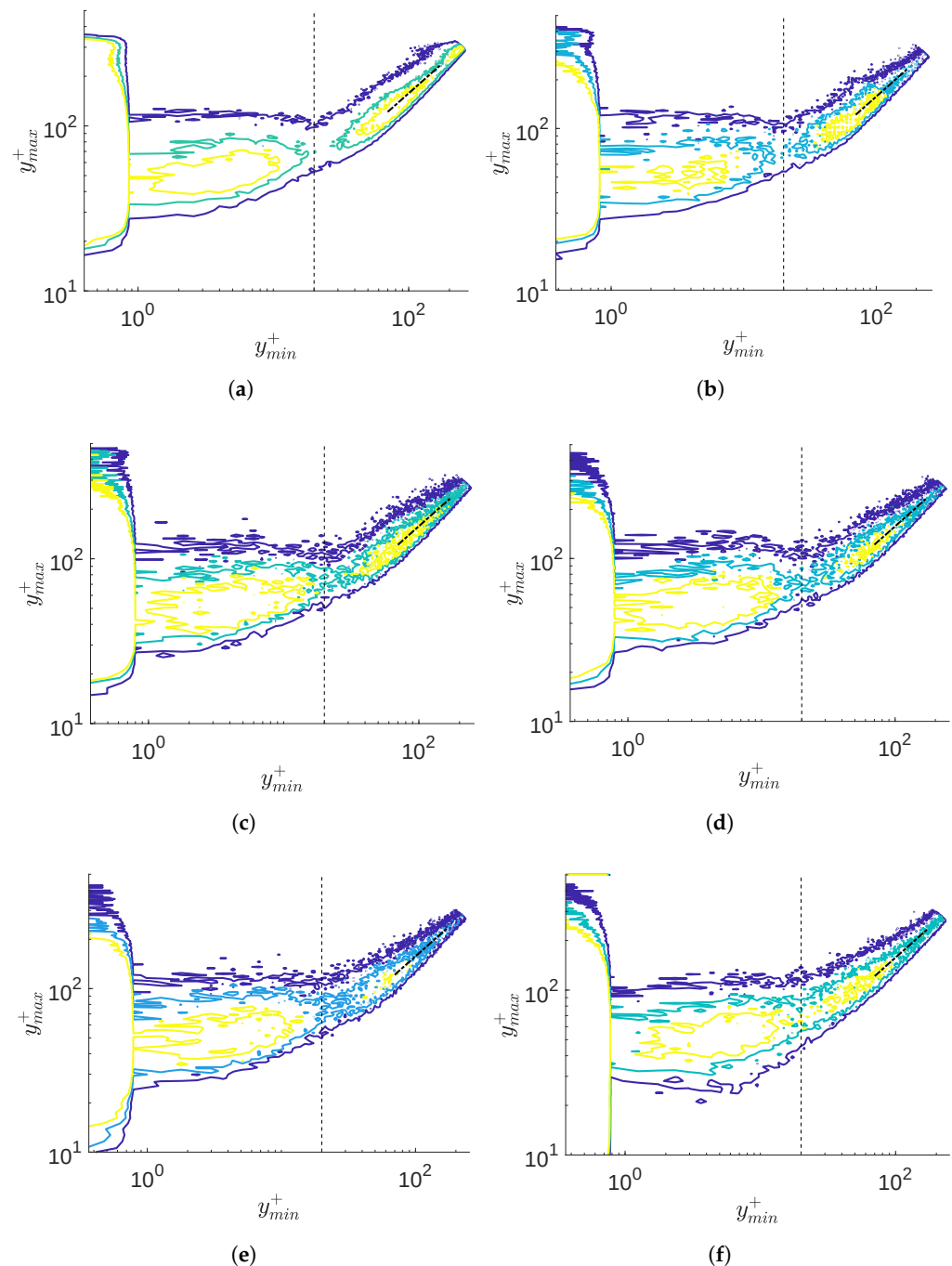


Figure 6. Joint PDF of the wall-normal distance to the closest domain wall from streak bottom ($y_{\min}^+$) and top ($y_{\max}^+$). Top row: cases C00P10 (a) and C02P08 (b). Middle row: cases C04P06 (c) and C06P04 (d). Bottom row: cases C08P02 (e) and C10P00 (f). Contours contain 50% (dark blue), 70% (light blue), and 90% (yellow) of the total data. The dash-dotted line $y_{\max}^+ \propto (y_{\min}^+)^{0.73}$ is for detached streaks.

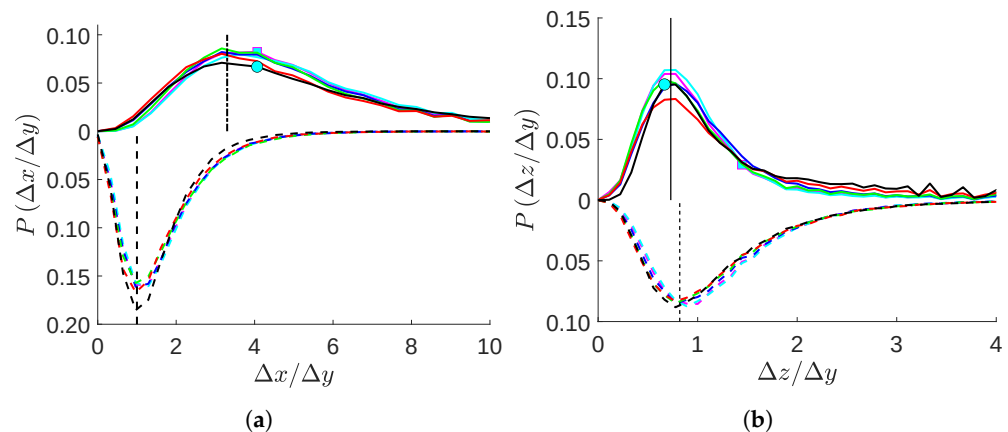


Figure 7. Lines as in Table 1. Solid lines correspond to attached streaks, dashed lines to detached streaks. (a) PDF of the aspect ratio $\Delta x/\Delta y$ of the identified streaks. (b) PDF of the aspect ratio $\Delta z/\Delta y$ of the identified streaks. Vertical lines in (a) mark $\Delta x/\Delta y = \{1.0, 3.3\}$; vertical lines in (b) mark $\Delta z/\Delta y = \{0.73, 0.82\}$.

Moving to the topology of the identified streaks, these structures are typically elongated and meandering, which makes it convenient to define a simpler geometric representation to study their spatial orientation [45]. To this end, a spline is constructed for each streak by computing its centre of mass in every Δy – Δz plane [21]. The spline points (x_s, y_s, z_s) are then used to generate a linear approximation of the form $(x_s, A_2x_s + B_2, A_3x_s + B_3)$ using a least-squares fit, where

$$A_k = \frac{N \sum_{i=1}^N x_{s_i} x_{k_i} - \sum_{i=1}^N x_{s_i} \sum_{i=1}^N x_{k_i}}{N \sum_{i=1}^N x_{s_i}^2 - \left(\sum_{i=1}^N x_{s_i} \right)^2},$$

$$B_k = \frac{\sum_{i=1}^N x_{k_i} \sum_{i=1}^N x_{s_i}^2 - \sum_{i=1}^N x_{s_i} \sum_{i=1}^N x_{s_i} x_{k_i}}{N \sum_{i=1}^N x_{s_i}^2 - \left(\sum_{i=1}^N x_{s_i} \right)^2},$$
(9)

with N denoting the number of spline points and $k = \{2, 3\}$, where $x_2 = y_s$ and $x_3 = z_s$.

The elevation and heading angles of the streaks, as well as their meandering, are then computed from this linear approximation with respect to the Cartesian box, following Gandía-Barberá et al. [17]. The elevation angle (θ) and heading angle (ψ), in radians, are defined as

$$\theta = \arctan(A_2),$$

$$\psi = \arctan(A_3).$$
(10)

The streak meandering (ϵ) is taken as the root-mean-square of the distance between the spline and its linear approximation at each x_s location, as in Kevin et al. [45].

Streaks are further analysed in terms of their heading and elevation angles, as defined in Equation (10). The PDF of the heading angle (Figure 8a) is centred at $\psi = 0^\circ$ and is symmetric about this value for both attached and detached streaks. This symmetry is likely related to the periodic boundary conditions imposed in the x – z plane of the numerical domain. Attached streaks remain largely confined within $\pm 10^\circ$, whereas detached streaks display a wider distribution, extending up to approximately $\pm 20^\circ$.

The PDF of the elevation angle (Figure 8b) shows a different behaviour. Attached streaks are centred around $\theta = 3.5^\circ$ and exhibit a clear asymmetry, which can be linked to the non-uniform mean shear induced by the impermeable wall and to the resulting constraint on the inclination of structures relative to the free stream [6]. Detached streaks

display, on average, a somewhat larger elevation angle, consistent with their position farther from the wall. However, the mean values of the heading and elevation angles remain broadly similar across all Couette–Poiseuille configurations for both attached and detached streaks. This is also a relevant result, since it indicates that the main effect of the wall-dependent threshold is not on the overall orientation of the structures, but rather on their extracted streamwise extent. In other words, the new criterion modifies primarily the geometry of the identified attached streaks without altering the general topological trends that remain common to all cases.

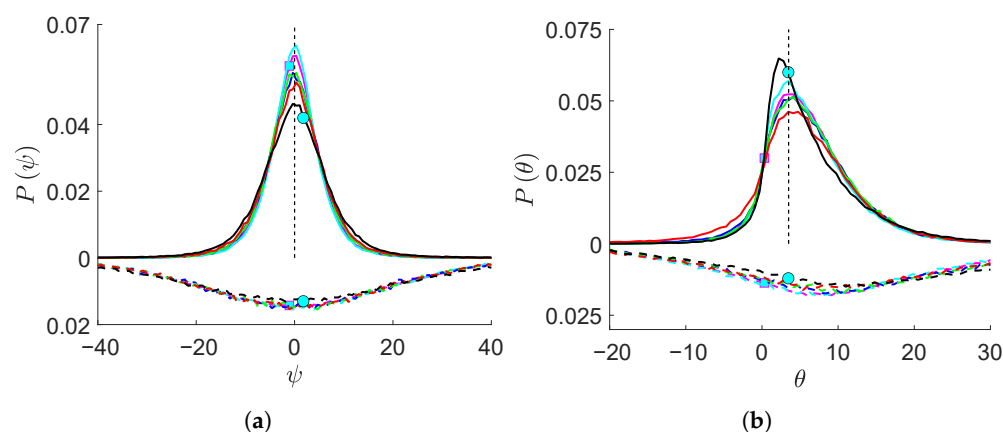


Figure 8. Lines as in Table 1. Solid lines correspond to attached streaks and dashed lines to detached streaks. (a) PDF of the heading angle ψ (in degrees) of the identified streaks. The vertical dashed line is located at $\psi = 0^\circ$. (b) PDF of the elevation angle θ (in degrees) of the identified streaks. The vertical dashed line is located at $\theta = 3.5^\circ$.

Following the topological analysis above, Figure 9a,b show the distributions of streak meandering and streak volume, respectively, as functions of streak height. The streak meandering increases with streak height [21,45] and follows the scaling $(\Delta y^+)^{1.5}$, in agreement with the behaviour previously reported in Ref. [17]. Likewise, the streak volume, measured in voxels, grows with streak height according to a power law close to $(\Delta y^+)^{2.5}$. Interpreted as an effective fractal dimension [13,14], this result suggests that attached streaks resemble shell- or flake-like objects. In both quantities, the scaling is lost for structures with $\Delta y^+ \leq 10$, whose growth is directly constrained by the proximity of the wall.

The agreement of these trends with the results obtained using the constant threshold is also relevant. It indicates that the meandering and volumetric growth of attached streaks are robust properties, largely independent of the precise thresholding strategy. In other words, the wall-dependent criterion does not modify the overall topological scaling of the structures, but mainly affects how their streamwise extent is extracted, as discussed above. This helps separate those properties that are intrinsic to the streaks from those that are more sensitive to the identification method.

3.2. Spatial Configuration of Paired Streaks

The non-dimensional relative position between two structures i and j is defined as

$$\bar{\delta}^{(i,j)} = \frac{\bar{x}_{\text{mc}}^{(j)} - \bar{x}_{\text{mc}}^{(i)}}{\bar{\Delta y}^{(i,j)}}, \quad (11)$$

where $\bar{x}_{\text{mc}}^{(i)}$ is the Cartesian position vector of the mass centre of structure i . Following Lozano-Durán et al. [13], Osawa and Jiménez [14], the relative position $\bar{\delta}^{(i,j)}$ is normalised with the mean wall-normal height of the selected pair, $\bar{\Delta y}^{(i,j)} = (\Delta y^{(i)} + \Delta y^{(j)})/2$.

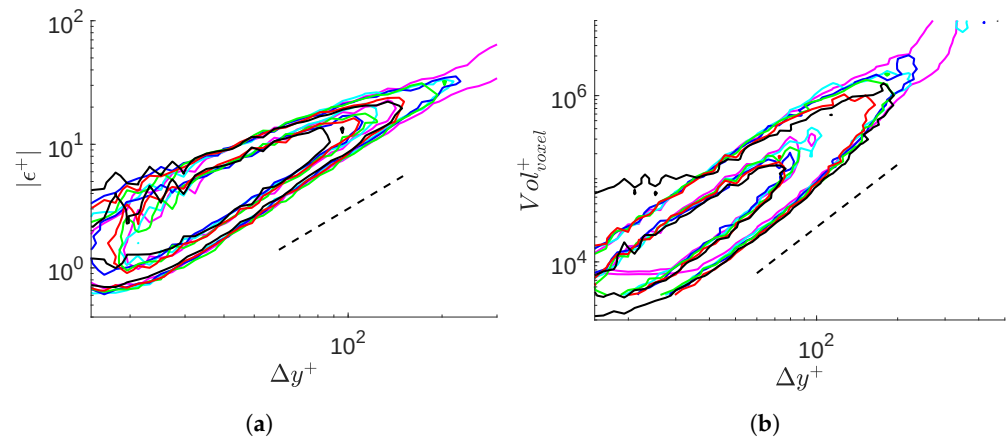


Figure 9. Lines as in Table 1. (a) Joint PDF of streak height versus streak meandering. The dashed line is $(\Delta y^+)^{1.5}$. (b) Joint PDF of streak height versus streak volume measured in voxels. The dashed line is $(\Delta y^+)^{2.5}$. In both panels, only attached structures are considered. All quantities are expressed in wall units. Contours contain 50% and 90% of the total data.

The relative position is measured only for structures of similar size [12,13,46], using the condition

$$1/2 < \Delta y^{(j)} / \Delta y^{(i)} < 2. \quad (12)$$

Gandía-Barberá et al. [17] reported a global redistribution of streaks along the spanwise direction of the domain. The pair analysis presented here extends that observation by showing how this redistribution modifies the relative distances between structures, providing a more direct description of the spatial organisation induced by the different Couette–Poiseuille configurations.

Figure 10a,b show the PDFs of the closest relative position between two attached streaks for the pure Poiseuille (C00P10) and pure Couette (C10P00) cases, respectively. In C00P10, attached streaks are predominantly aligned in the spanwise direction with a relative distance $\delta z \approx 1.4$, where δz is the spanwise component of $\vec{\delta}^{(i,j)}$ in Equation (11). In C10P00, this separation increases to $\delta z \approx 2.0$, and a secondary population of streaks appears with streamwise alignment at $\delta x \approx 2.5$, which is absent in the pure Poiseuille case. This is a clear indication that the change in forcing does not simply redistribute the streaks globally, but also alters the preferred spatial arrangement of attached pairs.

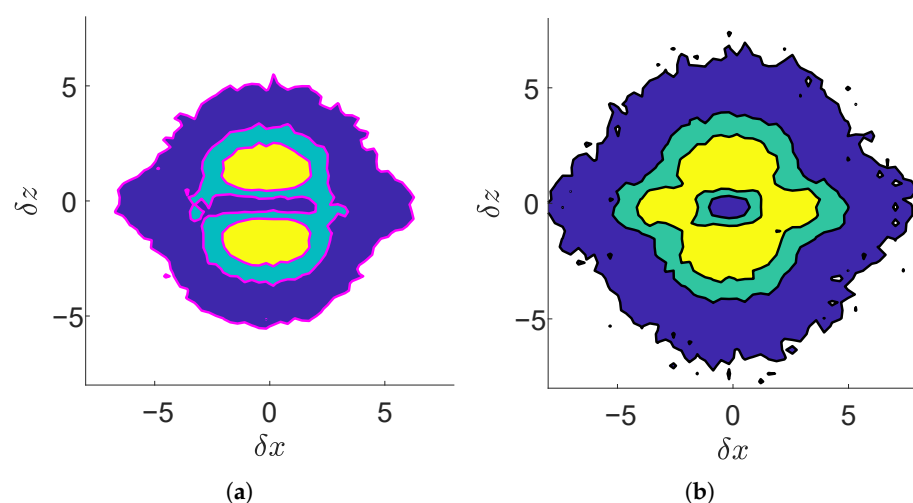


Figure 10. Cont.

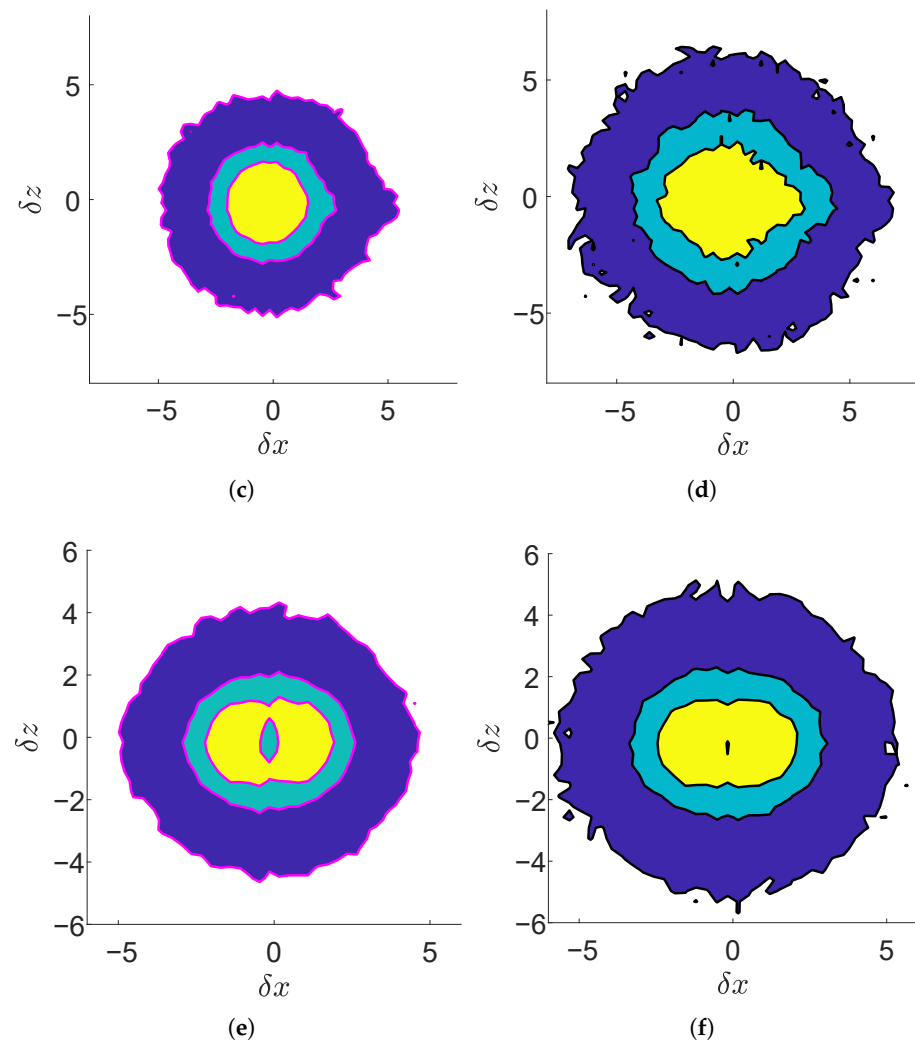


Figure 10. Two-dimensional PDFs of the closest relative position of (a,b) two attached streaks, (c,d) one attached and one detached streak, and (e,f) two detached streaks. The left column corresponds to case C00P10 and the right column to case C10P00. Contours contain 30% (dark blue), 50% (light blue), and 80% (yellow) of the total data.

Figure 10c,d display the relative position of pairs formed by one attached and one detached streak. In both pure Poiseuille and pure Couette flows, the distribution is nearly isotropic in the streamwise (δx) and spanwise (δz) directions, with 50% of the structures separated by less than two characteristic heights. This behaviour appears to be remarkably robust across the two limiting configurations. Detached streaks are commonly found downstream of the attached streak from which they originate after detachment [21]; however, in the present study the minimum distance between structures is computed without tracking their individual history.

Finally, Figure 10e,f show the relative distance between pairs of detached streaks. These structures tend to align in the streamwise direction, with an average separation $|\delta x| \leq 2$. The formation of detached streaks has been related to streak breakup induced by strong ejection or bursting events, conditioned on the presence of a Q2 structure [47]. Since Q2 structures are also known to form streamwise-aligned pairs in turbulent Poiseuille channel flows [13], the present result suggests that detached streaks retain part of that same spatial organisation. This provides an additional physical link between detached streaks and the bursting dynamics associated with ejections.

4. Conclusions

In this work, we have proposed a wall-dependent identification procedure for low-speed streamwise streaks in turbulent channel flows. The motivation for introducing this criterion was the well-known limitation of uniform thresholds in wall-bounded turbulence: when the threshold is chosen to properly capture the near-wall structures, very few objects remain visible farther from the wall, whereas lowering it to recover outer-layer motions produces an excessive concentration of structures close to the wall. Following the ideas of Bae and Lee [21] and the wall-dependent requirements discussed by Nagaosa and Handler and Del Álamo et al. [11,22], we reformulated the streak-identification procedure and applied it to a Couette–Poiseuille dataset at $Re_\tau \approx 250$. The percolation analysis gave an optimal value of $\alpha = 1.6$, located at the end of the percolation crisis and associated with the maximum number of identified structures. Testing a larger value, $\alpha = 1.9$, led only to minor differences, which supports the choice of the selected threshold.

To check whether this behaviour persists beyond the reference case, we also repeated the percolation analysis for a higher-Reynolds-number simulation at $Re_\tau = 1000$. In that case, the percolation crisis was again abrupt and easy to identify for both the classical and the wall-dependent definitions. Although this does not constitute a systematic high-Reynolds-number study, it does show that the threshold-selection procedure remains meaningful at larger Reynolds numbers.

The comparison between the classical u_τ -based definition and the wall-dependent one provides the main message of this paper. Several of the global trends obtained with the new method remain consistent with those found previously, which is important because it shows that the classification into attached and detached streaks is not an artefact of the identification procedure. At the same time, the comparison makes clear which properties are sensitive to the threshold choice. In particular, the classical definition is strongly dominated by the near-wall region and leads to an apparent disappearance of streaks farther from the wall, while the wall-dependent approach preserves a more balanced identification across the wall-normal direction.

The identified structures can still be separated into wall-attached and wall-detached families, with a transition region at $y_{\min}^+ = 20$. Both families retain clear self-similar geometrical trends. Attached streaks are elongated in the streamwise direction, whereas detached streaks are more isotropic and show less dependence on the specific Couette–Poiseuille forcing. One of the clearest quantitative differences introduced by the new definition is the reduction of the streamwise extent of attached streaks relative to the constant-threshold approach. This indicates that the classical method tends to overestimate their length.

The additional topological and spatial analyses lead to the same picture. The meandering and volumetric growth of attached streaks remain essentially unchanged, suggesting that these are robust properties of the structures themselves. By contrast, their extracted streamwise size is more affected by the thresholding strategy. The spatial arrangement of streaks also varies with the flow type. In pure Poiseuille flow, attached streaks are mainly aligned in the spanwise direction, whereas in pure Couette flow the spanwise separation increases and streamwise-aligned pairs also appear. Detached streaks, on the other hand, preferentially align in the streamwise direction, in a way that is consistent with their connection to bursting dynamics and intense Q2 events.

Overall, the main contribution of the present work is not simply to introduce a modified threshold, but to show more clearly how the definition itself affects the apparent organisation of streaks away from the wall. In that sense, the wall-dependent approach provides a more consistent basis for comparing structures across the channel and for interpreting their geometry and spatial distribution in wall-bounded turbulence.

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Abbreviations

The following abbreviations are used in this manuscript:

DNS	Direct Numerical Simulation
C-P	Couette–Poiseuille
PDF	Probability Density Function
ETT	Eddy Turnover Time
Re	Reynolds number
RMS	Root Mean Square

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