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Wall-based identification of coherent structures in wall-bounded turbulence

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Abstract. During the last decades, a number of reduced order models based on coherent structures have been proposed to describe wall-bounded turbulence. Many of these models emphasize the importance of coherent wall-normal velocity eddies (v-eddies), which drive the generation of the very long streamwise velocity structures observed in the logarithmic and outer region. In order to use these models to improve our ability to control wall-bounded turbulence in realistic applications, these v-eddies need to be identified from the wall in a non-intrusive way. In this paper, the possibility of using the pressure signal at the wall to identify these v-eddies is explored, analyzing the cross-correlation between the wall-normal velocity component and the pressure fluctuations at the wall in a DNS of a turbulent channel flow at Reτ = 939. The results show that the cross-correlation has a region of negative correlation upstream, and a region of positive correlation backwards. In the spanwise direction the correlation decays monotonously, except very close to the wall where a change of sign of the correlation coefficient is observed. Moreover, filtering the pressure fluctuations at the wall in space results in an increase of the region where the cross-correlation is strong, both for the positively and the negatively correlated regions. The use of a time filter for the pressure fluctuations at the wall yields different results, displacing the regions of strong correlation without changing much their sizes. The results suggest that space-filtering the pressure at the wall is a feasible way to identify v-eddies of different sizes, which could be used to trigger turbulent control strategies.

1. Introduction
Wall-bounded turbulence is one of the most ubiquitous features of engineering applications involving fluids. Typically, the engineer needs to control these turbulent motions, either damping (i.e., to reduce drag) or promoting them (i.e., to increase mixing). Reduced-order models of wall-bounded turbulence play a key role in the still-pending task of controlling turbulence, since they could allow the identification of the specific times and scales where the actuation is needed [1].

During the last decades, the community has witnessed the emergence of several of these reduced order models. Some of them are semi-empirical, based on observation of coherent structures [2] on canonical wall-bounded turbulent flows [3, 4, 5]. Some are time-periodic solutions of simpler wall-bounded flows [6], which can be related to the dynamics of fully turbulent flows [7]. In most of them, wall-attached vertical velocity (v) eddies (reminiscent of Townsend’s attached eddies [8]) are of special significance from a dynamical point of view, driving the generation of elongated streaks of streamwise velocity (u) through a linear amplification process [9]. The specific mechanisms by which the v-eddies are generated are less clear [10, 11, 12, 13], although there is agreement on the necessity of non-linearity in this part of
the cycle [14]. There is also reasonable agreement on that these \( v \)-eddies appear in all sizes, with heights ranging from the thickness of the buffer region to the thickness of the whole flow (i.e., the channel half-height or the boundary layer thickness).

From a technological point of view, the first step before using these reduced order models in any engineering application is to be able to identify these eddies with minimally-intrusive sensors at the walls. Two obvious choices are pressure taps or shear-stress sensors, where the latter should be more related to \( u \)-streaks and the former more related to \( v \)-eddies. Due to the central role of \( v \)-eddies in the generation of the streaks, and since it seems more reasonable to control the cause rather than the effect, the present work focuses on the detection of \( v \)-eddies from the pressure fluctuations at the wall. The choice is also motivated by previous works on the scaling of the spectra of the pressure fluctuations at the wall (\( p_w \)), which suggests that different frequency content on \( p_w \) might be related to turbulent sources at different wall-normal locations [15, 16]. Since then, several other authors have analysed the spectrum of the pressure fluctuations, using DNS using numerical [17, 18] or experimental data [19, 20], corroborating the scaling arguments mentioned above. Also, models for the wall-pressure have been formulated using structures based on Townsend’s attached eddy hypothesis [21], and some authors have linked specific features of the pressure fluctuations at the wall to coherent structures in the flow [22, 23].

Hence, the present paper focuses on the analysis of the cross-correlation between the pressure fluctuations at the wall and the wall-normal component of the velocity, using data from Direct Numerical Simulations (DNS) of turbulent channel flow. The specific objectives of this work are 1) to characterise the cross-correlation between the pressure fluctuations at the wall and the wall-normal velocity at different wall-distances, and 2) to evaluate if it is possible to discriminate \( v \)-eddies of a given size by filtering (in space or in time) the pressure fluctuations at the wall. The article is organized as follows: Section 2 presents the DNS details, as well as the definitions for the cross-correlation and the space and time filters. Section 3 presents the results for the un-filtered and filtered cases, and section 4 presents some conclusions.

2. Methodology

In order to evaluate the correlation between the wall-normal velocity component and the pressure fluctuations at the wall, a database with 1881 snapshots of a DNS of an incompressible turbulent channel flow is used. The turbulent channel flow has a friction Reynolds number \( Re_f = \frac{u_f h}{\nu} = 939 \), where \( u_f \) is the friction velocity, \( h \) is the half channel height and \( \nu \) is the kinematic viscosity. The snapshots cover a range of approximately \( 20 h/u_f \) eddy turn-over times, and they are approximately equidistant in time, at intervals of about \( \Delta t^{+} = 10 \). Note that throughout the paper, the + superscript indicates variables expressed in wall units (i.e., normalized with \( u_f \) and \( \nu \)).

The algorithm employed in the DNS is the same pseudo-spectral algorithm described in [24]. The simulation is run at a constant flow rate in a computational box of size \( L_x = 2\pi h \) and \( L_z = \pi h \) in the streamwise (\( x \)) and spanwise directions (\( z \)), respectively. These directions are periodic, and they are discretized with \( N_x = 512 \) and \( N_z = 512 \) Fourier modes, yielding a resolution in collocation points of \( \Delta x^{+} = 7.7 \) and \( \Delta z^{+} = 3.8 \). The discretization of the wall-normal direction (\( y \)) uses \( N_y = 385 \) Chebychev polynomials, resulting in a maximum grid spacing at the centre of the channel of \( \Delta y^{+} = 7.7 \). The wall is located at \( y = 0 \), and the channel centre is at \( y = h \).

The cross-correlation between the vertical velocity and the pressure fluctuation at the wall is defined as

\[
R_{v,pw}(x, y, z) = \langle pw(x', z', t')v(x' + x, y, z' + z, t') \rangle,
\]

where \( pw \) is the pressure fluctuation at the wall, \( v \) is the velocity component in the wall-normal direction, and the operator \( \langle \rangle \) indicates averaging over \( x', z' \) and \( t' \). The correlation depends
then on the horizontal separation \((x, z)\) between the points where \(p_w\) and \(v\) are measured, and on the wall-normal distance \(y\) at which \(v\) is measured. Note that no time lag between \(p_w\) and \(v\) is considered.

The cross-correlations between the vertical velocity and the filtered pressure fluctuations at the wall are defined analogously to equation 1. These cross-correlations are denoted \(R_{v,\tilde{p}_w}\) for the space filtered pressure fluctuations \((\tilde{p}_w)\), and \(R_{v,\pi_w}\) for the time filtered pressure fluctuations \((\pi_w)\).

The temporal filter is just a moving average over a characteristic time \(t_c\), hence the time-filtered pressure fluctuation is

\[
\bar{p}_w(x', z', t') = \frac{1}{t_c} \int_{t'-t_c}^{t'} p_w(x', z', t) dt.
\]

The spatially filtered pressure fluctuation at the wall is defined as

\[
\hat{p}_w(x', z', t') = \int_0^{L_x} \int_0^{L_z} p_w(x, z, t')K(x' - x, z' - z; l_c)dz dx,
\]

where \(K(x, z; l_c)\) is the kernel that defines the filter, and \(l_c\) is the characteristic length scale. Two kernels are considered in the present study for the spatial filter. Most of the results presented in section 3 correspond to a Gaussian filter,

\[
K(x, z; l_c) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{x^2 + z^2}{\sigma^2} \right),
\]

with a standard deviation \(\sigma = l_c/3\). For comparison, a circular top-hat filter of diameter \(l_c\) has also been considered,

\[
K(x, z; l_c) = \frac{4}{\pi l_c^2} \text{if } \sqrt{x^2 + z^2} \leq l_c/2; \quad K(x, z; l_c) = 0 \text{ otherwise.}
\]

Note that both kernels are normalized such that the integral of \(K(x, z; l_c)\) on the horizontal plane is one. Also, by choosing \(\sigma = l_c/3\), approximately 67% of the area of (4) lies inside the circle of diameter \(l_c\) defined by (5).

As usual, the unfiltered or filtered correlations are normalized with the corresponding standard deviations of \(p_w, \hat{p}_w\) and \(v\), to yield the correlation coefficients

\[
\rho_{v,p_w}(x, y, z) = \frac{R_{v,p_w}(x, y, z)}{\langle p_{w}^2 \rangle^{1/2} \langle v^2 \rangle^{1/2}},
\]

\[
\rho_{v,\hat{p}_w}(x, y, z) = \frac{R_{v,\hat{p}_w}(x, y, z)}{\langle \hat{p}_{w}^2 \rangle^{1/2} \langle v^2 \rangle^{1/2}},
\]

\[
\rho_{v,\pi_w}(x, y, z) = \frac{R_{v,\pi_w}(x, y, z)}{\langle \pi_{w}^2 \rangle^{1/2} \langle v^2 \rangle^{1/2}},
\]

where \(\langle p_{w}^2 \rangle, \langle \hat{p}_{w}^2 \rangle\) and \(\langle \pi_{w}^2 \rangle\) are constants and \(\langle v^2 \rangle\) is a function of the wall normal coordinate, \(y\).

3. Results

First, the correlation for the un-filtered wall pressure is characterized in figure 1, which shows a full three-dimensional view of \(\rho_{v,p_w}(x, y, z)\) as well as three different planes: the streamwise/wall-normal plane \(z = 0\) (figure 1b), a wall-parallel plane in the near-wall region at \(y^+ = 15\) (figure 1c) and a wall-parallel plane further away from the wall, at \(y = 0.1h\) (figure 1d). The solid and
Figure 1. Correlation coefficient $\rho_{v,p_w}(x,y,z)$, no filter. (a) Three-dimensional view. The plotted surfaces correspond to $\rho_{v,p_w} = [-0.1, -0.05, -0.025, 0.025, 0.05, 0.1]$, from blue to yellow (see colorbar in part b). The translucent plane is $z = 0$. (b) $\rho_{v,p_w}(x,y,z = 0)$. (c) $\rho_{v,p_w}(x,y^+ = 15, z)$. (d) $\rho_{v,p_w}(x,y = 0.1h, z)$. The back lines in (b − d) correspond to $\rho_{v,p_w} = -0.1$ (dashed) and 0.1 (solid). The colorbar in (b) is the same colorbar used in all panels.

dashed lines in figures 1b-d are $\rho_{v,p_w} = \pm 0.1$, which correspond also to the solid surfaces plotted in figure 1a. These regions ($|\rho_{v,p_w}| > 0.1$) will be referred to as the regions of strong correlation. Finally, note that the plane $z = 0$ is a symmetry plane for $\rho_{v,p_w}$, due to the statistical symmetry of the positive and negative $z$-directions in the turbulent channel flow.

Figure 1b shows that the correlation coefficient at $(x,y,z) = (0,0,0)$ is negative. This is the expected behaviour, since a negative (positive) wall-normal velocity should generate a positive (negative) pressure fluctuation at the wall. Figures 1a and b show that this negative correlation extends into a region that is tilted backwards, mostly upstream of the point where the pressure is measured. Although not apparent in the figure (the colorbar is saturated at $\pm 0.15$), the peak of negative correlation has a value of $(\rho_{v,p_w})_{\text{min}} = -0.43$, occurring at the wall, slightly upstream of the point where $p_w$ is measured ($x_{\text{min}}^+ = -10, y_{\text{min}}^+ = 0.5$). On the other hand, figures 1a and b also shows a relatively strong positive correlation region, tilted forward and occurring mostly downstream of the point where $p_w$ is measured. This positive correlation is somewhat weaker than the negative correlation (i.e., the peak value is $(\rho_{v,p_w})_{\text{max}} = 0.16$). Interestingly, the peak value is not attained at the wall, but within the near-wall region ($x_{\text{max}}^+ = 60, y_{\text{max}}^+ = 30$).

In terms of the spanwise structure of the correlation, figures 1c shows that the negatively
Figure 2. Evolution of the correlation coefficient using the space filtered pressure at the wall, \( \rho_{v,\tilde{p}_w}(x,y,z) \), for different filter lengths, \( l_c/h \). (a – c) Three-dimensional view. The plotted surfaces correspond to \( \rho_{v,p_w} = [-0.1, -0.05, -0.025, 0.025, 0.05, 0.1] \), from blue to yellow (see colorbar in part d). The translucent plane is \( z = 0 \). (a) \( l_c = 0.025h \). (b) \( l_c = 0.1h \). (c) \( l_c = 0.4h \). (d) \( \rho_{v,\tilde{p}_w}(x,y,z = 0) \). The shaded contours correspond to the unfiltered cases (\( l_c = 0 \)). The line contours correspond to \( \rho_{v,\tilde{p}_w} = 0.1 \) (solid) and \(-0.1\) (dashed). The line colour indicate the length of the spatial filter: \( l_c = 0 \) (unfiltered); \( l_c = 0.025h \); \( l_c = 0.1h \); \( l_c = 0.4h \);

The structure of the \( \rho_{v,p_w} \) shown in figure 1 is consistent with the conditional velocity fields obtained by [22], both for positive and negative pressure peaks. Indeed, the differences in the position and intensity of the peaks corresponding to \( \rho_{v,p_w}^{\min} \) and \( \rho_{v,p_w}^{\max} \) are consistent with the results of these authors, who obtained slightly different velocity structures when performing conditional averages for positive and negative pressure fluctuations. It is also interesting to note that the pressure fluctuations at the wall do not seem to be aware of the side-by-side organization of the \( v \)-velocity structures observed in previous works in the logarithmic and outer region [5]. In the pressure velocity correlation, this organization is only apparent in the near-wall region.

Next, the effect of filtering the pressure fluctuations in space is evaluated, using the Gaussian filter defined in equation (4). Figure 2 shows the effect of such filter on \( \rho_{v,\tilde{p}_w} \), for selected filter
Figure 3. (a) Peak value of the negative correlation coefficient \(-\rho_{v,pw}\) for different filter lengths, \(l_c/h\). (b) Characteristic lengths and wall-distances of the region of negative correlation, plotted versus the filter length, \(l_c/h\). Lines and symbols are: ——, \(l_y/h\); ○, \(y_c/h\); ▽, \(y_{min}/h\). Colors are black for the Gaussian filter (equation 4), blue for the cylindrical top-hat filter (equation 5). The dashed lines have logarithmic slopes of 1 and 1/2.

As the filter length increases, the regions of strong correlation (namely, \(|\rho_{v,pw}| > 0.1\)) become larger, extending further away from the wall. The inclination angle of these regions remains roughly the same, as it can be observed in the figure 2d. As a consequence, the streamwise separation also increases. Although not shown here, the results obtained filtering \(p_w\) with the top-hat filter defined in equation (5) are qualitatively similar, suggesting that the spatially averaged pressure fluctuations can be used to identify/discriminate \(v\)-eddies of different sizes.

In order to quantify the changes in the size and position of the regions of intense negative correlation, the vertical size \((l_y)\) and the wall-distance to the geometric centre \((y_c)\) of the volume satisfying \(-\rho_{v,pw} > 0.1\) are computed for a number of filter lengths, in the range \(l_c \in [0 - h]\). Figure 3 presents these values, together with the peak value of the negative correlation coefficient \((-\rho_{v,pw})_{min}\) and the wall-distance where this value is attained \((y_{min})\). The figure shows data from the two filters defined in the methodology section, equations (4) and (5), which agree remarkably well. This implies that the size of the \(v\)-eddies associated with different filters is roughly the same, irrespective of the details of the particular filter used. Of course, it might be necessary to adjust the cut-off length of the filters (in the present case, this is done by choosing the characteristic length of the Gaussian filter as 3 times the standard deviation).

It can be observed that for \(l_c \lesssim 0.05h \approx 50\nu/\nu_c\), the filter mostly reduces the value of the peak correlation (figure 3a), with little changes in \(y_{min}, l_y\) or \(y_c\) (figure 3b). In particular, \(y_{min} \approx 0\) for \(l_c \lesssim 0.05h\) (i.e., the point where the peak value of negative correlation is attained is at the wall). For \(0.05h \lesssim l_c \lesssim 0.3h\) the value of \((\rho_{v,pw})_{min}\) remains roughly constant, while \(y_c, l_y\) and \(y_{min}\) grow with a roughly constant logarithmic slope. For larger values of the filter length \((l_c \gtrsim 0.3h)\) the peak value of negative correlation starts to peel off, and for \(l_c \approx h\) the growth of \(y_c, l_y\) seems to saturate. Similar behaviour is observed for the sizes of the positively correlated region and for the lengths in the streamwise and spanwise directions of the regions of strong (negative and positive) correlation.

It is interesting to note that in figure 3b the logarithmic slope of the lengths associated the size of the region of strong correlation \((y_c \sim l_y \approx l_c^{1/2})\) is different than the slope of the wall-distance to the peak negative correlation \((y_{min} \approx l_c)\). At the present time, the reason for this difference is unclear. Also, the fact that \(l_y\) remains roughly proportional to \(y_c\) probably indicates that the
correlation coefficient is identifying $v$-velocity eddies that are attached to the wall, in the sense of being able to feel the presence of the wall, and not necessarily to reach to the wall [3, 26, 5].

Finally, the effect of filtering in time the pressure fluctuations at the wall is evaluated in figure 4, using the moving average filter defined in equation (2). The three-dimensional structure of the time-filtered $\rho_v \overline{p_w}(x, y, z)$ is shown in figures 4a, b and c, for $t_c \approx 0.01 h / u_\tau$, $0.01 h / u_\tau \approx 10 \nu / u_\tau^2$, $t_c = 0.02 h / u_\tau \approx 20 \nu / u_\tau^2$; $t_c = 0.04 h / u_\tau \approx 40 \nu / u_\tau^2$; $t_c = 0.08 h / u_\tau \approx 80 \nu / u_\tau^2$.

**Figure 4**. Evolution of the correlation coefficient using the time filtered pressure fluctuations at the wall, $\rho_v \overline{p_w}(x, y, z)$, for different averaging times, $t_c / h$. (a – c) Three-dimensional view. The plotted surfaces correspond to $\rho_v \overline{p_w} = [-0.1, -0.05, -0.025, 0.025, 0.05, 0.1]$, from blue to yellow (see colorbar in part d). The translucent plane is $z = 0$. (a) $t_c = 0.01 h / u_\tau$. (b) $t_c = 0.02 h / u_\tau$. (c) $t_c = 0.04 h / u_\tau$. (d) $\rho_v \overline{p_w}(x, y, z = 0)$. The shaded contours correspond to the unfiltered cases ($t_c = 0$). The line contours correspond to $\rho_v \overline{p_w} = 0.1$ (solid) and $-0.1$ (dashed). The line color indicates the averaging time in (2): $t_c = 0$ (unfiltered); $t_c = 0.01 h / u_\tau \approx 10 \nu / u_\tau^2$; $t_c = 0.02 h / u_\tau \approx 20 \nu / u_\tau^2$; $t_c = 0.04 h / u_\tau \approx 40 \nu / u_\tau^2$; $t_c = 0.08 h / u_\tau \approx 80 \nu / u_\tau^2$. The main effect of the time filter is to advect the correlation downstream, making the negatively correlated region more vertical. As shown in the representation of $\rho_v \overline{p_w}$ at the $z = 0$ plane depicted in figure 4d, this displacement is more apparent for the region of positive correlation and occurs with a small change in the size of the strongly correlated regions. Although not shown here, the peak values of the positive and negative correlations decay monotonously with the averaging time. Moreover, averaging times $t_c \gtrsim 0.1 h / u_\tau \approx 100 \nu / u_\tau^2$ result in loss of the correlation.

This loss of correlation is probably not surprising. Experimental data at very high Reynolds
numbers \( (Re_\tau \sim 10^5 - 10^6, \text{ see [19]} \) \) shows that the auto-correlation of \( p_w \) is \( \lesssim 1\% \) for \( tu_\tau/h > 0.025 \). At Reynolds numbers comparable to the present \( Re_\tau \), experiments [20] report that the duration of the pressure peaks at the wall is about \( t^+ \gtrsim 10 - 15 \), which are of the same order of magnitude as the \( t^+_c \) for which loss of correlation is observed in figure 4. Note that, assuming that the Taylor hypothesis is applicable, an advection velocity of about \( 10 - 20u_\tau \) over a time \( t \approx 0.1h/u_\tau \) results in a streamwise displacements of about \( 1 - 2h \).

Finally, it should be noted that the results of the time filtered \( \rho_v, p_w \) are probably not directly comparable to the space filtered ones: the time averaging defined in equation (2) is roughly equivalent to a spatial average in the streamwise direction only, while the spatial filters employed here are isotropic in \( x \) and \( z \).

4. Conclusions
The correlation between the wall-normal velocity and the pressure fluctuations at the wall has been characterized, using a DNS of a turbulent channel flow at moderate friction Reynolds number, \( Re_\tau = 939 \). The correlation coefficient shows a clear structure in the streamwise direction, with a negatively correlated region upstream of the point where the pressure is measured, and a positively correlated region downstream. In the spanwise direction, the correlation only changes sign in the near wall region. In particular, the correlation does not show any indication of spanwise pairs of \( v \)-eddies, as observed in other analysis [5].

Filtering in space the pressure fluctuations at the wall results in a growth of the regions of strong correlation, with sizes that are roughly proportional to \( l_c^{1/2} \) (where \( l_c \) is the characteristic length of the filter) for the two spatial filters considered here. This suggests that it should be possible to discriminate \( v \)-eddies of different times by filtering the pressure fluctuations at the wall. Further analysis at higher Reynolds numbers should be done to ascertain the limits of space filtering to detect \( v \)-structures of various sizes.

Finally, the effect of a simple moving time average of the pressure fluctuation at the wall has been analyzed. Contrary to the space filter, this time filter displaces the correlation in the streamwise direction, as a consequence of the advection of the eddies. The regions of strong negative correlation become more vertical, while the regions of strong positive correlation are lost. However, for the filter lengths and Reynolds numbers considered here, the time filter seems to have a smaller effect on the size of the regions of strong correlation, which suggests that these time filters are not as good candidates to discriminate \( v \)-eddies based on their pressure signature at the wall.

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