Reynolds shear-stress carrying structures in shear-dominated flows

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Abstract.
Four direct numerical simulation (DNS) databases are examined to understand the effect of the wall and near-wall turbulence on the Reynolds shear-stress carrying structures in shear-driven flows. The first DNS database is of a non-equilibrium adverse-pressure-gradient (APG) turbulent boundary layer (TBL) with momentum thickness Reynolds number ($Re_\theta$) reaching 8000. The second one is the same flow as the previous, but turbulence activity in the inner layer ($y/\delta < 0.1$) is artificially eliminated. The last two DNS databases are homogeneous shear turbulence (HST) with Taylor microscale Reynolds numbers ($Re_\lambda$) are 104 and 248. Results show that outer layer turbulence in the APG TBLs with large velocity defect is only slightly affected by the near-wall region turbulence which suggests outer layer turbulence sustains itself without necessitating near-wall turbulence. The Corrsin length scale ($L_c$) scales the size of the Reynolds shear-stress carrying structures in both APG TBLs and HSTs. The streamwise length of these structures is $\sim L_c$ or larger in all cases. The aspect ratio of the structures behaves similarly in both APG TBLs and HSTs when the size of the structures are normalized with $L_c$. Sweeps and ejections tend to form side-by-side pairs in both flow types. The spatial properties of sweeps and ejections, such as aspect ratios or relative positions are not affected by near-wall turbulence activity or presence of the wall. This suggests that the structures mostly dependent on the local mean strain rates.

1. Introduction
A turbulent boundary layer (TBL) subjected to an adverse pressure gradient (APG) develops a large mean velocity defect. This velocity defect significantly alters the nature of the flow. In canonical wall-bounded flows such as channel flows or zero-pressure-gradient (ZPG) TBLs, turbulence activity is predominantly found in the near-wall region. In contrast, Reynolds stresses peak in the outer layer in APG TBLs \cite{1, 2} and turbulence production in the outer layer is much higher in APG TBLs than in ZPG TBLs \cite{3}. These findings which highlight an important distinction between APG TBLs and canonical flows indicate the importance of outer layer in the APG TBLs.

The intense $uv$ structures, herein called Q structures, are streaky, streamwise elongated and mostly concentrated in the near-wall region in ZPG TBLs and APG TBLs with small velocity defect. \cite{4}. In the outer layer, most of the Reynolds shear stress is carried by the wall-attached (structures whose minimum wall-normal location is in the vicinity of the wall), tall
and streamwise elongated structures [4] as happens in the logarithmic and wake layer of channel flows [5]. However, the situation in APG TBLs with large velocity defect considerably differs. Consistent with the behavior of Reynolds stresses, Reynolds shear-stress carrying structures (Q structures) are mostly found in the outer layer of APG TBLs. The near-wall Q structures become disorganized and less numerous with increasing velocity defect [6]. Furthermore, the structures found in the outer layer become stronger than their counterparts in the near-wall region [4]. Even if both attached and detached structures are streamwise elongated, detached structures are slightly more isotropic than attached structures in APG TBLs when the defect is large [6].

Gungor et al. [1] demonstrated that Reynolds stresses and turbulence kinetic energy budgets behave similarly in the outer layer of APG TBLs and free shear layer flows such as mixing layer flows. This similarity suggests that the wall does not significantly affect turbulence in APG TBLs with a large velocity defect. The effect of the wall on shear flows was investigated by Dong et al. [7]. They compared structures in channel flows and homogeneous shear turbulence (HST) to distinguish the effect of wall and shear. They found that in both cases the Reynolds shear stress is carried by Q structures that are larger than the Corrsin length scale, which is defined as \( L_c = (\epsilon/S^3)^{1/2} \) where \( \epsilon \) is the turbulence dissipation and \( S \) is the mean shear. It represents the scale of the smallest structures that interact directly with the mean shear. Below \( L_c = 1 \), the turbulent structures become isotropic and decoupled from the mean shear. More importantly, it was found that the spatial properties of the large Qs were similar in both types of flows. The authors concluded that large Q structures are linked to local mean shear, rather than to the presence of a wall.

The present work aims to verify the latter conclusion in the case of APG TBLs with large velocity defect and also to determine if outer-layer turbulence depends on near-wall turbulence in these flows. To do so, we investigate the spatial properties of the Q structures in four DNS databases that are the APG TBL of Gungor et al. [8], the same APG TBL but with inner layer turbulence artificially eliminated, and two HST databases of Dong et al. [7] with Taylor microscale Reynolds numbers (\( Re_\lambda \)) at 104 and 248.

2. DNS Databases

Four databases are used to investigate the Reynolds shear-stress carrying structures in shear dominated flows. The first database (oAPG), described in Ref. [8], is a non-equilibrium APG TBL subjected to a strong APG that leads to an increasing mean velocity deficit. The flow evolves from a ZPG TBL to an APG TBL near separation. The DNS is performed with a box domain over a no-slip smooth wall, with spanwise periodicity and streamwise non-periodic inflow and outflow. The Reynolds number based on momentum thickness (\( Re_\theta \)) spans between 1500-8200 and the shape factor (\( H \)) increases from 1.4 to 3.0.

The second database (mAPG) is a non-equilibrium APG TBL, as well. The two APG TBLs, oAPG and mAPG, are the same flow cases with a major difference. In mAPG, the turbulence activity in the inner layer, which is defined as the region where the wall-distance (\( y \)) is below 0.1 of the local boundary layer thickness (\( \delta \)), is artificially eliminated. The region where the turbulence activity is eliminated starts at \( x \approx 10\delta_0 \), where \( \delta_0 \) is \( \delta \) at the inlet. The height of the region smoothly reaches \( y = 0.1\delta \) in 10\( \delta_0 \) in the streamwise direction to prevent any kind of numerical issues. The DNS code employs a spectral method in the periodic spanwise direction [9, 10]. To eliminate the turbulence activity in the inner layer, all modes except the zeroth mode are set to zero at every time step.

The lack of turbulence in the inner region significantly affects the mean flow field. In order to keep both cases identical, the spanwise- and time-averaged mean velocity profile from the original APG TBL case is imposed to the zeroth mode of the modified APG case throughout the boundary layer. Therefore, mean flow in both cases and hence integral variables such as \( \delta^* \)
or $\theta$ and the total mass are identical. This database is generated to examine the effect of the wall and inner layer turbulent activity on the Reynolds shear-stress carrying structures in the outer layer of APG TBLs.

The other two databases are HST databases, which are described in detail in Ref. [11] and [7]. The Reynolds numbers based on the Taylor microscale ($Re_\lambda$) of these databases are 104 (HST1) and 248 (HST2). They are chosen to investigate the effect of the wall and the mean strain field on the outer layer coherent structures in APG TBLs.

3. Flow Description of the APG TBLs

In order to understand the effect of the near-wall region turbulent activity on the outer layer turbulence, the turbulence statistics and Reynolds shear-stress budget of both APG TBLs are compared. Figure 1 shows the streamwise evolution of $\langle uu \rangle$ of oAPG and mAPG as a function of $x/\delta_0$ and $y/\delta_0$. The boundary layer grows in height as the flow develops. The maximum value of $\langle uu \rangle$ moves to the outer layer at approximately $28\delta_0$ in oAPG. It is clearly seen that the dominant turbulence energy is in the outer layer when the defect is large. The region where turbulence is eliminated in mAPG is seen in figure 1b. The interface between the turbulent and non-turbulent regions is at $y/\delta = 0.1$. Besides the lack of turbulence in the inner layer, the behavior of turbulence in the outer layer is very similar in both flows.

Figure 2 displays wall-normal profiles of $\langle uu \rangle$ and $\langle uv \rangle$ of oAPG and mAPG at two streamwise positions corresponding to $H = 1.6$ and 2.5, as shown in figure 1, along with the ZPG TBL of Sillero et al. at $Re_\theta = 6000$ [9]. Reynolds stresses are normalized with Zagarola-Smits velocity ($U_{ZS} = U_e\delta^*/\delta$, where $U_e$ is the velocity at the boundary layer edge and $\delta^*$ is the displacement...
Figure 2. \( <uu> \) (a) and \(-<uv>\) (b) of oAPG and mAPG as a function of \( y/\delta \) at two streamwise positions corresponding to small \( (H = 1.6) \) and large \( (H = 2.5) \) velocity defect situations along with the ZPG TBL of Sillero et al. [9]. Blue, red and green straight lines indicate the large and small velocity regions of the original APG TBLs and the ZPG TBL, respectively. The blue and red dashed lines indicate the large and small velocity defect regions of the manipulated APG TBL, respectively. Turbulence statistics are normalized with \( U_{ZS} \).

thickness). The original APG TBL (solid lines) behaves almost like a ZPG TBL when the velocity defect is small \( (H = 1.6) \). Near-wall turbulence activity is less intense but the well-known inner peak of \( \langle uu \rangle \) is present. All Reynolds stresses decrease with increasing velocity defect when they are normalized with \( U_{ZS} \). Furthermore, turbulence activity in the inner region reduces considerably and the outer layer turbulence becomes dominant. This behavior of turbulence with increasing velocity defect demonstrates the importance of the outer layer in APG TBLs and highlights the main distinction between APG and ZPG TBLs [1, 2].

The turbulence statistics of mAPG, shown in figure 2 with dashed lines, present that turbulence has effectively been removed in the inner region, \( y/\delta = 0.1 \). Above \( y/\delta = 0.1 \), there is an immediate increase in both \( <uu> \) and \(-<uv>\). This sharp increase is similar to the behavior of turbulence in the region just above the wall in wall-bounded flows. For the small velocity-defect position at \( H = 1.6 \), both Reynolds stresses of mAPG recover values comparable to those of oAPG at approximately \( y/\delta = 0.45 \). There is almost a perfect match for both cases above that point. However, this is not the case for the large velocity-defect position at \( H = 2.5 \), where the Reynolds stresses of mAPG remain slightly smaller than those of oAPG. Despite the differences, the results suggest that turbulence in the outer layer can sustain itself in the absence of near-wall turbulent activity.

Figure 3 presents the Reynolds shear stress budget of oAPG and mAPG as a function of \( y/\delta \) for the two streamwise positions. The Reynolds shear-stress budget is given as follows:

\[
\frac{D(u_i u_j)}{Dt} = \frac{\partial(u_i u_j u_k)}{\partial x_k} + \nu \nabla^2 \langle u_i u_j \rangle - \left( \langle u_i u_k \rangle \frac{\langle U_i \rangle}{\partial x_k} + \langle u_j u_k \rangle \frac{\langle U_j \rangle}{\partial x_k} \right) - \frac{1}{\rho} \left( u_i \frac{\partial p}{\partial x_j} + u_j \frac{\partial p}{\partial x_i} \right) - 2\nu \left( \frac{\partial u_i}{\partial x_k} \frac{\partial u_j}{\partial x_k} \right)
\]

Here \( \nu \) is viscosity, \( U \) and \( u \) indicate the instantaneous and fluctuating velocity and \( \langle \cdot \rangle \) is the averaged values. The terms are, in order, mean convection, turbulence convection, viscous diffusion, production, pressure and dissipation. Near the interface between the non-turbulent and turbulent regions in mAPG, there is a nonphysical behavior due to the transition from the non-turbulent region to the turbulent region. It is important to state that this kind of nonphysical behavior near the interface is excepted. Despite this nonphysical behavior, the
contribution of different terms to the \(-\langle uv \rangle\) balance follow the same trend. Whereas the values of the budget of oAPG and mAPG are almost exactly the same in the region where \(y/\delta\) above 0.3 of the small defect position, there is a difference between oAPG and mAPG in the large defect position.

As previously mentioned, the outer layer turbulence is dominant and much more important than the inner layer turbulence activity in APG TBLs with large velocity defect. That the turbulence production peaks in the outer layer supports this, as well. APG TBLs with large velocity defect have similarities with free shear layer and mixing layer flows [1]. Hence the following section scrutinizes this similarity between HSTs and APG TBLs.

4. Similarities of Shear Dominated Flows

The Corrsin shear parameter defined as \(S^* = \frac{S q^2}{\epsilon}\), where \(S\) is the mean shear, \(q^2\) is twice of the turbulence kinetic energy and \(\epsilon\) is the turbulence dissipation, is the ratio of turbulence dissipation time to the mean shear deformation time. It measures the importance of the interaction of the shear with the energy-containing eddies. When \(S^* \gg 1\), the flow and the turbulence scales are dominated by the mean shear, and when \(S^* \lesssim \mathcal{O}(1)\) turbulence is decoupled from the mean shear [12]. Figure 4(a) presents \(S^*\) as a function of \(y/\delta\) for two streamwise positions of oAPG and mAPG corresponding to \(H = 1.6\) and 2.5 and the ZPG TBL database of Ref [9] at \(Re_\theta = 6000\). Below \(y/\delta = 0.3\), in the near-wall region, \(S^*\) is very high but it suddenly drops, then slowly increases. Above \(y/\delta = 0.8\), \(S^*\) slowly tends to zero, which indicates that the effect of the mean shear diminishes in this region. Between \(y/\delta = 0.3 - 0.8\), \(S^*\) is almost constant for all cases and approximately 10. That \(S^*\) is almost constant and \(S^* \gg 1\) between \(y/\delta = 0.3 - 0.8\) implies that the mean shear dominates the large-scale turbulent structures in the outer region of the boundary layers. \(S^*\) in HSTs is approximately 7.5 [7]. The values of \(S^*\) in APG TBLs and HSTs are similar.

In order to understand these similarities between two APG TBLs and shear-driven flows, the premultiplied co-spectra of the two APG TBLs and HSTs are examined. Figure 4(b) shows the premultiplied 1D co-spectra of the large defect position at \(H = 2.5\) of oAPG and mAPG at \(y/\delta = 0.5\) along with the co-spectra of HSTs as a function of the streamwise wavelength.
Figure 4. (a) Corrsin shear parameter, $S^*$, of two streamwise locations of oAPG and mAPG corresponding to $H = 1.6$ and $H = 2.5$ and ZPG TBL as a function of $y/\delta$. The vertical lines indicate the region between $y/\delta = 0.3$ and 0.8 where $S^*$ is almost constant. (b) Premultiplied 1D co-spectra of the APG TBLs at $y/\delta = 0.5$ and HSTs as a function of $\lambda_x/L_c$. Blue, red, green and black indicate oAPG, mAPG, HST1 and HST2, respectively.

5. Spatial properties of the Reynolds shear-stress carrying structures

5.1. Structure Identification Method

Q structures are identified to investigate the spatial properties of Reynolds shear-stress carrying structures. They are divided into four based on their quadrant positions in the $u$-$v$ plane: outward interactions ($Q_1$, $u > 0$ and $v > 0$), ejections ($Q_2$, $u < 0$ and $v > 0$), inward interactions ($Q_3$, $u < 0$ and $v < 0$) and sweeps ($Q_4$, $u > 0$ and $v < 0$). The present study focuses on $Q_2$ and $Q_4$ events. Q structures are defined as connected regions satisfying the following condition [5]

$$u(x)v(x) > H^*\sigma_u\sigma_v,$$

where $H^*$ is the threshold constant which is also called hyperbolic-hole size and $\sigma$ is the root-mean-square. Connectivity is defined with the six orthogonal neighbors in the mesh of the DNS. For this study, a percolation analysis is not performed. $H^* = 1.75$ is chosen based on the previous channel flow study of Lozano et al. [5] and the APG TBL study of Maciel et al. [6].

This technique has been used for channel flows [5], APG and ZPG TBLs [6, 13] and homogeneous shear turbulence [7] using spatial data. In the current study, the Q structures of the APG TBLs are detected using temporal data collected at every time step at one streamwise location corresponding to large defect position ($H = 2.5$) from the whole $y-z$ plane. The
The temporal data is converted into spatial data using Taylor’s frozen turbulence hypothesis. The local mean velocity at the center of the structure is assumed to be its convective velocity. The center of the structures is calculated as the arithmetic mean of the maximum and minimum \( y \) locations of the structures. For HST, spatial data are employed to identify the Q structures. As it was mentioned before, \( S^* \) is almost constant between \( y/\delta = 0.3 \) − 0.8 for both APG TBLs. Therefore, only the structures whose centers are in this region are considered in the analysis. In addition to this, wall-attached structures, defined with a minimum wall distance of \( 0.05y/\delta \) or lower, are discarded, as well, because shape and orientation of the wall-attached structures are significantly different from those of the wall-detached structures [7]. Furthermore, very small Q structures that have a volume smaller than \( 3(\Delta z)^3 \) are rejected, because their size is too small for the numerical grid. Figure 5 displays the spatio-temporal development of the 3D Q2 structures obtained using the structure detection method and a single Q2 structure with the circumscribing box. The dimensions of the box are employed to define and analyze the spatial properties of the structures.

5.2. Aspect Ratios of the Q2 and Q4 Structures

The shape and orientation of the structures can be investigated through their aspect ratios. Figure 6 presents joint probability density functions (pdfs) of dimensions of the box circumscribing the wall-detached Q2 and Q4 structures in the region of interest for oAPG and mAPG. When the streamwise and spanwise dimensions of the boxes are less than approximately 0.5\( \delta \), the structures are mostly isotropic. As the streamwise size of the structures increases, the structures become streamwise elongated. Furthermore, Q2 structures are slightly more streamwise oriented than Q4 structures. Although there are minor differences between the structures in oAPG and mAPG, the spatial properties of the structures in both APG TBLs are very similar to each other. Joint pdfs of \( \Delta x \) and \( \Delta y \), and \( \Delta z \) and \( \Delta y \) of the structures in oAPG and mAPG are also consistent with the study of Maciel et al. [4] that was performed using the spatial data. They reported that detached Q2 and Q4 structures are slightly streamwise elongated in ZPG and APG TBLs, too.
Figure 6. Joint pdf of $\Delta y/\delta$ and $\Delta x/\delta$ (left column), and $\Delta y/\delta$ and $\Delta z/\delta$ (right column) for Q2 and Q4 structures. From top to bottom, Q2 of oAPG, Q2 of mAPG, Q4 of oAPG and Q4 of mAPG. Contours levels are $[0.06:0.4:3.64]$. Axes are normalized with $\delta$. The dashed line indicates $\Delta x/\delta = \Delta y/\delta$ and $\Delta z/\delta = \Delta y/\delta$. 
Figure 7. Average aspect ratio of the circumscribing boxes for combined Q2 and Q4 structures as a function of the box diagonal (d) of the structure. The box diagonal is normalized with $L_c$. Blue, red, green and black lines indicate oAPG, mAPG, HST1 and HST2. Filled (-▲- and ■-) and empty (-○- and -□-) symbols indicate ratio of $\Delta x$ to $\Delta y$ ($a_{xy}$) and ratio of $\Delta z$ to $\Delta y$ ($a_{zy}$), respectively. The figure in the inset is the same figure with larger axis ranges.

Figure 7 presents the average aspect ratio ($a_{ij}$, the ratio of $\Delta i$ to $\Delta j$) of the circumscribing boxes for Q2 and Q4 structures in oAPG, mAPG and HSTs as a function of the diagonal of the boxes (d). The box diagonal is normalized with $L_c$. The aspect ratios in both APG TBLs perfectly match regardless of the box diagonal. This shows that the inner layer turbulence activity does not change the shape of the Reynolds shear-stress carrying structures in the outer layer. In both APG TBLs and HSTs, there is a similar trend: $a_{zy}$ steadily decreases between $d/L_c = 1 - 10$ from values above one to about 0.8. In the APG TBLs, $a_{zy}$ increases after $d/L_c = 10$, but in HSTs it continues to decrease. $a_{xy}$ of HSTs very slightly increases until diagonal of the boxes becomes approximately $30L_c$. $a_{xy}$ is always above one for all flows, but the streamwise elongation is small except for very large Q structures in the APG TBLs. $a_{xy}$ of the APG TBLs remains fairly constant for small structures but it dramatically increases after $d/L_c = 10$. The reason of this dramatic increase in $a_{xy}$ and weak increase in $a_{zy}$ is probably that the structures are bounded in the wall-normal direction and unbounded in the streamwise direction. As the structures become larger, they cannot grow in the wall-normal direction because of the presence of the wall. In HST, the flow is unbounded in the wall-normal direction, so they keep growing in that direction as well [7]. The detached Q structures with diagonal smaller than approximately $3L_c$ in channel flows are mostly isotropic, however their $a_{xy}$ is slightly larger than $a_{xy}$ of the structures in HSTs [7].

For $a_{zy}$, there is a perfect match for all the cases when $d/L_c$ is between 1 – 10. Although $a_{xy}$ of the APG TBLs and HSTs behave slightly differently from each other, the values of $a_{xy}$ of the four cases are very close. Overall, in both HSTs and APG TBLs, the structures become more streamwise elongated and narrower in the spanwise direction as the structures become larger. The Reynolds shear-stress carrying structures have therefore similar geometrical features in both types of flows. The situation for channel flows is also similar to HSTs and APG TBLs [7].

5.3. Relative positions of Q2 and Q4 Structures
Spatial organization of Q structures is analyzed through relative positions of Q structures. Figure 8 presents the joint pdfs, $p^3(r_x, r_z)$, of relative positions of Q structures of the same and different kind in oAPG and mAPG in a wall-parallel plane. Indices $i$ and $j$ stand for quadrant
of Q structures. The relative positions of $i$ structure with respect to $j$ structure are obtained as,

$$r_x = \frac{x^j - x^i}{0.5(d^j + d^i)} \quad \text{and} \quad r_z = \frac{z^j - z^i}{0.5(d^j + d^i)},$$

where $d^i = \sqrt{\Delta x^2 + \Delta z^2}$ is the wall-parallel diagonal length of the structure and, $x$ and $z$ are the spatial coordinates of the structures. The temporal data is employed to obtain the relative positions of Q structures. A single convection velocity (mean velocity at $y/\delta = 0.5$) is used to transform the temporal data into spatial data. In order to reduce the effect of using a single convection velocity for all structures, only the structures between $y/\delta = 0.4 - 0.7$ are considered for this analysis.

Q2 structures of the same kind tend to form an upstream-downstream configuration in both APG TBLs. This is also true for the relative positions of Q4 structures with respect to Q4 structures, although it is not presented here. The pdfs of relative positions of Q structures of different kind are intentionally weighted towards positive $r_z$ to test the symmetry of the structures in the spanwise direction. The weighting is performed by choosing the direction of nearest Q structure of different kind as a positive direction ($r_z > 0$). This means that a secondary peak with negative $r_z$, in addition to the primary one with $r_z > 0$, indicates the presence of Q structures surrounded by two Q structures of the other type. Conversely, a weak secondary peak points to presence of side-by-side sweeps and ejections pairs. Side-by-side pairs are indeed the most dominant configuration in both APG TBLs. The results in both APG TBLs are very

Figure 8. Joint pdfs of relative positions of Q2 structures with respect to Q2 structures, $p_{22}$ (left), Q4 structures with respect to Q2 structures $p_{42}$ (center), Q2 structures with respect to Q4 structures $p_{24}$ (right). Top row is oAPG and the bottom row is mAPG. Contours are normalized with the probability at long distance ($p_{far}$).
similar to each other, suggesting that near-wall turbulence activity does not affect the spatial organization of outer Q structures. The pdfs of relative positions of Q structures in oAPG and mAPG are also consistent with the paper of Maciel et al. [4]. They found that streamwise alignment of Q structures of the same kind and presence of side-by-side sweeps and ejections are the most probable events in APG and ZPG flows. Furthermore, similar results were reported for the outer layer of channel flows by Lozano et al. [5] and HSTs by Dong et al. [7].

6. Conclusion
In this study, APG TBL and HST DNS databases are analyzed to investigate the Reynolds shear-stress carrying structures in shear-dominated flows. These databases are chosen to understand the effect of the inner layer turbulent activity and the wall on the outer layer Reynolds shear-stress carrying structures in APG TBLs. Turbulence statistics of the two APG TBL cases indicate that the elimination of turbulence in the inner layer only slightly reduces outer layer turbulence. Furthermore, Reynolds shear-stress carrying structures in the outer layer of both APG TBLs have almost identical spatial properties. Outer layer turbulence is therefore not significantly affected by inner layer turbulence. Moreover, detached Q2 and Q4 motions in both APG TBLs and HSTs have very similar geometric properties for the structures whose diagonal length, $d$, is less than approximately $8L_c$. Furthermore, structures in channel flows behave similarly until $d$ becomes approximately $3L_c$. The relative positions of Q2 and Q4 structures in all these flows are very similar too. All these results indicate that the wall and the near-wall turbulence activity do not heavily affect the spatial properties of outer Reynolds shear-stress carrying structures in TBLs. These structures appear to be mostly dependent on the local mean strain rates.

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References
[1] A. G. Gungor, Y. Maciel, M. P. Simens, and J. Soria. Scaling and statistics of large-defect adverse pressure gradient turbulent boundary layers. Int. J. Heat Fluid Flow, 50:109–124, 2016.
[2] Y. Maciel, T. Wei, A. G. Gungor, and M. P. Simens. Outer scales and parameters of adverse-pressure-gradient turbulent boundary layers. J. Fluid Mech., 844:5–35, 2018.
[3] P. E. Skåre and P. Krogstad. A turbulent equilibrium boundary layer near separation. J. Fluid Mech., 272:319–348, 1994.
[4] Y Maciel, A G Gungor, and M P Simens. Structural differences between small and large momentum-defect turbulent boundary layers. Int. J. Heat Fluid Flow, 67:95–110, 2017.
[5] A. Lozano-Durán, O. Flores, and J. Jiménez. The three-dimensional structure of momentum transfer in turbulent channels. J. Fluid Mech., 694:100–130, 2012.
[6] Y. Maciel, M. P. Simens, and A. G. Gungor. Coherent structures in a non-equilibrium large-velocity-defect turbulent boundary layer. Flow Turbul. Combust., 98:1–20, 2017.
[7] S. Dong, A. Lozano-Durán, A. Sekimoto, and J. Jiménez. Coherent structures in statistically stationary homogeneous shear turbulence. J. Fluid Mech., 816:167–208, 2017.
[8] A. G. Gungor, Y. Maciel, M. P. Simens, and T. R. Gungor. Direct numerical simulation of a non-equilibrium adverse pressure gradient boundary layer up to $Re_\theta= 8000$. In 16th Europ. Turbul. Conf., Stockholm, Sweden, Europ. Mechanics Soc., 2017.
[9] J. A. Sillero, J. Jiménez, and R. D. Moser. One-point statistics for turbulent wall-bounded flows at Reynolds numbers up to $\delta^+ \approx 2000$. \textit{Phys. Fluids}, 25:105102, 2013.

[10] G. Borrell, J. A. Sillero, and J. Jiménez. A code for direct numerical simulation of turbulent boundary layers at high Reynolds numbers in BG/P supercomputers. \textit{Comput. Fluids}, 80:37–43, 2013.

[11] A. Sekimoto, S. Dong, and J. Jiménez. Direct numerical simulation of statistically stationary and homogeneous shear turbulence and its relation to other shear flows. \textit{Phys. Fluids}, 28:035101, 2016.

[12] J. Jiménez. Near-wall turbulence. \textit{Phys. Fluids}, 25:101302, 2013.

[13] C. Atkinson, A. Sekimoto, J. Jiménez, and J. Soria. Reynolds stress structures in a self-similar adverse pressure gradient turbulent boundary layer at the verge of separation. In \textit{J. of Physics: Conf. Ser.}, volume 1001, page 012001. IOP Publishing, 2018.