

Near-Wall Lagrangian Particle Tracking Measurements of Flow over Checkerboard Roughness by means of 4-Pulse Shake-the-Box

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ABSTRACT

Four-pulse Lagrangian Particle Tracking (LPT) by means of the Shake-the-Box (STB) approach was used to examine the flow over three surfaces within a zero pressure gradient turbulent boundary layer (TBL). The three surfaces examined were a smooth wall reference case, a uniform sandpaper wall, and a checkerboard pattern consisting of 50% coverage of each surface. At low Reynolds numbers in turbulent channel flow, the checkerboard surface showed surprisingly low drag compared to the average drag of the uniform (smooth and rough) reference cases. The corresponding flow field suggests that the flow perceives the checkerboard surface as a homogeneous boundary condition, which is not the case at higher Reynolds number. The present investigation aims to identify whether a similar phenomenon is present in TBLs. The volumetric nature of STB measurements is used to examine the form that heterogeneity takes in the velocity and acceleration fields above the checkerboard. Regular repeating patterns are found in both streamwise velocity and acceleration fields, that correspond to the checkerboard roughness below. Quantitative magnitudes of accelerations are unexpectedly high and this is examined statistically using the context of smooth wall data to examine a possible bias error.

1. Introduction

The effect of homogenous roughness is relatively well understood. It can be condensed into a single quantity, the equivalent sandgrain height, which is used in predictions (Moody, 1944). Introducing spatial heterogeneity into roughness reduces this predictability. Simple heterogenous roughness configurations, such as alternating strips of smooth and rough material, have been shown to produce flow responses that depend on further parameters such as the heterogeneity wavelength relative to the boundary layer depth (Vanderwel & Ganapathisubramani, 2015). Few studies have looked into the drag created by these surfaces, and little reference data is available.

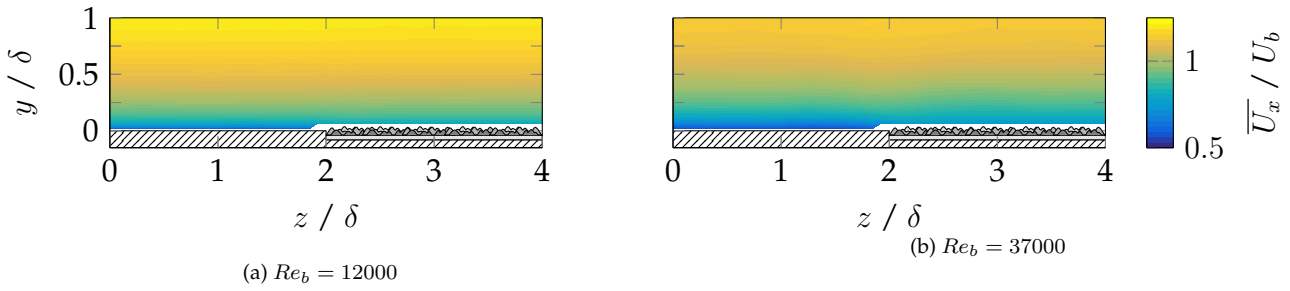


Figure 1. Velocity flow field (time-averaged streamwise velocity) above the checkerboard patterned-surface 5 mm behind the step change. Due to this being channel flow data the velocities are normalised using the bulk velocity U_b . In this case δ corresponds to the channel half height.

The most extensively researched example of heterogeneous roughness is a stream-wise infinite-length strip configuration (Hinze, 1967; Wangsawijaya et al., 2020). This is a surface that is invariant in the streamwise direction but varies in the cross stream direction. Studies into this surface have identified large turbulent secondary motions that move the fluid from the smooth strips onto the rougher surfaces between them. The corresponding flow fields reflect the heterogeneity of the surface throughout the entire boundary layer.

Roughness strips have also been studied when oriented in a spanwise configuration. The surface heterogeneity reflects in repeatedly emerging internal boundary layers. The work by Bou-Zeid et al. (2004) shows that these internal boundary layers reached a blending height at two strip-lengths downstream of rough-smooth or smooth-rough transitions. This shows that in isolated cases, the influence of both streamwise and spanwise aligned strips extends significantly into the flow. Combination of both isolated cases leads to a two-dimensional pattern of alternating smooth and rough squares in streamwise and spanwise directions across the surface. This so-called checkerboard heterogeneous roughness can be thought of as both streamwise and spanwise alternating roughness, however it has not been studied as much as either type has independently.

The study that is documented in this work is building on a previous investigation by this group in which the global drag of a checkerboard surface was measured in a turbulent channel flow (Schmidt et al., 2026). This study also examined literature on streamwise and spanwise strip type roughness as a point of comparison to the checkerboard roughness. It was found that at higher Reynolds numbers the drag over the checkerboard roughness was very similar to that of the strip type roughness oriented in streamwise direction. However; at lower Reynolds numbers it was found that the checkerboard had lower drag than the strips. The study into global drag was complemented by scanning HWA measurements, which were used to visualise the streamwise mean flow field over two neighbouring rough and smooth surface parts. The corresponding results for the checkerboard surface are shown in Figure 1a for the low Reynolds number case and in Figure 1b for the high Reynolds number case. In these figures it can be seen that more flow heterogeneity is present in the high Reynolds number data, here the velocity isocontours visibly deflect

above the roughness. In comparison the low Reynolds number data in Figure 1a shows very little influence from the checkerboard, suggesting that this surface is perceived as a homogeneous one by the flow. The flow fields do not show any traces of large scale turbulent secondary motions that occur over streamwise strips.

The present study aims to identify whether similar flow field features – i.e. appearing heterogeneity with increasing Reynolds number, no traces of turbulent secondary flow – can also be found over the checkerboard surface pattern when placed into a turbulent boundary layer instead of the formerly studied channel flow. In addition, we aim to measure cross-sectional velocity components to identify in which velocity components flow heterogeneity starts to develop. Lagrangian particle tracking (LPT, Schröder & Schanz, 2023) by means of a four pulse shake-the-box (STB) system (Novara et al., 2016) is used as the optical measurement technique due to its ability to measure all flow components of a fluid flow in three dimensions and over a large volume in the wind tunnel (cp. also Leister et al., 2025).

Using a four pulse STB system to obtain volumetric Lagrangian measurements enables the above mentioned heterogeneity to be examined in both the velocity and acceleration fields. While velocity measurements within a boundary layer are well understood, acceleration measurements are harder to come by and little comparison data exists. The present results are taken using time resolved STB as opposed to four pulse STB (Schanz et al., 2019). This study aims to plot acceleration fields across the same volumes as velocity fields in order to further contextualise the influence of the checkerboard. Additionally, it is hoped that the smooth and rough reference cases will provide insight into the general subject of boundary layer accelerations. To this end direct numerical simulation data of a similar smooth wall boundary layer case is introduced as an additional point of reference.

2. Methodology

Three different roughness cases are measured in a wind tunnel at two flow velocities. The Reynolds numbers, based on boundary layer height at the beginning of the roughness plates, and freestream velocity, ($Re = U_\infty \delta / \nu$) are $Re = 13,400$ and $Re = 33,200$, which will be referred to as low and high Reynolds number below. The three roughness cases measured are: homogeneously rough, homogeneously smooth, and checkerboard roughness. The fully rough case is a surface of 100 % P60 sandpaper, and the homogeneously smooth case is a surface of polished aluminium. The heterogeneous case is made up of a pattern with 50 % coverage of each of these two materials in alternating squares, with a side length of 50 mm as indicated in Figure 2. In the checkerboard pattern the squares in which sandpaper is placed are milled into the aluminium plate before the sandpaper is glued into these squares. This ensures that the mean height of the sandpaper surfaces coincides with the location of the wall in the smooth surface sections, but with significant local deviation

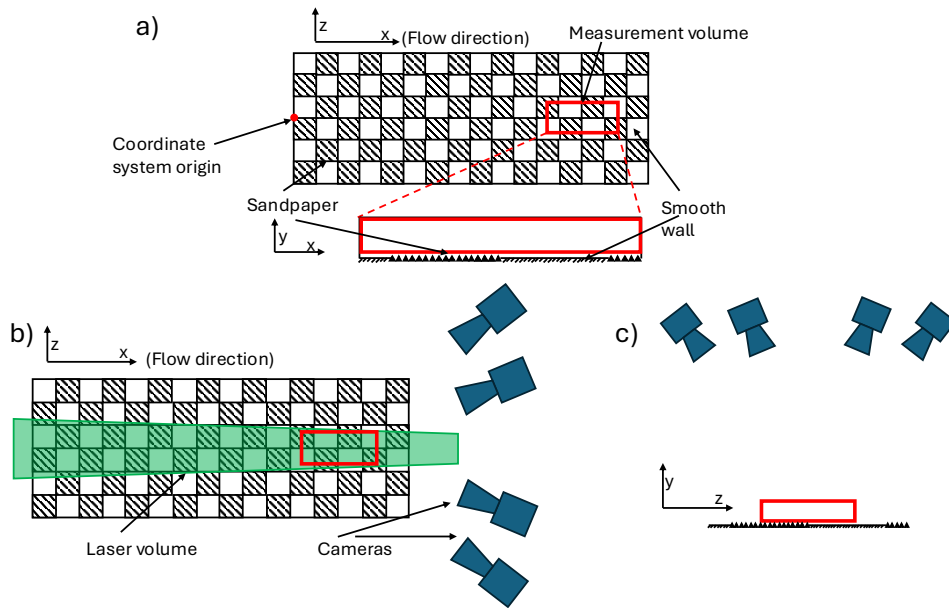


Figure 2. (a) A top view of the checkerboard roughness and measurement volume in the wind tunnel with a cut out showing the rough and smooth patches. (b) The same top view as in (a), but with laser volume and camera positions shown. (c) Cross stream view of the cameras and measurement volume, demonstrating the top down view of the cameras (this is also visible in Figure 3(b)).

due to the roughness peaks and valleys of the sandpaper.

2.1. Experimental Procedure

For the STB experiments two Evergreen dual pulse lasers are superimposed to create a four-pulse laser system. This system is used to illuminate a wall parallel fluid volume near the surface. Measurements are carried out using four LaVision Imager CX12 cameras, which are suspended on a rail above the flow in order to improve measurement quality by giving an optimal angle relative to the laser volume. This angle was chosen so that dense data could be acquired without exceeding the particle-per-pixel limit of the Shake the box algorithm (Novara et al., 2016). This had the unfortunate effect of making the image backgrounds brighter than the particle images in certain areas (this can be observed in Figure 3 (c)).

Each camera frame is intentionally double exposed, which creates four particle images, with two stored on each camera frame. The resulting particle tracks are short relative to time resolved STB (TR-STB), but there are some significant advantages to the multi pulse STB system (MP-STB). The major advantages of low-speed equipment are the larger chip-sizes (thus spatial resolution) and higher pixel depth of the cameras, and the higher pulse energy of low speed lasers. The use of this equipment, instead of high speed equipment, made it possible to resolve a volume of $80,000 \text{ mm}^3$

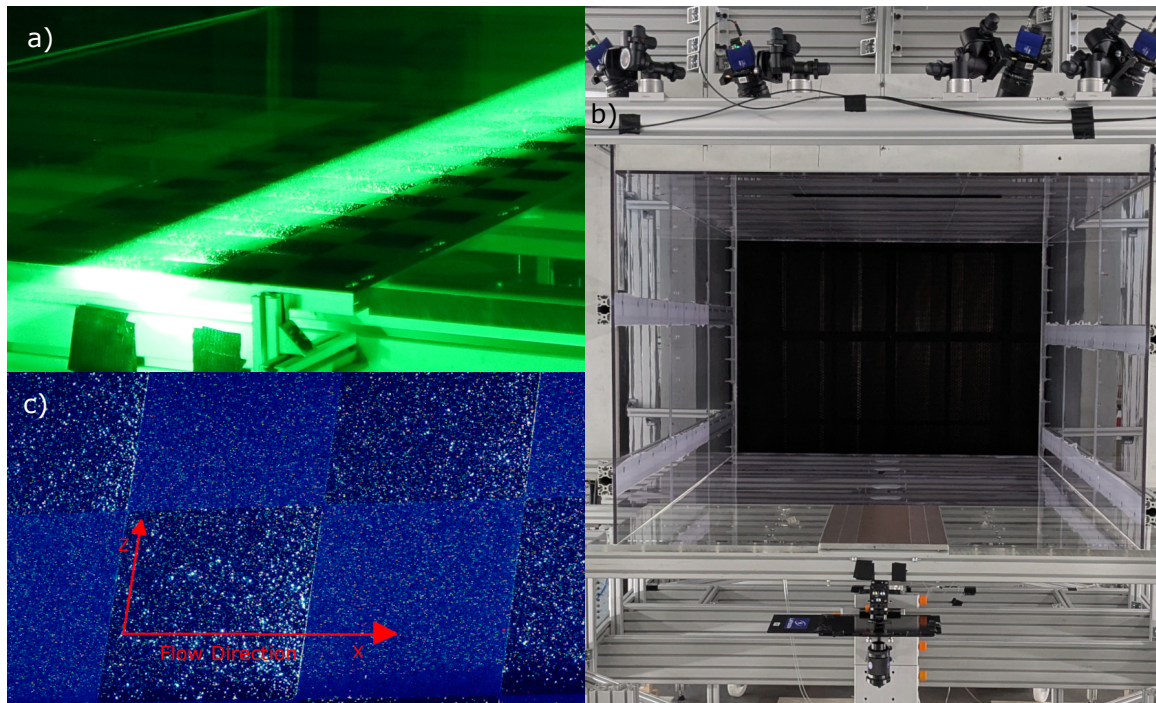


Figure 3. (a) The laser volume being shone upstream above the checkerboard roughness. (b) The wind tunnel outlet, here the cameras can be seen at the top of the image (cp. Figure 2). In this case they are looking down on the fully rough sandpaper surface, which can be seen as a brown patch on the lower surface of the wind tunnel.(c) An example particle image before any preprocessing, the brightness of the sandpaper peaks on the checkerboard can be seen here to be significantly brighter than particles in the foreground.

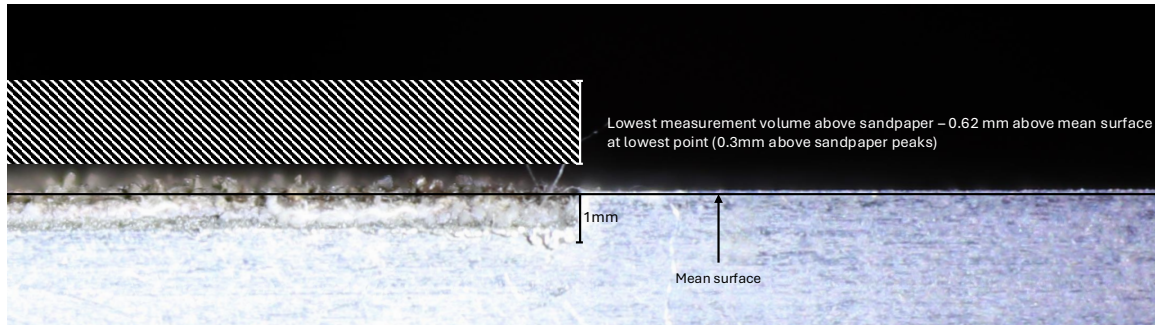


Figure 4. Annotated photo showing the end of the checkerboard plate and near-wall measurement volume location.

with a high particle density, in comparison a similar experiment by this group carried out using TR-STB resolved a volume of 800 mm^3 . The large laser volume described here is visible in Figure 3 (a). This increase in measurement volume has made it possible to observe large scale flow patterns above the checkerboard as the measurement volume now has dimensions in the same order of magnitude as the checkerboard pattern.

Data is acquired at a high particle density down to a minimum height of 0.6 mm above the mean wall (0.3 mm above the sandpaper peaks). An annotated image explaining the location and size of the near-wall dataset is shown in Figure 4, in this figure the size of the sandgrains is visible in the sandpaper to help scale the measurement volumes. Some sparse particles are found lower than this limit, all the way down to in-between the sandpaper peaks in some areas. Obtaining high density data lower than 0.6 mm is not achieved in this case due to the sandpaper reflecting the edges of the laser volume at a higher brightness than it illuminates the particles within the volume. It is also found that there are fewer particles to detect in the extreme near wall region.

2.2. Data processing

Initial particle tracking was carried out using the STB algorithm in Davis 11.2. This was used to export particle track data to Matlab for further processing and the calculation of higher order statistics. This was done for 5000 independent frames, each representing a reference time and three subsequent time steps, stored across an image pair for each of the four cameras. At each time step approximately 10,000-30,000 particles were found within the measurement volume.

Using the MP-STB system described here it is possible to measure acceleration statistics, in a similar manner as can be done using TR-STB. This is in contrast to two pulse low speed particle tracking, which only provides velocity information for each particle. It was found while carrying out these measurements, that varying the time-step (Δt) between laser pulses created the most detailed flow information. All time steps were varied according to the flow velocity, however; the three Δt between consecutive laser pulses followed a pattern of relative lengths of the form $2 : 1 : 5$. This was chosen as it was found that a low Δt between the camera frames was necessary, possibly due

to camera vibrations, but that the STB algorithm lost very few particles in the longer third Δt . Making this change to the relative Δt from a default of 1 : 1 : 1 gave lower uncertainty in velocity, and particularly in acceleration measurements, by measuring a longer particle track.

Uncertainty in individual particle track data is approximately 1.1 % for streamwise velocities. Uncertainty is largest in the y direction, with a mean uncertainty of 5 % of U_∞ . The Lagrangian particle data is sorted into bins so that it can be more easily interpreted graphically. In order to have a high confidence, bin sizes were chosen so that the lowest number of datapoints within a bin, in the core measurement volume is always greater than 4000. The results of the core measurement volume, as sketched in Figure 2, will be discussed in section 3 alongside Figure 5, 6, and 7.

The coordinate system used here takes the centerline of the wall at the upstream edge of the roughness as the origin. The streamwise coordinate is taken as x , vertical is taken as y , and cross stream is taken as z . Distances in the x , and z directions are normalised using the roughness patch size ($s = 50$ mm), while distances in the y direction are normalised using the boundary layer height at the start of the surface plate, ($\delta = 35$ mm for higher and $\delta = 29$ mm for the lower Reynolds number). These depths were measured at the center of the measurement area and are assumed to be constant between the upstream and downstream ends of this area. Velocities are normalised using the mean streamwise velocity (U_∞), which is equal to 18 m s^{-1} and 6 m s^{-1} for these cases. In all wall parallel plots roughness underneath the plot area is indicated by crosshatched sections.

2.3. Experimental Challenges

Obtaining high quality particle track data in these cases is challenging for several reasons. It is found that at high speeds the flow tends to cause enough camera shake that all real particles are not traceable, without the carrying out of a single-image correction and a volume self calibration. The presence of sandpaper in the background also causes a bright pattern of background artifacts to be visible, despite the laser volume being chopped off at the bottom so that the direct beam was not impinging on the background. This cannot be easily mitigated through background subtraction, because the cameras move relative to the background, meaning that a sliding minimum subtraction is ineffective on its own. Instead, large object identification through clustered bright pixels is effective in subtracting out the moving sandpaper peaks. This was followed by a subtraction of 105 % of the sliding minimum over 21 images, the 21 image length sample was chosen to smooth out any camera shake, but this made scaling up the subtraction strength necessary. Resolving the flow extremely near the sandpaper is important as it has been seen in previous work that - depending on Reynolds number - the influence of the checkerboard can be visible in the time averaged flow fields in the very near-wall region only (Schmidt et al., 2026).

In order to optimise the near wall data as much as possible, two datasets are taken above the checkerboard roughness. The first of these uses the same laser volume as in the two homogenous

cases, this extends vertically from $y = 1\text{--}10\text{ mm}$. A second dataset is also taken in which the laser volume is narrowed and translated closer to the wall, this one extends from $y = 0.6\text{--}1.3\text{ mm}$. Due to this data being time averaged, these datasets are stitched together.

3. Discussion

3.1. Flow behaviour above the checkerboard

The vector plot shown in Figure 5 shows two different datasets taken at different heights. This plot only contains the crosstream (u_z), and vertical (u_y) velocity components, which are of the order of 1% of the velocity of the streamwise component (u_x).

The two datasets are visible as a higher, more sparse field of vectors, and a lower, more dense region. These are above and below $y/\delta = 0.045$. It can be seen that the two data sets agree well and that there is no significant noise in both of them, despite the low magnitudes of these velocity components. It can also be seen when plotting vectors in different locations along the downstream direction that the area of the flow displaying a downwards (negative u_y) velocity always corresponds to the area above a smooth patch. Figure 5 was included to verify the accuracy of the near wall data relative to the main dataset, despite the higher complexity involved in obtaining near wall data. The common patterns visible between these two datasets provide confidence in the existence of this pattern, despite it being at a magnitude less than 1% of that of the freestream velocity.

It is hypothesized on the basis of earlier studies that heterogeneity in the surface is causing lower drag than an equivalent homogenous surface, which in turn should make the identification of this

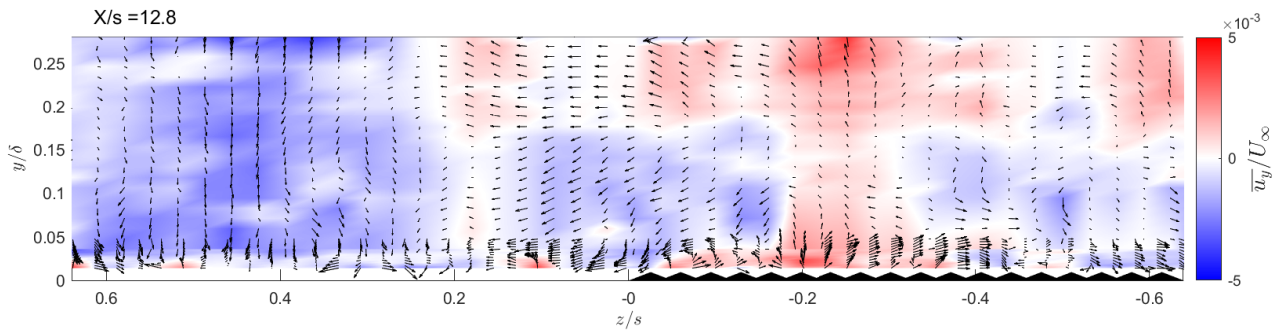


Figure 5. Vector plot of the u_y and u_z components of flow velocity in the cross-stream plane, above the checkerboard roughness (local rough patch indicated with triangles). The location of this slice ($x/s = 12.8$) is indicated on the following figures. In this plot the agreement between the high and low datasets is demonstrated, the low dataset is visible in the thin slice of high density vectors at the bottom of the figure. Plot background is coloured with the u_y velocity component. The data in this plot is time averaged but not spatially averaged in the downstream direction more than is necessary for data binning.

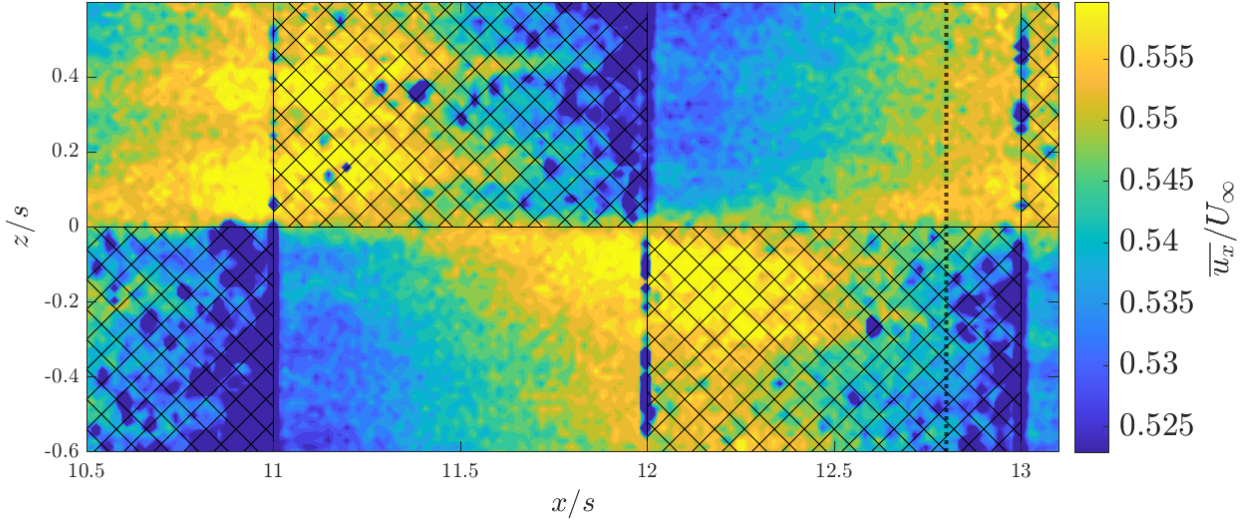


Figure 6. The u_x component of flow velocity in a wall parallel slice above the checkerboard roughness, extracted at $Y/\delta = 0.022$ (0.64 mm). Rough patches are indicated using textured lines. The dotted line indicates the location of the slice shown in Figure 5.

footprint in the flow possible. However, current observations indicate that this holds true only for very few quantities and across small spatial limits. Heterogeneity can be most clearly seen in the u_x flow velocity in Figure 6, it is also visible in the u_y velocity field, but with significant noise. The u_z velocity shows no regular pattern above the sandpaper and appears as largely uniform noise.

In Figure 6 the streamwise velocity peaks above the checkerboard transitions, instead of above the squares. This shows that it takes a noticeable distance for the influence of the roughness to propagate upwards into the boundary layer. For the investigated height of $y/\delta = 0.022$ in Figure 6 it appears to be roughly half of the checkerboard square length. This is recognisable as a characteristic of streamwise alternating roughness, as studied previously by Bou-Zeid et al. (2004). This pattern is also visible in the lower Reynolds number dataset but with significantly reduced intensity.

3.2. Analysis of accelerations

From the above observations of velocities it can be extrapolated that the streamwise accelerations should likewise be comprised of deceleration peaks above the roughness, if they are responsible for this varying velocity component. This does indeed appear to be the case, as seen in the plot of streamwise acceleration values ($\overline{a_x}$), shown in Figure 7. Here, decelerations follow the shape of the checkerboard squares below the flow, with a less visible propagation delay than in the case of Figure 6. It should also be noted that the time averaged acceleration values measured are many

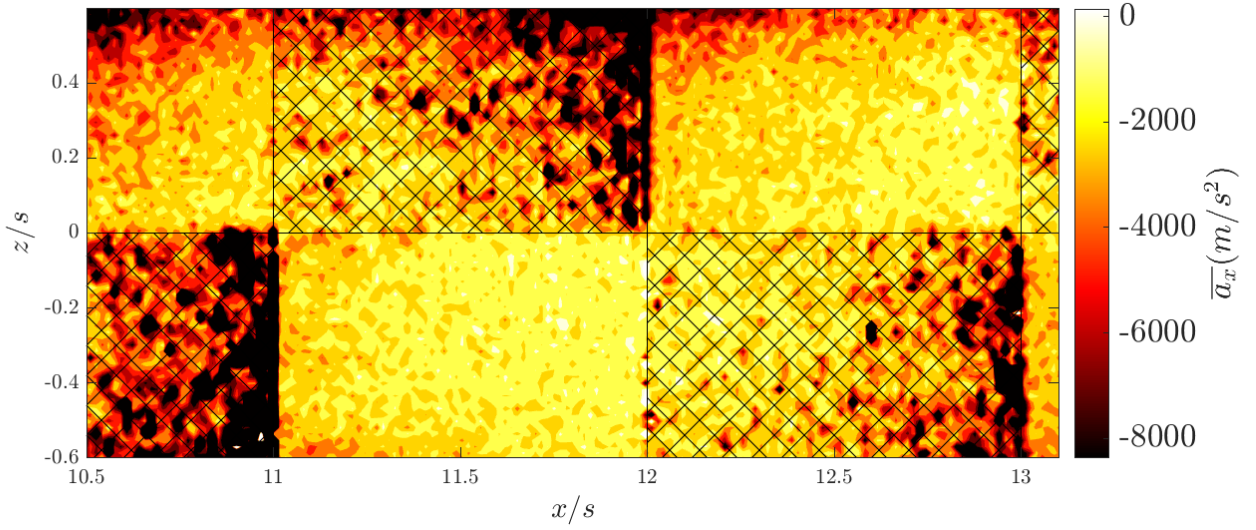


Figure 7. Wall parallel slice of the streamwise acceleration ($\overline{a_x}$) values above the checkerboard roughness, extracted at $y/\delta = 0.022$. Only the streamwise acceleration is shown as this is the dominant component. Similar to Figure 6 the rough patches are indicated using textured lines.

orders of magnitude higher than the accelerations expected on physical grounds. However, experimentally obtained magnitudes in the range of the present study have been observed in previous studies into Lagrangian acceleration statistics from particles (Toschi & Bodenschatz, 2009; Ni et al., 2012; Lawson et al., 2018). However, these studies were aimed at individual tracks, and it might be expected that in this case the magnitudes would converge towards lower values when averaged. Irrespective of magnitudes we can still observe the spatial patterns and sign of the components of acceleration, such that an evaluation of the resulting topology stemming from the presence of the checkerboard is still possible – even though without quantitative comparison of the considered cases.

It can be seen in Figure 7 that the streamwise decelerations reach the highest magnitude near the trailing edge of the sandpaper squares. The gradual increase in deceleration magnitude across the square length follows the pattern one might expect as an internal boundary layer grows across each square. The response rate visible at the transition to smooth squares is close to immediate, this response rate is also seen in the downwards velocity component in Figure 5 if this slice is taken near the start of a square. This is an indication that the change in acceleration here may be due to higher velocity fluid descending from higher in the boundary layer. The deceleration then decreases further up until a minimum value at the start of the next rough square.

While these fields align with the roughness squares of the checkerboard, they do not fully agree in location with Figure 6. In the case of Figure 6 the velocity peak is at the end of the smooth squares, and there is not such a sharp step change at the boundary. Instead, the velocity more gradually

transitions across this border.

For both Figure 6 and 7 only data for $Re = 33,200$ is shown. In the case of the lower Reynolds number measurements these patterns were less obvious, and were more obscured by background noise, but the same pattern was present. This trend relative to Reynolds number agrees with what is expected from the preliminary HWA findings shown in Figure 1a and 1b.

Bin averaging the particle tracks across a larger area in the x and z directions allows vertical profiles of statistics with a larger number of data points to be collected. Velocity profiles are shown for all surfaces across high and low speed in Figure 8 (a). In these it can be seen that for the low speed case the flow is relatively unaffected by roughness at a distance greater than $y/\delta = 0.1$. There is a slightly greater slowing of the flow above the sandpaper surface. For the higher speed (18m s^{-1}) case it can be seen very clearly that the flow is slowed more by the rough surface at all heights, with the checkerboard roughness landing in-between the smooth and rough surfaces.

Streamwise accelerations are shown in Figure 8 (b) and it can be seen that all profiles show a mean stream-wise deceleration in the boundary layer, which increases in strength near the wall. This data was averaged over an x and z distance of s in each direction, centred on $x/s = 12, z/s = 0$, this particular area was chosen as it makes up a repeating unit of the checkerboard roughness, and as such it fully represents the spatially averaged characteristics of the heterogenous surface. The fully smooth and fully rough plates are averaged over the same area for consistency. All three datasets are plotted from both the lower and higher speed cases, the same trend is visible across both. In the higher speed case a larger difference is visible near the wall; however all three curves have significant noise. The profiles in Figure 8 (b) show the larger influence on the boundary layer of increasing roughness. For the $U_\infty = 18\text{m s}^{-1}$ curves this pattern is more pronounced, and can be observed as the increased deceleration at equivalent boundary layer depth.

To obtain a first reference for the measured data we employ results of a direct numerical simulation (DNS) of a zero-pressure gradient turbulent boundary layer. In these simulations the time-averaged (material) acceleration can be determined a posteriori from the mean flow fields as outlined in the following. The Lagrangian nature of STB measurements delivers the full left-hand side of the Reynolds-averaged Navier Stokes (RANS) equations, i.e. the mean material acceleration,

$$\bar{a}_j = \frac{\overline{Du_j}}{Dt} = \frac{\partial \bar{u}_j}{\partial t} + \bar{u}_i \frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \overline{u'_i u'_j}}{\partial x_i} \quad (1)$$

including the Reynolds stress tensor $\overline{u'_i u'_j}$. Consequently, the remaining right-hand side of the RANS equations (without body forces) balances the mean acceleration

$$\bar{a}_j = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_j}{\partial x_i \partial x_i}. \quad (2)$$

For the case of a (quasi two-dimensional, statistically steady) zero pressure gradient turbulent

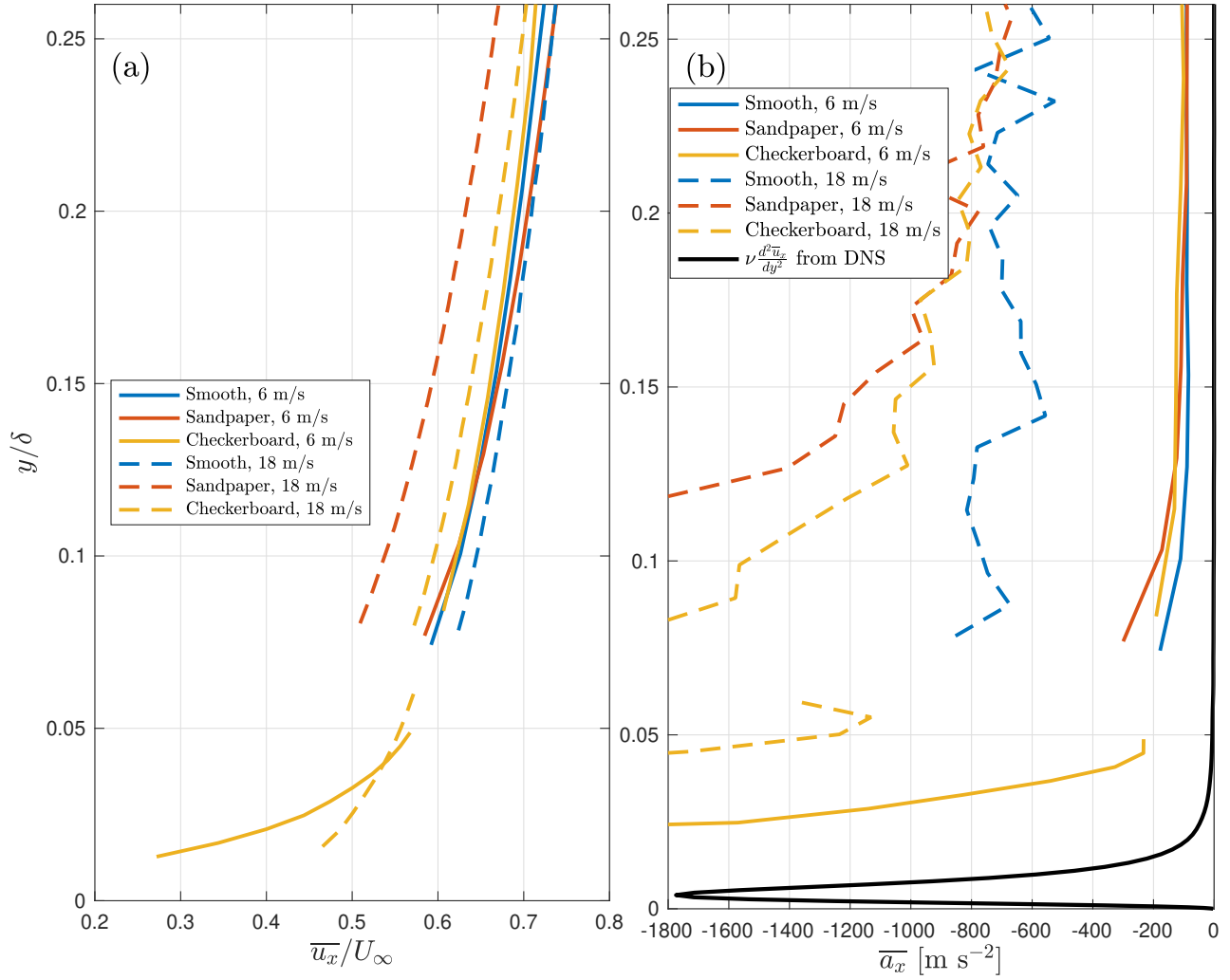


Figure 8. Vertical profiles of streamwise velocity and streamwise acceleration above the Checkerboard, Sandpaper, and Rough wall for the $U_\infty = 6 \text{ m s}^{-1}$, and $U_\infty = 18 \text{ m s}^{-1}$ cases. The datapoints making up these profiles are bin averaged across volumes of $50 \text{ mm} \times 50 \text{ mm} \times 0.6 \text{ mm}$ in the x , z , and y directions respectively. Checkerboard data shows data from two different datasets at high and low y positions. In plot (b) comparison data from a zero-pressure gradient smooth wall turbulent boundary layer, acquired through direct numerical simulation is shown. Unlike the other lines this is not binned material acceleration and is instead the streamwise viscous term of the Reynolds-averaged Navier Stokes equation.

boundary layer the streamwise mean acceleration is thus given by

$$\bar{a}_1 \simeq \nu \frac{d^2 \bar{u}_x}{dy^2} \quad (3)$$

DNS data of a smooth wall turbulent boundary layer was used to confirm that the neglected terms on the right hand side are indeed significantly smaller than the remaining one. The data also reveals that, for this particular flow, the major contribution to mean acceleration (cp. 1) is due to the wall normal gradient of the Reynolds shear-stress $\overline{u'_1 u'_2}$. Here, the DNS data is used to obtain reference data for $\bar{a}_1$.

The corresponding Re_θ , based on freestream velocity U_∞ and momentum thickness θ , for the DNS is 2500. For reference, the Re_θ of the experimental cases was 1420 for the 6m s^{-1} case, and 3410 for the 18m s^{-1} case. Translating the DNS data into physical units based on $\rho = 1 \frac{\text{kg}}{\text{m}^3}$, $\nu = 1.5 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}}$ and $u_\infty = 18 \frac{\text{m}}{\text{s}}$ yields the result plotted in Figure 8 (b) jointly with the experimentally obtained values. It can be seen that a large discrepancy is present between the simulated viscous term and the measured material accelerations for the smooth wall. Strong deceleration in the DNS data is limited to a very thin near-wall region (around 1% of the boundary layer thickness) while the experimental data reveal significantly stronger deceleration also further away from the wall. While the qualitative behaviour of the experimental curves is reasonable from a physical point of view (stronger deceleration near the wall for all cases, strongest deceleration for the homogeneous sandpaper and weakest for the smooth surface), the quantitative values appear to be off.

A section of the data used to generate the experimental profiles shown in Figure 8 is expanded in Figure 9. With (a) and (c) displaying statistics for streamwise velocity, and (b) and (d) showing statistics for streamwise acceleration. This data is binned over a small distance in the y direction and the same repeating unit in x and z that is used in Figure 8. It is equivalent to one data-point making up the vertical profiles.

In the case of velocities it can be seen that a well converged mean velocity of 13.3m s^{-1} is reached relatively fast with a relative standard deviation of $\sigma_{u_x}/\overline{u_x} \approx 10\%$. For accelerations the mean converges towards a value of -48.7m s^{-2} , which is in the range we have been observing in profiles up to this point. However; this mean value has a standard deviation of 5880m s^{-2} , which corresponds to a ratio $\sigma_{a_x}/\overline{a_x} = \mathcal{O}(10^2)$. The size of this standard deviation indicates that the accelerations measured by individual particles are more varied than the velocities experienced by these same particles. If we assume that these values follow a normal distribution then 99.7% of values will fall within the mean ± 3 standard deviations. In the case of the velocities this is $13.3 \pm 4.11 \text{ m s}^{-1}$, and in the case of accelerations this is $-48.7 \pm 17640 \text{ m s}^{-2}$. Despite the large number of particles in a sample at one voxel (324,000 in this case) it is possible that the magnitudes of the acceleration values are making convergence slow, and that the discrepancy in values visible in Figure 8 (b) is caused by the accelerations being less converged than would be hoped.

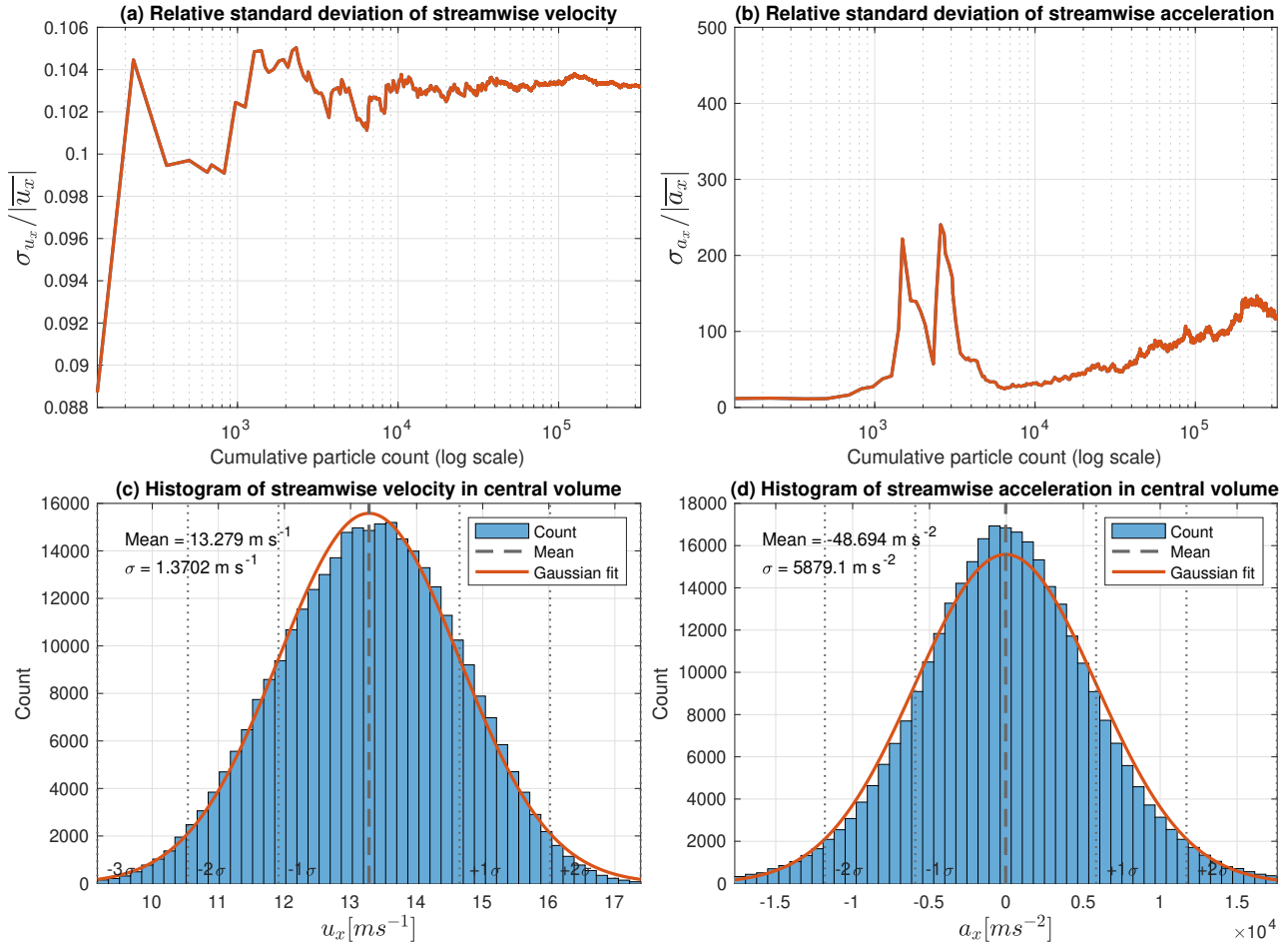


Figure 9. Analysis of the acceleration and velocity data from the smooth wall $U_\infty = 18 \text{ m/s}$ MP-PTV case. This was binned over a volume of $50 \text{ mm} \times 50 \text{ mm} \times 0.6 \text{ mm}$ in the x , z , and y directions respectively. This corresponds to the data used to plot one point in the STB profiles in Figure 8.

It is speculated that an artificial source of acceleration could be caused by imperfectly corrected camera shake. Measures have been taken to curtail the influence of this on acceleration results by removing particles discovered in frames with higher mean accelerations; however this was not found to significantly reduce the standard deviation of acceleration values. This would indicate that either there is a constant shaking due to the cameras in every time step, or this is not the source of the variation. Still, it is hard to fully eliminate the possibility of camera shake being a cause when the cameras were positioned relatively close to the flow.

4. Conclusions

Dense near-wall MP-STB data was acquired down to within 0.3 mm of the highest sandpaper peaks, which provided the data necessary to confirm the local flow heterogeneity caused by the sandpaper. A full repeating unit of the checkerboard is well resolved at this height and presented in Figure 6. This is the first time this particular heterogeneity has been observed using an experimental optical technique.

Flow over the checkerboard roughness shows increasing heterogeneity as the Reynolds number increases; this is in agreement with the preliminary HWA channel flow study. Only one physical length scale s of the checkerboard patches has been examined, however; by varying the Reynolds number we vary the ratio of patch size to flow length-scales. It is currently hypothesized, based on the data presented here, that patch size scaled with inner units needs to exceed a threshold for the flow to perceive the surface as heterogeneous.

The heterogeneity observed here is visible only close to the wall, and even then only in a few of the flow components. It is observed that the u_x flow component is influenced the most by the checkerboard roughness, with the u_y component being slightly affected, and the u_z component being close to the noise-floor of this experiment. The Lagrangian nature of the data acquired using MP-STB furthermore allowed the observation of material acceleration data, in which visible heterogeneity was observable in the same flow components as it was for velocity. These statistics are presumed to be unique to the turbulent boundary layer case, and are not expected to have been similar in the channel-flow case if they had been measured.

The location and shape of the visible heterogeneity is reminiscent of the internal boundary layers that could be observed by Bou-Zeid et al. (2004) in the case of a roughness of the span strips. It is believable that in this case internal boundary layers are also forming due to the roughness step changes in the streamwise direction.

Quantitative measurements of material acceleration met significant challenges when being compared to DNS data, there are several speculated causes for experimental error or slow convergence of data. The relative size of the standard deviations of the acceleration and velocity measurements

compared to their mean values was also interesting to note. It is possible that acceleration measurements at sufficient accuracy for DNS comparison should be carried out using TR-PTV instead of MP-PTV, in highly turbulent cases such as this, in order to reduce volatility in acceleration values. Nevertheless there seems to be a constant negative bias of the acceleration statistics which is speculated to scale with the flow velocity and not roughness type. This can be seen in Figure 8 (b), in the way that the $U_\infty = 6\text{ m s}^{-1}$ data reaches a constant value above $y/\delta = 0.15$, which is similar across all roughnesses. This negative offset could be caused by imperfect single image correction, camera or setup shaking, or tracks disproportionately going missing due to high positive accelerations. This negative offset seems to be consistent across all measured results. The analysis of this peculiarity is documented in detail in order to give potentially useful information for future STB experiments.

Despite this negative bias to the acceleration results, the topology of the near-wall streamwise acceleration field (a_x) yields interesting observations on the relative accelerations. It can be seen in Figure 7 that neither the rough or smooth patches show constant acceleration, instead the deceleration above the rough patch increases towards its trailing edge while the deceleration above the smooth patches decrease towards its trailing edge. Despite this gradual change the a_x field also seems to cross a step change as it transitions from one roughness to the next. This contrasts with the velocity field in the same location shown in Figure 6, in which this step change is less visible and the flow speed more gradually increases. The flow topology of Figure 7 is more similar in pattern to the fast information transmission seen in the u_y velocity component (Figure 5) than the slow transmission of the u_x component seen in Figure 6.

It is presumed that the more accurate map of flow acceleration can be inferred from the velocities in figure Figure 6 and that the flow is truly accelerating above these smooth patches. This can be explained physically by high velocity fluid descending from higher in the boundary layer to replace the lower speed fluid above the previous rough patch. It is not fully clear where the displaced fluid exits this system, possibly it is either accelerated or displaced laterally into neighbouring rough patches lower than is visible in these measurements.

Future work aims to identify a critical patch size in viscous units above which the flow perceives the surface as heterogeneous and in which velocity component the flow heterogeneity starts to develop. It is also intended that further research is carried out on the subject of streamwise boundary layer development above heterogenous roughness, and how far the heterogeneity extends in the wall-normal direction.

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