Abstract
Quadrant analysis based on the Reynolds decomposition was performed on the data from turbulent boundary layer flows above variously rough surfaces. An estimation of a convective velocity for events significant in terms of momentum flux, and the statistics of a length and amplitude of the individual events, together with their spectral analysis, was performed. Based on the analyses, we were able to detect a few individual sweep and ejection events with a length longer than 6\(\delta\), which could be considered as very large scale motions (VLSM). We also identified number of events with a longitudinal dimension equal to approximately 3\(\delta\) labelled as large scale motions (LSM). The analyses were executed for various Reynolds numbers. The number of detected structures increases with the momentum of the flow.

Keywords: wind tunnel, large scale motion, quadrant analysis

1 Introduction
Detection of the large scale motion and the very large scale motion in the turbulent flows attracted the attention of the scientific community since it represents a unique organised feature containing high degree of correlation and large momentum [1, 2, 3, 4, 5]. The existence of VLSM was firstly termed by [1], who identified an extremely long pattern in the flow. These patterns had the longitudinal dimension larger than 6\(\delta\), where \(\delta\) denotes the boundary layer thickness. The patterns could have achieved a length up to 10\(\delta\) or even 20\(\delta\). Later, the numerical simulation revealed VLSM as a relatively narrow worm-like tube of high momentum inside the flow [6].

In this paper, the five types of surface roughness were tested as they generate a turbulent flow analogous to the environmental flows over a terrain with obstacles. The geometry of the surfaces was designed so it replicated the surface turbulent boundary layer above several surface roughness categories, namely slightly rough, moderately rough, rough and very rough category, according the guideline VDI [7].

2 Experimental Set-up
The measurement campaign was conducted in a pressure driven wind tunnel with a test section of the dimensions 0.25 m \(\times\) 0.25 m \(\times\) 3.00 m. A fan, followed by a 3 m long tunnel duct and a contraction pipe, was installed upstream of the test section. At sufficiently long downstream fetch from the tunnel mouth, the temporally-spatial measurement of flow dynamics by means of time-resolved particle image velocimetry (TR-PIV) was conducted. The main 2-component 2-dimensional (2C 2D) TR-PIV measurements were performed for four nominal velocities (5-13 ms\(^{-1}\)) in order to study dependence on the Reynolds number. Reynolds number, based on a thickness of the boundary layer \(\delta\) and a friction velocity \(u^*\), according formula \(Re\tau=\delta\cdot u^*/\nu\), ranged \(Re\tau=570-7080\).
The modified Quadrant analysis was applied to identify VLSM. We were able to determine a duration, frequency and length of non-vortical structures which contribute mostly to the momentum and turbulent kinetic energy (TKE) of the flow. The axis parallel with prevailing flow direction is labelled as $X$, the lateral one as $Y$ and the wall-normal as $Z$.

![Diagram of model surface labelled M4](image)

**Figure 1:** Scheme of a model surface labelled M4, covered by the roughness elements, and with installed spires at the beginning. The green triangle denotes a laser sheet illuminating the investigated region (IR).

### 3 Results

The Quadrant analysis was applied to the velocity data from PIV measurement. The quadrant analysis is capable to identify a specific structure based on the direction of momentum flux contained inside it. As its name suggests, the quadrant analysis separates the momentum flux captured in one event into four quadrants based on the sign of both the longitudinal and vertical velocity fluctuations. Hence, the method represents a stronger criterion for detection of a structure compared to any method, which localises only the acceleration and deceleration of the longitudinal velocity. The definition of the quadrant analysis is sketched at the bottom in Fig. 2.

For each quadrant, the onset, the cessation and the length of the compact body of specific quadrant event was evaluated. To achieve it, the spatially relative cumulative contribution from particular event to total momentum flux $\tau_{\text{total}}$ in the entire investigated region (IR) was expressed by ratio of sum of the momentum flux from particular event $\tau_i$ (T) over the surface occupied by this event to the total momentum flux within the entire IR at each dimensionless time instance $\tau_{\text{total}}$, where $T=tU_\delta/\delta$. In case that the top of the boundary layer was not reached before the outer edge of a ceiling boundary layer starts, the maximum wind speed across the profile and its elevation was implemented into the formula for dimensionless time $T'=tU_{\text{max}}/H_{\text{max}}$. To avoid any unambiguity of the operations with negative and positives momentum flux terms, the absolute values of all the momentum flux values were used. The contribution was plotted in Fig. 2a, b for sweep and ejection.

The onset and the cessation of the compact body of specific quadrant event, defined as the time instance when relative contribution exceeds the threshold of 30% (red horizontal line in fig. 2), was calculated for the reference flat surface (surface layer M1) and Reynolds numbers $Re_\tau=570$ and $Re_\tau=1170$. Figure 3a, b shows the every single event detected by our algorithm together with its dimensionless length. The abscissa represents the onset of each event in the non-dimensional time $T'=tU_\delta/\delta$. The ordinate represents the normalised length $L/\delta$ (physical length of the compact structure normalised by the boundary layer thickness $\delta$).

All the identified events are spatially compact, their front edge and rear edge is clearly detectable. Each structure’s length was calculated as the time interval of its presence multiplied by a convective
velocity of the structure. Since the upper edge of each event move faster than the bottom of the event, the convective velocity of the whole event is derived by a special procedure. The sweep curve (red) in Fig. 2 is subtracted from the ejection curve (green), output is labelled $\delta S(T^*)$, and it is correlated with all the local time-series of local $\delta S_{u'w'}(T^*, x, z) = \tau_{\text{ejection}}(T^*, x, z) - \tau_{\text{sweep}}(T^*, x, z)$ across the entire IR($x, z$). The location [$x, z$] achieving the highest correlation between $\delta S(T^*)$ and $\delta S_{u'w'}(T^*, x, z)$ is considered to be a proper location for the estimation of the convective velocity of the large structures (see Fig. 4). The local time-mean velocity at this particular point is extracted and multiplied with a duration time of each event. By this, the length of the structure is obtained.

Figure 2: Relative intermittent contribution to the total momentum flux from the sweep and ejection events for surface M1 and two different Reynolds numbers a) $Re = 570$ and b) $Re = 1170$. The red horizontal line denotes threshold factor 30%. The diagram at the bottom represents a definition of the quadrants.

This methodology can be described with a certain level of simplification such that we were looking for one and only location, which was regarded as the most representative in terms sweep-ejection behaviour for the whole domain. At this one location, the behaviour of the sweep-ejection correlates strongly with an integral behaviour of the whole BL (or with the outer layer perhaps).
emphasize that the scale of the structure is not spatially limited just for the log-layer but expands into the entire BL.

Based on the Quadrant analysis, the average stream-wise length achieved is approximately $L=2-4\delta$ (these structures were considered as LSM). We were able to detect also a few individual sweep and ejection events with the length longer than $6\delta$, which could be considered as VLSM. A few events reached even the length of $L=10\delta-20\delta$. These few VLSM structures were hidden in the Fourier and wavelet spectral statistics and they were not detectable in the spectrograms. In a sum, we detected 50 sweep events and 90 sweep events for $Re_\tau=570$ and $Re_\tau=1170$, respectively.

![Figure 3](https://example.com/figure3.png)

Figure 3: Individual dominant sweep events identified in the flow. The relative contribution of the event has to be higher than 30% of the instantaneous total momentum flux to prevent a detection of noise.

![Figure 4](https://example.com/figure4.png)

Figure 4: Correlation coefficient between local $\delta S_{uw}(T^*, x, z)$ and integral $\delta S(T^*)$ for the surface M4. The dimension of PIV investigated region is re-scaled in respect to the boundary layer depth.
An overview for all the nominal velocities (5, 7, 10 and 13 ms$^{-1}$) and all five types of the surfaces (M1-M5) are depicted in Fig. 5. Notwithstanding, the number of identified (V)LSM is however small for small Reynolds number Re. Hence we evaluated median instead of mean values. The median lengths are plotted in absolute (non-normalised) values to compare physical changes between the differently rough surfaces. The only noticeable changes, however, can be seen for the reference surface M1 (check the solid lines in Fig. 5). With the increasing nominal wind speed, and consequently with increasing Re, the increase in the length of the sweep structures is documented. This is apparently striking for the low threshold factor. Similar results were observed also for other quadrant events - inward, ejection and outward, respectively. The other surfaces with higher roughness did not indicate any Reynolds dependence for the length of structures.

![Figure 5: The statistics with plotted median length of the sweeps in dimension values to mutually compare the physical character of the flows.](image)

4 Conclusion

The analysis of the five surface roughness models was executed and the test of Reynolds independence was performed. The number of large scale motions and a few very large scale motions were detected by means of Quadrant analysis. The momentum of the wind speed affected the number of the observed events, hence with the increasing Reynolds number, the number of identified large events increased. In terms of statistics, the length of the LSM and VLSM increased with the Reynolds number in case of the flat reference surface M1. Other surfaces did not exhibit a significant statistical Reynolds number dependence in the length of the large scale structures.

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References


