An Experimental Study of Turbulent Flow in the Vicinity of Transverse Square Bars

Dubravka Pokrajac

Abstract This paper presents results from an experimental investigation of rough turbulent open channel flow over transverse square bars. Bar spacing was systematically varied between 2 and 20 bar heights. Velocities were measured by means of Particle Image Velocimetry (PIV), which captured details of flow fields above and between the bars. The streamlines calculated from the time-averaged flow velocities show the shape of persistent vortices in the gap between the bars. Further analysis is based on Double-Averaged Navier-Stokes equations (DANS). Momentum exchange between the flows above and within the gaps is explored using spatial quadrant analysis and the decomposition of the spatially averaged turbulent stress.

1 Introduction

Simple strip roughness has been extensively studied (e.g. [1, 2, 3]) because it is relevant for engineering practice (heat exchangers, street canyons in the urban roughness layer, river groin fields) and at the same time offers an opportunity for furthering the fundamental science and understanding of flow over any rough boundary.

This study uses the PIV velocity measurements to explore the spatial structure of turbulent flow above and between transverse square bars. Particular attention is paid to momentum exchange between the high-momentum flow above the roughness and the low-momentum flow within the gap between the bars. Because of flow heterogeneity it is very convenient to add a second averaging step, spatial averaging, to conventional time/ensemble averaging of flow quantities. Spatial averaging of non-linear momentum flux introduces new stress terms in the DANS equations. They are investigated using new versions of quadrant analysis suggested in [5, 6].

Dubravka Pokrajac
School of Engineering, University of Aberdeen, Fraser Noble Building, Old Aberdeen AB24 3UE,
United Kingdom e-mail: d.pokrajac@abdn.ac.uk

2 Experimental Setup

Experiments were carried out in a 0.4m wide and 11m long tilting hydraulic flume. They involved steady uniform flow with fully developed rough boundary layer. The flow depth was $H=50\text{mm}$. The rough beds were formed by fixing square bars (height $k = 6.2\text{ mm}$) to the flat base of the flume along the whole length. The spacing between the axes of adjacent bars, measured in terms of bar height was: $L = 2, 3, 5, 6, 7, 8, 10, 12, 15$, and 20. Roughness Reynolds numbers (ku_* / ν) were around 200.

Velocities were measured by means of a Particle Image Velocimetry (PIV) system. A double pulsed Nd-Yag laser was positioned above the flume to illuminate vertical planes in the longitudinal centerline of the flume. Camera resolution was 1008×1008 pixels. VidPIV analysis software was used for evaluating the velocity field from the PIV images. The measurement window was always positioned between the axes of adjacent elements. Depending on the spacing between the bars this resulted in the physical size of a pixel of 50 to $125\text{ }\mu\text{m}$. The of interrogation areas was 32×32 pixels. A single experiment produced around 300s long time series of the two velocity components at 128×128 points across the measurement window, with a sampling frequency of 13Hz. Further details about experimental setup can be found in [6].

Fig. 1 Streamlines calculated from the time-averaged velocities for various bar spacing. Please note that x and z have different scales.

3 Results and discussion

The right-handed Cartesian coordinate system is used with (x, y, z) denoting stream-wise, lateral and bed-normal coordinate axes, respectively, and (u, v, w) denoting the corresponding velocity components.

Time-averaged (u, w) field was used to calculate streamlines shown in Figure 2. For the smallest spacing $L = 2$ there is only a single stationary vortex, whereas for $L = 3, 4, 5$ there is also a second vortex in the upstream corner of the gap. At spacing $L = 6$ another vortex has formed in front of the downstream bar. Flow re-attachment first occurs around spacing $L = 7$. For $L > 7$ the re-attachment point remains approximately at 5-6 roughness heights from the beginning of the gap. The streamlines above the roughness follow the shape of flow separation: for small spacing, $L = 2, 3, 4, 5$, they are approximately parallel, whereas from spacing $L = 6$ onwards they become more and more 'wavy' as external flow penetrates into the gap.

Further analysis makes use of so-called Double-Averaging Methodology [4], which involves two averaging steps, one in time and one in space. Spatial averaging was performed over thin wall-parallel volumes spanning between the axes of adjacent bars i.e. over single rows in the matrix of measured velocities. The following notation is used: $\bar{u}, \langle u \rangle, u', \tilde{u}$ denote time average, spatial average, deviation from the time average and deviation from the spatial average (spatial perturbation), respectively, of any flow quantity, for instance streamwise velocity. For fixed roughness all these operators commute. Furthermore, spatial averaging operators and rules are analogous to their time/ensemble averaging counterparts, e.g. $\langle uw \rangle = \langle u \rangle \langle w \rangle + \langle \tilde{u} \tilde{w} \rangle$. An instantaneous velocity at a point can be decomposed into

$$u = \langle \bar{u} \rangle + \langle u \rangle' + \tilde{u} + \tilde{u}' \quad (1)$$

so that applying two averaging steps to kinematic momentum flux yields four terms. For instance averaging uw twice yields

$$\langle \bar{u} \bar{w} \rangle = \langle \bar{u} \rangle \langle \bar{w} \rangle + \langle \tilde{u} \tilde{w} \rangle + \overline{\langle u \rangle' \langle w \rangle'} + \overline{\tilde{u}' \tilde{w}'} \quad (2)$$

The first term on the right hand side of (2) is macroscopic momentum flux whereas other three (with negative sign) become, respectively: dispersive stress (called form-induced stress in some literature), large scale turbulent stress and small scale turbulent stress [6]. As illustrated in Figure 2, this result is obtained regardless of the order of the two averaging steps (time/space or space/time). In the next two sections the dispersive stress and the large scale turbulent stress are further explored using new versions of quadrant analysis [5, 6]. The value of u_* used for scaling was determined from spatially-averaged Reynolds stress measured at the level of roughness crest i.e. $u_*^2 = -\langle \overline{u' w'} \rangle_{\text{crest}}$.

Fig. 2 Double averaged momentum flux. Spatial averaging is performed from left to right, and temporal averaging from bottom up. Either time/space, or space/time averaging results in the resolved momentum term (dark grey) and three apparent stress terms (light grey).

3.1 Persistent spatial velocity perturbations

A spatial quadrant diagram shows spatial perturbations of time-averaged velocity components ($\tilde{u}, \tilde{w}$) for a series of points within the same averaging volume i.e. along a wall-parallel plane. Figure 3 shows four quadrant diagrams for three bar spacings $L = 3, 5, 15$. Because the persistent flow structures cause regular and smooth changes of the velocity components the shape of each quadrant diagram traces a single orbit over a single bar spacing. There is a clear difference between the three sets of quadrant plots: for the small spacing $L = 3$ velocity perturbations below the roughness crest (white symbols) are much larger than those above (black symbols); for medium spacing $L = 5$ the perturbations below and above the crest are similar and the latter show a distinct ring-like shape; for large spacing $L = 15$ perturbations above the roughness crest become dominant and continue to be ring-like.

Alternatively it is possible to colour-code all measurement points according to the quadrant where they belong. These plots, called 'quadrant maps' are also shown in Figure 3. Stationary vortices behind the bars are shown as regular Q2 and Q4 diagonal strips, enclosing a single Q1/Q3 strip. For spacing $L = 3$ flow structure above the roughness is random, whereas from $L = 5$ onwards it shows a regular Q1, Q4, Q3, Q2 sequence of quadrants, which is a consequence of a stationary wave formed above the bars.

3.2 Large-scale turbulent velocity fluctuations

Large-scale turbulent velocity fluctuations $\langle u \rangle', \langle w \rangle'$ are related to the turbulent motion of the fluid instantaneously occupying an averaging volume. Significant values of $\langle u \rangle', \langle w \rangle'$ show the presence of turbulent structures larger than the averaging volume [6]. Quadrant diagrams of $\langle u \rangle', \langle w \rangle'$ plotted for an averaging volume resemble conventional quadrant diagrams (Figure 4). Alternatively, the color-coding of quadrants can be used for plotting an instantaneous quadrant 'profile', which shows the quadrant colour for each level above the bed. Time series of such quadrant profiles, sampled above the threshold of $0.5u_*^2$ are shown in Figure 4. Irrespective of the bar spacing Q2 and Q4 events are dominant, with other two quadrants almost entirely

Fig. 3 Quadrant maps (top panels) and quadrant diagrams (bottom panels, observation plane level shown in the top panels) for bar spacing $L = 3, 5, 15$. The shade of grey for quadrant maps is progressively darker from Q1 to Q4.

absent. Individual profiles typically belong to the same quadrant over majority of the flow depth. This confirms that the turbulent events indicated by those profiles indeed have large spatial scales, comparable with the flow depth. In this respect all three spacings are similar. However, bar spacing affects the depth of penetration of the large structures: for $L = 2$ they are limited to the level of the roughness crest whereas for $L = 5$ and $L = 15$ they penetrate well below the crest.

4 Conclusions

PIV measurements of turbulent flow over transverse square bars were carried out, with a range of bar spacing (2-20 bar heights). Results show the geometry of stationary vortices between the bars. Flow reattachment first occurred around spacing 7. The reattachment point was always at 5-6 bar heights.

New forms of quadrant analysis were performed, based on the double decomposition of flow velocity. Spatial quadrant diagrams show regular persistent spatial structures governed by the geometry of the stationary vortices. Quadrant analysis of large-scale turbulent fluctuations reveals Q2 and Q4 structures which covered majority of the flow depth. For small bar spacing ($L \leq 3$) they remained above the roughness crest whereas for $L \geq 5$ they penetrated into the gap between the bars.

Fig. 4 Top panels: Time series of the quadrant profiles for bar spacing $L = 3, 5, 15$, sampled over the threshold $|\langle u \rangle' \langle w \rangle'| < 0.5u_{\tau}^2$. The shade of grey for quadrant profiles is progressively darker from Q1 to Q4. Level of the roughness crest is shown with a full line. Bottom panels: Quadrant diagram for a plane shown with a dashed line in the top panel.

Acknowledgements This investigation was funded by United Kingdom Engineering and Physical Sciences Research Council (Grant GR/R51865/01).

References

1. Djenidi, L., Elavarasan, R., Antonia, R.A.: The turbulent boundary layer over transverse square cavities. *J. Fluid Mech.* **395**, 271–294 (1999)
2. Krogstad, P.-A., Andersson, H.I., Bakken, O.M., Ashrafian, A.: An experimental and numerical study of channel flow with rough walls. *J. Fluid Mech.* **530**, 327–352 (2005)
3. Leonardi, S., Orlandi, P., Smalley, R.J., Djenidi, L., Antonia, R.A.: Direct numerical simulations of turbulent channel flow with transverse square bars on one wall. *J. Fluid Mech.* **491**, 229–238 (2005)
4. Nikora, V., McEwan, I., McLean, S., Coleman, S., Pokrajac, D., Walters, R.: Double averaging concept for rough-bed open-channel and overland flows: Theoretical background. *ASCE J. Hydraulic Eng.* **133**(8): 873–883 (2007)
5. Pokrajac, D., Campbell, L.J., Nikora V., Manes, C., McEwan, I.: Quadrant analysis of persistent spatial velocity perturbations over square-bar roughness. *Expts. Fluids* **42**, 413–423 (2007)
6. Pokrajac, D., McEwan, I., Nikora, V.: Spatially averaged turbulent stress and its partitioning. *Expts. Fluids* **45**, 73–83 (2008)