Turbulence structure and coherent motion in a straight laboratory flume

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Abstract: Improvements on the understanding of coupling between the near-bed flow and the sediment transport are needed for the numerical simulation. In the present paper analyses are based on experimental work carried out in a straight channel, constructed at the laboratory of the Dipartimento di Ingegneria Civile, Ambientale ed Aeronaautica - Palermo’s University (Italy), for two different roughness conditions of the side-walls. Detailed measures of flow velocity field have been obtained through an acoustic velocimeter profile (DOP 2000). The results show that the flow is characterized by alternating high-low speed fluid regions which lead to the formation of turbulent coherent structures. The conditioned quadrant analysis and the space-time correlations of the conditioned data are applied to define the occurrence of turbulent events.

Keywords: Open channel flow, flow turbulence structure, burst cycle, walls roughness, laboratory experiments.

1 INTRODUCTION

Several researches (among others Nezu and Rodi, 1986; Nezu and Nakagawa, 1993; Shvidchenko and Pender, 2001) on turbulence characteristics in open channel flow have emphasised the formation, near the walls (i.e. in the "wall region"), of turbulent coherent structures which occur at different positions and times, but possessing a common coherent pattern (Pope, 2001). These structures evolve cyclically according to the sequence ("bursting sequence") of four events: inward interaction, ejection, sweep and outward interaction (Kline et al., 1967; Corino and Brodkey, 1969; Cantwell, 1981; Nezu and Nakagawa, 1993; Shvidchenko and Pender, 2001). The study of the evolution of these events is important for the analysis of sediment transport phenomena (Kaftori et al.; 1995; Nino and Garcia, 1996; Shen and Lemmin, 1999). Especially ejection and sweep events, which are related to turbulent energy production, are important. Most studies have been conducted on the evolution of vertical turbulent structures (see as an example Nelson et al., 1995) but very few studies have focused on the evolution of horizontal turbulent structures (White and Nepf, 2007). But, some authors (Yalin, 1992; da Silva, 2006) have exalted the role of horizontal turbulent structures on the formation of alternate bars on the bed. Recent experimental investigations conducted in a straight laboratory channel with alternating bars (double-row) on the bed (Termini, 2005; Termini and Lo Re, 2006; Termini and Sammartano, 2007) have highlighted the formation of horizontal turbulent structures which evolve with the same spatial periodicity of the alternate bars. However, still today, the dynamics and consequences of coherent structures have not yet been clarified (Nezu and
Nakagawa, 1993). Particularly, improvements of the understanding of the side-walls influence on the mechanism of turbulence production need. Thus, in this paper preliminary experimental results on the effect of side-wall roughness on the formation of horizontal turbulent structures are reported. The analysis is conducted by applying the conditioned quadrant analysis to select the most significant events.

2 EXPERIMENTAL APPARATUS

Experiments have been carried out in a straight canal constructed at the laboratory of the Dipartimento di Ingegneria Civile, Ambientale ed Aeronautica – University of Palermo. The channel is 0.4 m wide and 7.0 m long. The bed of the channel (longitudinal slope of 0.45%), consists of quartz sand ($D_{50} = 0.65$ mm, $D_{16} = 0.55$ mm, $D_{84} = 0.90$ mm). The bed is fixed in a first reach 1.0 m long and it is mobile in the remaining 6.0 m. The channel’s side-walls are rigid and made of plexiglas. The plan-view of the experimental apparatus is shown in Figure 1.

Two experimental runs were conducted: for the first run (run 1) the side-walls of the channel were smooth (plexiglas) and for the second run (run 2) rough side-walls were used. In this last case the plexiglas channel’s side-walls were covered with the same sand as on the bottom. The experimental runs were conducted with flow discharge of 0.013 m$^3$/s (run1: Re=32538, run 2: Re=35975). During each experiment (duration of about 7 hours) the instantaneous velocity components (longitudinal, transverse and vertical) were measured along five verticals of 17 cross-sections (cross-sections C-Y of Figure 1). The first four cross-sections (C, E, K and F) were spaced 50 cm; in the channel reach between section F and section Y, the consecutive sections were spaced of 20 cm. The transversal and longitudinal velocity components were measured by using the 2D (side-looking) Acoustic Doppler Velocimeter (ADV) (sampling frequency of 25 Hz); the vertical velocity component was measured by using the Acoustic Doppler Profiler (DOP2000) (see details in Termini and Sammartano, 2008).

3 DATA ANALYSIS

3.1 Methods

In this work, the analysis is restricted to the channel reach between section F and section L (see Figure 1). In order to analyze the formation of turbulent structures along this reach, the turbulent fluctuation components, $u_i'$ (with $i = 1, 2, 3$; $i = 1$ = longitudinal direction, $i = 2$ = transverse direction, $i = 3$ vertical direction) have been estimated from the instantaneous velocity components, $u_i$, measured during each run (smooth and rough side-walls). Paying special attention to the evolution of turbulent structures with vertical axis, in this work only the longitudinal and transverse components have been considered.

First, the formation of horizontal turbulent coherent structures has been investigated by applying the quadrant analysis. Thus, the instantaneous products $u_1'u_2'$ have been estimated as deviations of the instantaneous flow velocity components from the corresponding time-averaged values. Analyses on the time-average flow field can be found in previous works (Termini and Sammartano, 2007, 2008).

![Figure 1. Experimental apparatus](image-url)
In order to define properly the probability of occurrence of each event in the $k$-th ($k = 1, II, III, IV$) quadrant, it is necessary to isolate the contribution of the most significant events. For this purpose, an "excluding area" has been identified on the plan $u_1',u_2'$. This "excluding area" is bounded by the hyperbolic curves of equation (Nezu and Nakagawa, 1993):

\[
|u_1',u_2'| = q \sqrt{u_1'^2 + u_2'^2}
\]

(1)

where $q$ represents the threshold level of exclusion. On the basis of analyses conducted in a previous work (see Termini and Sammartano, 2008), it has been assumed a threshold level $q = 1$, which represents the value of good compromise between the significance of events and the acceptable number of $u_1' - u_2'$ pairs. Thus, for each measurement point, the time series $u_1'$ and $u_2'$ have been filtered, by the aforementioned excluding area on the plan $u_1',u_2'$. The filtered time series ($u_1',t$ and $u_2',t$) have been used to define the probability of occurrence of each event in the $k$-th quadrant.

Taking into account the central-limit theorem, the joint probability density function ($P_{12}$) of the variables $u_1', u_2'$, has been determined in terms of variances and the correlation coefficient, $\rho_{12}$, (see in Pope 2001) as:

\[
P_{12} = A_{12} \exp \left[ B_{12} \left( \frac{u_1'^2}{u_{1,f}^2} - 2 \frac{\rho_{12} u_1'u_2'}{u_{1,f} u_{2,f}} \right) + \frac{u_2'^2}{u_{2,f}^2} \right]
\]

\[
B_{12} = \frac{-0.5}{1-\rho_{12}^2} e^{-\rho_{12}^2} u_{1,f} u_{2,f} \left( u_{1,f}^2 + u_{2,f}^2 \right)^{\frac{3}{2}}
\]

(2)

Then, in order to identify the spatial-temporal cycle of observed turbulent structures, the conditional averaging technique (Nezu and Nakagawa, 1993) has been applied.

In order to identify the spatial-temporal cycle of observed turbulent structures the conditional averaging technique (Nezu and Nakagawa, 1993) has been applied. By considering the filtered time series $u_{1,f} - u_{2,f}$, the conditional average has been estimated as:

\[
<u_{1,f}(\Delta x, \tau) > = \frac{\sum \left( u_{1,f}(z,t+\tau) \right) \left[ u_{1,f}(z,t) \right]_{k_0}}{\sum u_{1,f}(z,t) \left[ u_{1,f}(z,t) \right]_{k_0}}
\]

(3)

where the subscripts $S$ and $S_0$ identify, respectively, the initial and the reference sections, $\Delta x$ is the spatial lag, $\tau$ is the lag time and the symbol $< >$ indicates the average conditioning.

### 3.2 Results

a) Quadrant analysis

In Figures 2a-2b the distributions of $P_{12}$ estimated, respectively along axis 1 and axis 3 (channel axis), in smooth side-walls condition (at a distance from the bed of $z = 1.0$ cm) are reported. The distributions of $P_{12}$ estimated in rough side-walls condition (at a distance from the bed of $z = 0.7$ cm), respectively along axis 2 and axis 3, are reported in Figures 2c-2d. On the plane $u_1' - u_2'$, $P_{12}$ is represented by an ellipse with long axis rotated according to the more frequent event.
From Figure 2a it can be observed that (in run 1) near the walls (axis 1), the long axis of the ellipse lies in the second and fourth quadrants for sections G, I and L; for the sections F and H the long axis of the ellipse is in quadrants I and III. In particular, along the axis 1, the peak value of \( P_{21} \) is in quadrant II for sections G and I; for section L the peak of the distribution lies in quadrant IV. Thus, it could be supposed that an ejection event occurs in section G and a sweep event occurs in section L. Along the channel axis (Figure 2b), the long axis of the ellipse assumes the direction opposite to that obtained at the same sections near the wall (i.e. at axis 1); for sections F and H the axis of the ellipse is rotated so to fall in the second and fourth quadrants with the peak value in fourth quadrant. In sections G, I, L the peak of the distribution is in quadrants I and III. For sections G and L the peak lies in quadrant I (outward interaction), while in section I it is located in quadrant III (inward interaction).

On the basis of the aforementioned it can be supposed that a vortex forms in section F near the walls; then it grows, moving away from the walls, so that an event of ejection occurs near the section G; due to the interaction with the main flow (section H), a new vortex forms (section I) and in section L a sweep event occurs. In the case of rough side-walls (run 2), it can be observed that, near the walls (axis 2), the probability density distribution shows (Figure 2c) a peak value in fourth quadrant at sections F, H and L; events of quadrant III occur in sections G and I. Therefore, it can be assumed that events of the same type occur in sections distant of 40 cm (as well as in the case of smooth side-walls). Along axis 3 (Figure 2d) events of quadrant III occur in sections F, G and L while events of quadrant II and IV occur in sections H and I. In particular, the position of the peaks of the distributions seem to indicate that sweep events occur in section H, while events of ejection are observed in section I; outward interaction events occur in sections F and G, while in the section I the type of event is not clearly discernible.

On the basis of aforementioned it seems that as effect of the side-wall roughness the spatial lag of sequence of turbulent events increases as one moves from the walls to the channel axis.

On the basis of the aforementioned, the average length of events of the same type seems to be proportional to \( \lambda_n = 0.40 \) m. This yields a value of the scale ratio that is proportional to the channel width \( B (\lambda = n \lambda_n - \text{with} n=1, 2) \).

b) Correlation and Conditional Averaging

The identification of the spatial lag \( \Delta x \) has been operated by taking into account the results obtained by the quadrant analysis (Figures 2a-2b). Thus, in the case of smooth side-walls, a value of \( \Delta x = 40 \) cm has been selected. Furthermore, assuming \( k = II, IV \) (events of ejection and sweep) along axis 1, the section G has been considered as the initial section (\( S0 = G \)) and the section I as reference section (\( S = I \)); along axis 3 it has been assumed \( S0 = F \) and \( S = H \).

In Figures 3a-3b the conditional averages calculated for the variables \( <u_i(\Delta x, t)> \), \( <u_i(\Delta x, t)> \), varying the time lag, have been reported. It may be noted that ejection and sweep events assume a peak value at time intervals approximately of 0.4-0.6 sec. Furthermore, along the both axes 1 and 3, positive peaks of \( <u_i(40, t)> \) correspond to negative peaks of variable \( <u_i(40, t)> \) and viceversa. This trend confirms that events of the same type, belonging to a whole sequence, occur in sections G and I along axis 1 and in sections F and H along axis 3.

In the case of rough walls (Figures 2c-2d), the analysis of the probability density function has highlighted (along axis 2) that a spatial lag of 40 cm occurs between events of the same type, as well as in the case of smooth walls. Along axis 3 such spatial lag seems to increase. Therefore, in this case, the sequence of events has been analyzed by assuming section F as the initial section for both axes 2 and 3, and, respectively, sections H and L as the reference sections.

Thus, the spatial lag has been assumed \( \Delta x = 40 \) cm along axis 2, and \( \Delta x = 80 \) cm along axis 3. It has been also assumed \( k = II, IV \) for axis 2 and \( k = I, III \) for axis 3.
The behaviours of the conditional average, calculated respectively along axis 2 and axis 3, are shown in Figures 4a-4b. These figures show that at axis 2 (Figure 4a) the peaks occur at time intervals of 0.4-0.6 sec. Furthermore, along axis 3 (Figure 4b) the sign of the peaks is mainly concorde, confirming that the sequence of events occur in the first quadrant. Thus, Figures 4a-4b seem to confirm that, near
the channel’s side-walls, events of the same type form with a spatial lag of 40 cm (as well as in the case of smooth walls). A greater spatial lag (of 80 cm) seems to occur along the channel axis. Thus, as effect of the roughness of the side-walls, the spatial lag of events of the same type seems to increase moving from the walls to the channel axis.

Figure. 4. Conditional averaging – rough side-walls: a) axis 2 \( k = II, IV \); b) axis 3 \( k = I, III \).

4 CONCLUSIONS

In the present work the formation of horizontal turbulent structures in a laboratory straight channel for two different roughness conditions of the side-walls has been analyzed. The joint probability density function has been determined to evaluate the occurrence of each event. The most significant events have been identified by filtering the turbulent fluctuation time series for a threshold level \( q = 1 \). Thus, the conditional averaging technique has been applied to determine the spatial and temporal lags of events of the same type. The analysis has showed that in the case of smooth side-walls the turbulent events occur alternatively near the walls and along the channel axis with a spatial lag of 40 cm. It seems that as effect of the side-wall roughness the spatial lag of sequence of turbulent events increases as one moves from the walls to the channel axis.

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