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Experimental Observation Of Turbulent Structures In A Straight Flume

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Abstract: Experimental and theoretical studies of the structure of turbulence in open-channel flows have shown that the dynamics of the wall layer turbulence is dominated by the formation and growth of turbulent structures which evolve periodically as part of the so-called bursting phenomena. In the present paper experimental results obtained in a straight flume for different roughness conditions of the channel walls are described. The occurrence of turbulent events is verified by applying the conditioned quadrant analysis. The information about the spatial and temporal scales of the events is obtained through the space-time correlations of the conditioned data.

Keywords: Open channel flow; sediment transport; bed-forms; flow turbulence structure; boundary roughness.

1. INTRODUCTION

The dynamics of wall layer turbulence is dominated by the formation and growth of turbulent structures (coherent structures) which evolve periodically as part of the so-called bursting sequences (Kline et al., [1967]; Corino and Brodkey, [1969]; Jackson, [1976]; Cantwell, [1981]; Kline and Robinson, [1990]). A bursting sequence consists of four events: inward interaction; ejection; sweep; outward interaction. Considerable experimental work has been conducted in order to investigate the “vertical” bursting sequences, that are formed by eddies whose axes of rotation are perpendicular to the vertical plane. Few studies have been performed in order to analyze the “horizontal” bursting sequences that are formed by eddies whose axes of rotation are perpendicular to the horizontal plane (Utami and Ueno, [1991]; Yalin, [1992]). Recent experimental analyses (Termini and Sammartano, [2007]; Termini and Sammartano, [2008]) conducted in a straight laboratory channel, with smooth banks and rough bed, have highlighted that the horizontal bursts could be responsible of the formation of alternate bars on the bed. This result is in accordance with other researches conducted in this field (Yalin, [1992]; da Silva, [2006]). However, the evolution of such horizontal turbulent structures strongly depends on the roughness condition of the channel walls that could affect the spatial length of the burst cycle (Nezu and Nakagawa, [1993]; Termini and Sammartano, [2009]).

The aim of the present work is to obtain better understanding on the effect of roughness conditions of channel boundaries on the evolution of “horizontal” turbulent events. The statistics of turbulent events are analyzed in different locations along a straight laboratory channel for two different values of roughness of the channel walls.

2 EXPERIMENTAL SET UP

The data analyzed in the present work were collected during experiments performed in a straight channel constructed at the Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, University of Palermo, Italy. The channel is 0.40 m wide and 7 m long. The plane view of the experimental channel is shown in Figure 1.
The channel banks are rigid and constructed of Plexiglas strips. The channel’s bed is rigid and covered by quartz sand ($D_{50} = 0.65$ mm, $D_{16} = 0.55$ mm and $D_{84} = 0.90$ mm); the longitudinal bed slope is of 0.45%. Two runs were conducted with water discharge of 13 l/s: the first run (called run 1) was with rough bed and smooth banks; the second run (called run 2) was with rough bed and banks (the channel banks were covered by the same quartz sand used for the bed).

During each run the vertical, stream-wise and transverse instantaneous flow velocity components were acquired along 5 verticals of 17 measurement cross-sections (sections C-Y of Figure 1). The distance between two consecutive cross-sections was of 20 cm. A 2D side-looking probe Acoustic Doppler Velocimeter (ADV) was used to measure the stream-wise and the transverse velocity components; an Acoustic Doppler Velocity Profiler (DOP 2000), was used to measure the instantaneous profile of the vertical velocity component (Lemmin and Rolland, [1997]).

In the present paper only the channel reach between sections F and L (see Figure 1) is analyzed. Since the attention is turned on the evolution of the horizontal bursts, only the longitudinal and transverse flow velocity components are examined.

3 THE HORIZONTAL FLOW VELOCITY FIELD

Figures 2 and 3, respectively, show the contour lines of the time-averaged longitudinal ($U$) and transverse ($V$) flow velocity components at a distance $z = 1$ cm from the bed, for both runs. The contour lines of Figure 2 (run 1) clearly show the formation of regions of different velocity patterns. Particularly, high values of the longitudinal velocity occur in the sections F and I; low values of longitudinal velocity are found in sections H and L. Thus, moving from section F to section H a reduction of the longitudinal flow velocity can be observed. As Figure 2 shows, the transverse flow velocity increases in value passing from section H to section I. Such observed trend of both the velocity components seems to suggest the development of ejection or sweep events near section F and between sections I and L; sequences of inward and/or outward events occur between sections H and I. The transverse velocity component presents a positive peak value at section I and a negative peak value at section F. Thus, the contour lines of the transverse velocity component show a changing of sign along each cross-section.

For run 2, as Figure 3 shows, the longitudinal velocity component has low peak values at sections F and H; high peak values of longitudinal velocity are found at sections G and L. The observed trend seems to identify the formation of ejection or sweep events near section G; events of inward and/or outward interaction seems to verify at section F. Between sections H and L an increasing trend of the transverse flow velocity can be observed. High positive values of the transverse flow velocity are found along the walls; at the channel axis only negative peak values can be observed in sections F, G and L.
In order to have a 3D view of the transverse flow velocity pattern, in Figure 4, the iso-surfaces of the transverse velocity component, $V$, are reported. This figure allows us to observe how the transverse velocity changes along the analyzed channel reach. In particular, as previously observed from Figures 2 and 3, Figure 4a shows that a positive peak value of $V$ is found at section I; a negative peak value is found at section F. Moreover, Figure 4 highlights that, at section I, the transverse velocity component decreases in value passing from the bed to the free surface. Similar behaviour can be observed at section G. Negative values of the transverse flow velocity can be observed, at longitudinal axes 2 and 4, near sections F and H.

In the case of rough walls (run 2), the changing of sign of the transverse flow velocity component occurs passing form axis 1 (where it is $V > 0$) to axis 5 (where it is $V < 0$). Along each longitudinal axis the transverse velocity flow changes sign along the vertical and the longitudinal directions.
Figure 4. Iso-surfaces of the transverse velocity component \( V \) (cm/s): a) run 1; b) run 2.

4. JOINT PROBABILITY DENSITY DISTRIBUTION

In order to analyze the evolution of the coherent turbulent structures, the conditional quadrant analysis (Nezu and Nakagawa, [1993]) has been applied. The instantaneous turbulent fluctuation components \( u_i(z,t) \) (with \( i = 1 \) in longitudinal direction, \( i = 2 \) in transverse direction; \( t \) is the time) have been estimated as difference of
the \(i\)-th instantaneous flow velocity component and the corresponding depth-averaged value. Then, the instantaneous plane \(u'_1 - u'_2\) has been divided into four quadrants; each quadrant corresponds to a turbulent event: quadrant I - outward interaction \((u'_1 > 0, u'_2 > 0)\); quadrant II - ejection event \((u'_1 < 0, u'_2 > 0)\); quadrant III - inward interaction \((u'_1 < 0, u'_2 < 0)\); quadrant IV - sweep event \((u'_1 > 0, u'_2 < 0)\).

In order to select only the strongest events for each measurement point, an excluding parametric hole on the plane \(u'_1 - u'_2\) has been determined (Cellino and Lemmin, [2004]). The time series have been filtered by excluding only the couples \(u'_1' - u'_2\) falling inside of such parametric hole. The contributing turbulent event has been identified through a discriminating function \(I_k(z, t)\) (where the index \(k = I, II, III, IV\) indicates the quadrant where the generic event falls) defined as:

\[
I(z, t) = \begin{cases} 
1, & \text{if the couple } [u'_1(z, t), u'_2(z, t)] \text{ falls in the } k\text{-th quadrant,} \\
0, & \text{otherwise} 
\end{cases} 
\]  

(1)

The filtered time series, \(\hat{u}_1(z, t)\) and \(\hat{u}_2(z, t)\), have been obtained as:

\[
\hat{u}_i(z, t) = \frac{u_i(z, t) \cdot I_k(z, t) > q \sqrt{u'_1(z, t)^2 + u'_2(z, t)^2}}{q = 1} ; \quad i = 1, 2
\]

(2)

where \(q\) is the threshold level identifying the dimension of the excluding hole. The value of the parameter \(q\) has been assumed equal to 1 according with results obtained in previous works (Termini and Sammartano, [2007]; Termini and Sammartano, [2008]).

The joint probability density function, \(P_{12}(z)\), of couples \(\hat{u}_1(z, t) - \hat{u}_2(z, t)\), has been estimated (Pope, [2000])

\[
P_{12}(z) = \frac{1}{2\pi} \exp \left[ -\frac{1}{2} \left( \frac{\hat{u}_1(z, t)^2}{2\sigma_{u_1}^2} + \frac{\hat{u}_2(z, t)^2}{2\sigma_{u_2}^2} + \frac{\rho_{u_1u_2}}{\sigma_{u_1}\sigma_{u_2}} \right) \right]
\]

where

\[
A_{12} = \left[ 4\pi^2 \cdot \frac{\hat{u}_1(z, t)^2}{2\sigma_{u_1}^2} \cdot \frac{\hat{u}_2(z, t)^2}{2\sigma_{u_2}^2} \cdot (1 - \rho_{u_1u_2}^2) \right]^{-0.5} ; B_{12} = \frac{-0.5}{1 - \rho_{u_1u_2}^2}
\]

\[
C_{12} = \left[ \frac{\hat{u}_1(z, t)^2}{\hat{u}_1(z, t)^2} - 2 \frac{\rho_{u_1u_2}}{\sigma_{u_1}\sigma_{u_2}} \frac{\hat{u}_1(z, t)^2}{2\sigma_{u_1}^2} \cdot \frac{\hat{u}_2(z, t)^2}{2\sigma_{u_2}^2} \right]^{0.5} + \frac{\hat{u}_2(z, t)^2}{\hat{u}_2(z, t)^2}
\]

\[
\rho_{u_1u_2} = \frac{\hat{u}_1(z, t) \cdot \hat{u}_2(z, t)}{\left[ \frac{\hat{u}_1(z, t)^2}{\hat{u}_1(z, t)^2} + \frac{\hat{u}_2(z, t)^2}{\hat{u}_2(z, t)^2} \right]^{0.5}}
\]

(3)

On the plane, \(\hat{u}_1(z, t) - \hat{u}_2(z, t)\), the distribution of \(P_{12}(z)\) is an ellipse whose long axis is rotated according to the more frequent event.

In Figure 5 the contour-lines of \(P_{12}(z)\), estimated, at \(z = 1.0\) cm for run 1 and at \(z = 0.7\) cm for run 2, are reported. In this figure the angular coefficient of the long axis of each ellipse, \(m\), is also reported. The sign of \(m\) allows the identification of the couple of quadrants where the products \(\hat{u}_1(z, t) \cdot \hat{u}_2(z, t)\) assume the same sign; the location of the peak of the distribution allows the identification of the specific event occurring in the examined measurement point.
Figure 5a reports the contour-lines of $P_{12}$ determined for run 1 at axes 1 and 3. From Figure 5a it can be observed that, in the case of smooth bank (run 1), near the bank (axis 1) the long axis of the ellipse falls in quadrants I and III for sections F and H. While in sections G, I and L the long axis of ellipse is rotated so to fall in quadrants II and IV. This means that events of ejection and/or sweep develop in such sections. Moreover a peak of $P_{12}(z)$ is located in the fourth quadrant, so that sweep event seems to occur in section L. At axis 3 (channel axis), the long axis of the ellipse has the opposite direction to that observed near the bank in the corresponding section: in sections F and H the long axis is rotated so to fall in quadrants II and IV; in sections G, I and L the long axis falls in quadrants I and III. In section F the peak of the distribution is not clearly distinguishable and in section H it seems to occur in quadrant IV.

The contour-lines of $P_{12}(z)$ determined, in case of rough banks (run 2), along axes 2 and 3 are reported in Figure 5b. This figure shows that near the bank (axis 2) the angular coefficient of the long axis is negative (quadrants II and IV) in sections F, H and L. In
sections F and L, high peaks of $P_{12}(z)$ seem to occur in quadrant IV, while in section H the peak of the distribution occurs in quadrant II. The long axis of the ellipse of sections G and I is rotated so to fall in quadrants I and III. In section G the peak seems to occur in quadrant I. At channel axis (axis 3), the angular coefficient of the long axis of the ellipse is positive in sections F, G and L and negative in sections H and I. The peaks of $P_{12}$ are clearly distinguishable in sections F, G and L where events of quadrant I occur. Thus, sweep events occur in section H and ejection events are in section I.

5 CONCLUSION

This work presents some experimental results on the occurrence of horizontal turbulent events (inward interaction, ejection, sweep and burst) in a straight laboratory channel for two different roughness conditions of the channel walls.

In order to analyze the evolution of the horizontal coherent turbulent structures along the channel, for each the considered roughness condition of the walls, only the longitudinal and transverse flow velocity components are examined in the present work.

The occurrence of the turbulent events is identified by applying the conditional quadrant analysis. The strongest events are filtered by identifying an excluding hole with a threshold level $q=1$; the probability of occurrence of each event is determined through the joint density function of the filtered turbulent fluctuation components.

The analysis highlights that, in the case of smooth banks (run 1), ejection and/or sweep events with spatial length of 40 cm occur; an entire horizontal burst cycle seems to have a spatial length of about 80 cm. The burst cycles develop alternatively near the bank (axis 1) and at the channel axis (axis 3). As the bank roughness increases (run 2), the events evolve away from the walls (axis 2). Consequently, it seems that, as effect of banks roughness increasing, the spatial length of the turbulent events and the thickness of the horizontal eddies increase.

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