ANALYSIS OF COHERENT FLOW STRUCTURES IN A BEND BASED ON INSTANTANEOUS-VELOCITY PROFILING

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ABSTRACT

Coherent flow structures hold the key to a better understanding and modelling of hydrodynamic processes. This paper highlights the unique capabilities of an Acoustic Doppler Velocity Profiler (ADVP) for the experimental investigation of coherent flow structures. Contrary to most commercial velocity meters that measure point-by-point, the ADVP simultaneously measures the quasi-instantaneous velocity vector along an entire profile. This allows to obtain detailed spatial-temporal flow information, and by adopting Taylor's frozen turbulence hypothesis even to visualize flow planes. Whereas most available data on coherent flow structures were obtained in straight uniform flow, this paper illustrates ADVP-measurements of two kinds of coherent flow structures in open-channel bends, where the highly three-dimensional flow is characterized by the existence of cross-stream circulation (helical flow). The first kind concerns the turbulent bulk-oscillation of the pattern of cross-stream circulation cells, whereas the second concerns turbulent coherent structures associated with the bursting process.

1. INTRODUCTION

Turbulence plays a dominant role in the river environment. It dissipates the flow energy, influences the mean-flow pattern, determines the sediment transport as bed-load and suspended load, spreads and mixes transported quantities such as heat, pollutants, oxygen or sediment, triggers the exchange of oxygen at the water surface, etc.

Turbulence modelling in the past aimed at describing the effects of turbulence in a time-averaged way (velocity distribution, conveyance capacity, spreading and mixing characteristics, etc.). It is now generally accepted that the above mentioned processes cannot adequately be described by the averaged effects of turbulence, but are closely related to and conditioned by highly intermittent turbulence events, such as coherent structures.

A prerequisite to enhance our understanding of the relation between these coherent structures at the one side and the mentioned hydrodynamic processes at the other is the availability of detailed experimental data. Such data can give guidance in the model development and form an important tool for the validation of numerical simulations. They are particularly relevant with respect to Large-Eddy-Simulation (LES) techniques. High-quality experimental data on coherent structures are scarce and almost exclusively concern the case of straight uniform flow (Nezu & Nakagawa, 1993; Cellino & Lemmin, 1999; Hurther, 2001), which may not be representative of the highly three-dimensional flow in natural rivers (Blanckaert & Graf, 2001, Blanckaert & de Vriend, 2002).

This paper highlights the capabilities of an Acoustic Doppler Velocity Profiler (ADVP) in the experimental investigation of coherent flow structures. This unique instrument, conceived and built in our laboratory, is briefly presented. The paper subsequently illustrates two different kinds of coherent flow structures measured in open-channel bends, where the highly three-dimensional flow is characterized by the existence of cross-stream circulation (also called helical motion or secondary flow). The first kind concerns the turbulent bulk-oscillation of the pattern of cross-stream circulation cells, whereas the second kind is associated with turbulent bursting events. While this paper concentrates on the capabilities of the Acoustic measuring technique, the illustrated flow structures will be presented and analysed in detail in forthcoming papers (for example Blanckaert & de Vriend, 2002, for the bulk oscillation).

2. ACOUSTIC DOPPLER VELOCITY PROFILER (ADVP)

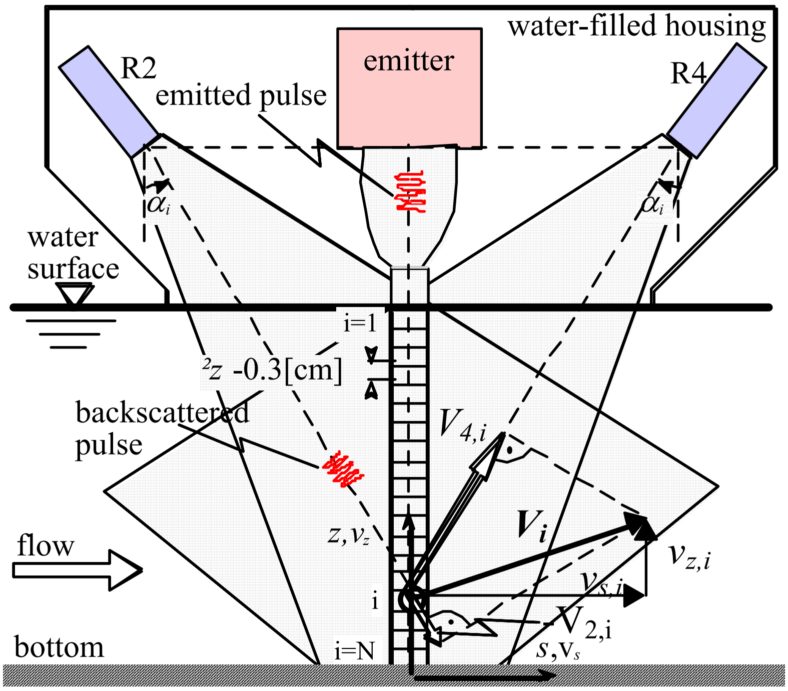

Figure 1. The Acoustic Doppler Velocity Profiler (ADVP)

The non-intrusive Acoustic Doppler Velocity Profiler, conceived and built in our laboratory, measures the quasi-instantaneous velocity vector with a resolution of turbulence scales. It consists of a central emitter, symmetrically surrounded by four wide-angle receivers, R1 to R4 (only two are visible in Figure 1). From these data, the mean velocity vector, $\overline{v}(v_s,v_n,v_z)$, can be derived, as well as the fluctuating velocity vector, $\overline{v'}(v'_s,v'_n,v'_z)$, the turbulent stress tensor, $\overline{v'_j v'_k}$ ($j,k=s,n,z$), and even higher-order turbulent correlations, $\overline{v'^a_j v'^b_k}$ ($j,k=s,n,z$ and a,b integer).

This ADVP has important advantages over most commercially available acoustic Doppler velocity meters:

(i) Whereas most commercial instruments measure point-by-point, our ADVP simultaneously measures all the velocities along its main axis. The measured profiles are subdivided into a string of equal measuring volumes of size $(\pi 0.7^2/4)x(0.3)=0.12$ cm^3. This profiling capability allows to do measurements much faster, hence to cover much finer measuring grids than with point-wise instruments. Furthermore, it provides a unique possibility to investigate experimentally spatial-temporal flow characteristics like coherent flow structures, and to visualize flow planes (see below).

(ii) Whereas three receivers are required to measure the three-dimensional velocity vector, our ADVP disposes of four receivers. The fourth receiver yields a redundant velocity information, which is used to improve the turbulence resolution of the measurements (Hurther & Lemmin, 2001; Blanckaert & Lemmin, 2002).

The working principle of the ADVP can be summarized as follows. 1Mhz acoustic pulses sent by the emitter with the pulse-repetition frequency (*prf*), are backscattered along the entire water column by targets (micro air-bubbles) moving with the water, and recorded by the four receivers. The actual measuring volume corresponding to a recorded signal is determined by the time of flight with respect to the emitter. From a number *NPP* (number of pulse-pairs) of recorded Doppler information, one quasi-instantaneous velocity can be estimated. The velocity sampling frequency is thus defined by $f=prf/NPP$, which is typically about 25 Hz, but depends on the flow characteristics. More information on the working principle of the ADVP, its experimental accuracy and its comparison with other velocity meters can be found in Lemmin & Rolland (1997), Hurther & Lemmin (1998, 2001), Blanckaert & Graf (2001) and Blanckaert & Lemmin (2002).

As mentioned before, coherent flow structures are the key to a better understanding and modelling of hydrodynamic processes. Conditional sampling techniques are required to detect and investigate coherent turbulence structures. In their monograph, Nezu & Nakagawa write (1993, p.171): "In order to detect coherent motions from measurements of velocity fluctuations, one must first know the basic features of the coherent structures from flow visualizations; only then can one determine a procedure such that only certain significant information is observed". The profiling capability of our ADVP is a powerful tool for the visualisation of flow planes. The transversal (section 3) or vertical (section 4) dimension of the flow field is covered by measuring simultaneously all the velocities along the acoustic beam. The horizontal dimension is obtained by transforming the measured temporal flow evolution into a longitudinal spatial evolution, according to Taylor's frozen turbulence hypothesis, $x=-Ut$ (the minus sign expresses that events measured at a later time t originate from further upstream).

Previous investigations on coherent turbulence structures in clear water flow as well as flow carrying suspended sediments (Cellino & Lemmin, 1999; Hurther, 2001) testify of the ADVP's reliability in the investigation of coherent flow structures. Hereafter, ADVP-measurements of two types of coherent structures in open-channel bends are presented.

3. BULK-BEHAVIOUR OF CROSS-STREAM CIRCULATION CELLS

Flow in open-channel bends is characterized by the existence of cross-stream circulation (also called helical flow or secondary flow). The bulk-behaviour of the pattern of cross-stream circulation cells was investigated in the laboratory flume shown in Figure 2. It has vertical Plexiglass sidewalls and consists of a 2 m long straight entry reach, followed by a 120° bend with constant centreline radius of curvature, R=2 m. The bar-pool bottom topography is in static equilibrium with the flow, which characteristics are summarized in Table 1. Transversal velocity profiles were measured in the cross-section at 60° in the bend, with the ADVP mounted in a box attached to the outer bank. The measuring grid covered only the outer half of the cross-section (Figure 2). The measuring frequency was 44.6 Hz and the sampling period was 180 s. This experiment has been reported in detail by Blanckaert & Graf (2001) and Blanckaert (2002b).

R [m]	B [m]	Q [l/s]	H [m]	S_s [‰]	U [m/s]	C [$\sqrt{m}$/s]	Re [10^3]	Fr [/]	R/B [/]	R/H [/]	B/H [/]
2	0.40	17	0.11	1.89	0.38	35	42	0.36	5	17.9	3.6

Q: flow discharge
H: reach-averaged flow depth
S $_s$: reach-averaged water-surface gradient
U: reach-averaged velocity
C: Chezy friction factor
Fr $=U/(gH)^{1/2}$: reach-averaged Froude number
Re $=UH/\nu$: reach-averaged flow Reynolds number
ν: molecular viscosity

Table 1. Hydraulic conditions

Two cells of cross-stream circulation are discernable in the pattern of cross-stream motion, (v_n,v_z), shown in Figure 2. Besides the classical helical motion – termed centre-region cell – a smaller and weaker counter-rotating outer-bank cell occurs in the corner formed by the outer-bank and the water surface.

Although the existence of this outer-bank cell has been reported long before (Mockmore 1943, Einstein & Harder 1954, Rozovskii 1957, etc.), it is still poorly understood, which is mainly due to a lack of high-quality experimental data. The visualization of outer-bank cells requires measurements on a fine grid with a high precision (velocities of O(1cm/s)). Our ADVP allowed us to systematically investigate these outer-bank cells. Outer-bank cells measured under different hydraulic conditions have been reported by Blanckaert (2002a).

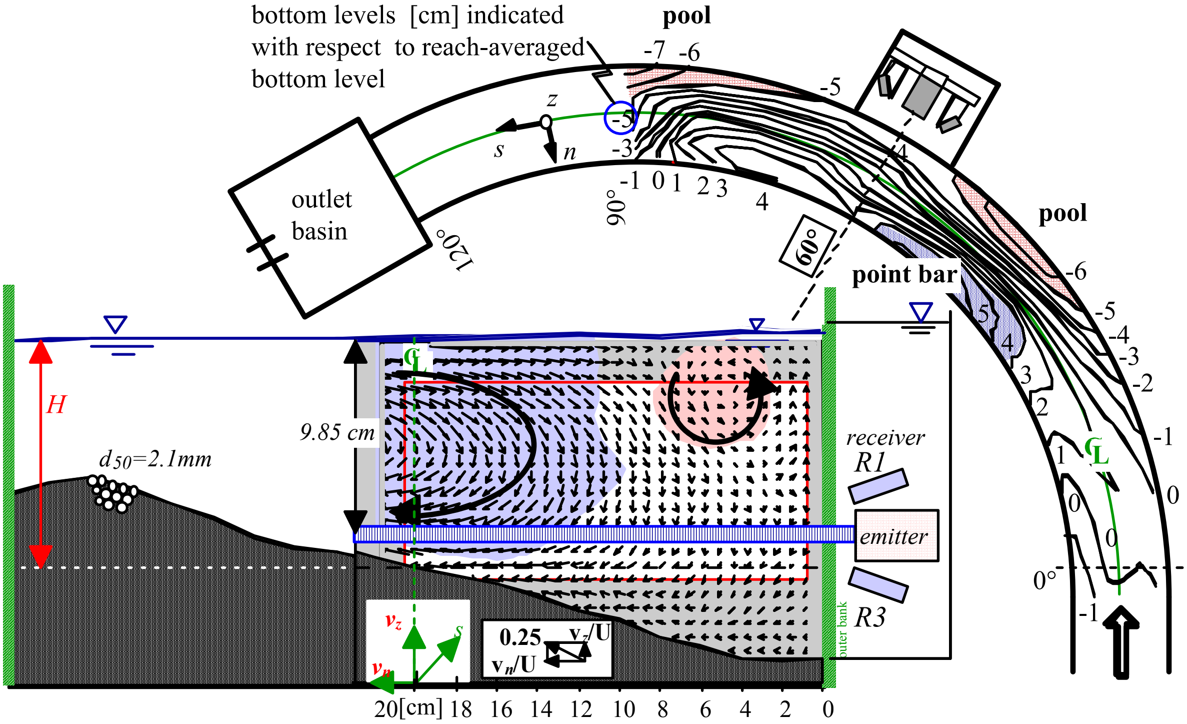

Figure 2. The small-flume experiment

Moreover, the profiling capability of our ADVP allowed us to investigate the bulk-behaviour of this pattern of circulation cells. Figure 3 visualizes the transversal velocity fluctuations in the horizontal plane 9.85 cm below the water surface (cf. Figure 2). The vertical axis covers the measured profile from the outer bank onto near the centreline, whereas the horizontal axis represents the longitudinal spatial evolution, which is obtained from the measured temporal evolution according to Taylor's frozen turbulence hypothesis.

The resulting flow image indicates an a-typical coherence of the transversal velocity fluctuations over the width. Blanckaert and de Vriend (2002) have made an in-depth analysis of this observation and came to the following conclusion:

These width-coherent transversal fluctuations represent a turbulent bulk-oscillation of the pattern of circulation cells in the longitudinal and transversal directions, which has the characteristics of a wave-like motion: it contributes significantly to the turbulent kinetic energy but hardly generates turbulent shear stresses. The reduction of part of the turbulence into a wavelike motion changes the turbulence structure in the investigated bend: for a given amount of turbulent kinetic energy, there is less turbulent shear than in straight flow. This modified turbulence structure leads to a general reduction of turbulence activity in the bend. Differences with straight-flow turbulence can be parameterised by the streamline curvature.

This modified turbulence structure and resulting reduced turbulence activity are potentially important phenomena with respect to environmental processes as sediment transport and spreading and mixing of transported quantities. They had not been observed before, and could only be resolved thanks to the profiling capability of our ADVP.

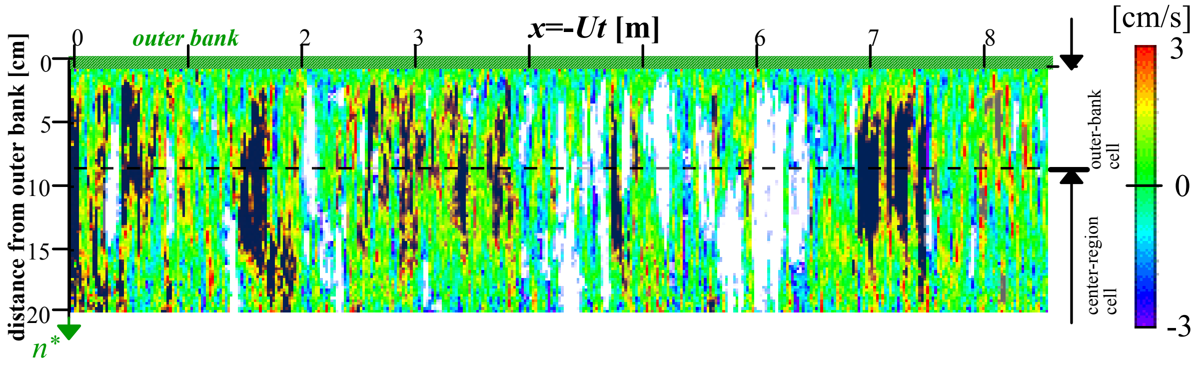

Figure 3. Bulk-oscillation of the pattern of cross-stream circulation cells

4. TURBULENT COHERENT STRUCTURES

As mentioned before, turbulent coherent structures are the key to a better understanding and modelling of hydrodynamic processes. Turbulent coherent structures associated with the bursting process are more efficient in the spreading and mixing of transported quantities (suspended sediment, pollutants, oxygen, heat, etc.) over the entire water column than small-scale turbulence, they dominate the transport of sediment as bed-load and suspended load and they are primary mechanisms in the generation of turbulent kinetic energy and turbulent shear stresses.

By reorienting these turbulent coherent structures, the cross-stream circulation in open-channel bends is expected to alter their characteristics over the entire water column. The available experimental data on turbulent coherent structures associated with the bursting process is mostly limited to the case of straight uniform flow (Nezu & Nakagawa, 1993; Cellino & Lemmin, 1999; Hurther, 2001), and data in three-dimensional flows are particularly scarce.

Turbulent coherent structures were measured in the laboratory open-channel bend shown in Figure 4. It consists of a 9 m long straight entry reach, followed by a 193° bend with constant centreline radius of curvature, R=1.7 m, and a 5 long straight exit reach. The vertical sidewalls are made of Plexiglas and the horizontal bottom is covered with a nearly uniform sand, 1.6 mm < d < 2.2 mm, that was fixed by spraying a paint on it, thus preserving its roughness. The measuring frequency was 31.25 Hz and the sampling period was 90 s. The hydraulic conditions are summarized in Table 2. The parameters R/B = 1.31, R/H = 8 and B/H = 6.1 correspond to a sharp bend that is narrower than usual natural lowland rivers. These ratios do occur, however, in mountain rivers and man-made channels. The experiment has been reported in more detail by Blanckaert (2002b).

R [m]	B [m]	Q [l/s]	H [m]	S_s [‰]	U [m/s]	C [√m/s]	Re [10^3]	Fr [/]	R/B [/]	R/H [/]	B/H [/]
1.7	1.3	104	0.21	0.56	0.38	35	81	0.26	1.31	8.0	6.1

Table 2. Hydraulic conditions (see Table 1 for the legend)

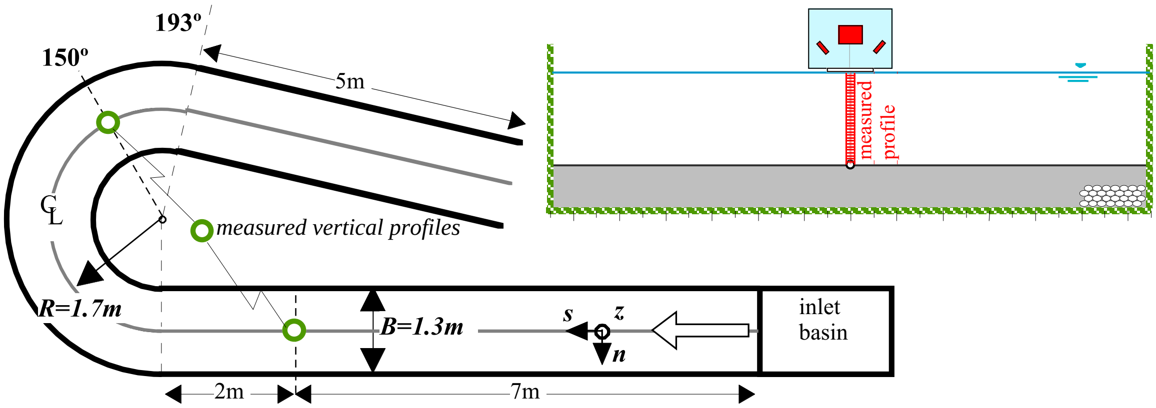

Figure 4. The large-flume experiment

This paper presents visualizations of turbulent coherent structures in vertical planes, obtained by measuring vertical profiles at the centreline of the flow (cf. Figure 4). Figure 5 shows the signature in vertical planes of the instantaneous Reynolds-stress signal, normalized with the overall shear velocity, $v'_s(t)v'_z(t)/u_*^2$ (unfortunately, only a crude representation is possible in black and white printing mode). This quantity is an appropriate detector since it is directly related to the turbulent coherent structures that characterize the bursting process. Figure 5a shows the measurements in the straight flow 2m upstream of the bend, whereas Figure 5b shows the measurements at 150° in the bend (cf. Figure 4).

In the straight flow, the average Reynolds stress $\overline{v'_s v'_z}$ (right side of Figure 5a) has a typical triangular distribution. The instantaneous Reynolds-stress signal clearly reveals the existence of intermittent flow regions with high positive and negative values, which are mainly located in the lower half of the water column. The negative values, corresponding to the so-called sweep and ejection events, dominate over the positive values, corresponding to inward and outward interactions, which is in agreement with the negative sign of $\overline{v'_s v'_z}$ and with data reported by Nezu & Nakagawa (1993) and Hurther (2001).

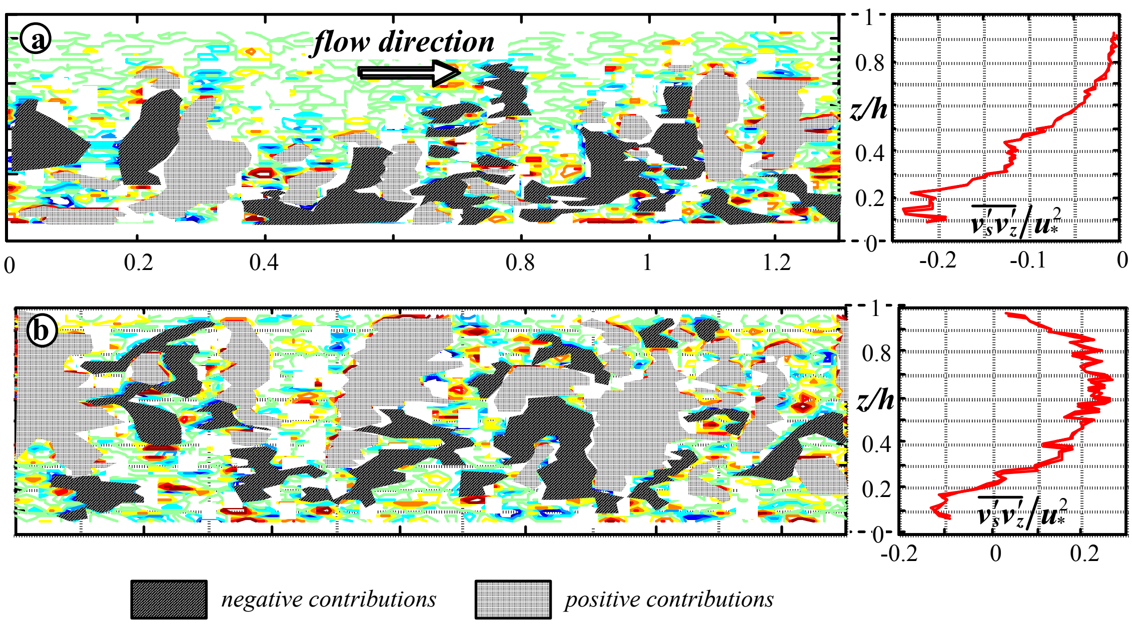

Figure 5: Turbulent coherent structures at the centreline: (a) in the straight flow 2m upstream of the bend; (b) at 150° in the bend, visualized by means of the normalized instantaneous Reynolds stress, $v'_s(t)v'_z(t)/u_*^2$.

At 150° in the bend, the average Reynolds stress $\overline{v_s' v_z'}$ (right side of Figure 5b) is positive over most of the flow depth. Near the bottom, it decreases strongly to attain negative bottom values of comparable magnitude as in the straight flow. In the lower part of the water column, the turbulent coherent structures have a similar signature as in the straight flow. Contrary to the straight flow, important coherent structures exist in the upper part of the water column in the bend. The positive contributions are dominant, which is in agreement with the average Reynolds stress.

These observations confirm that the existence of cross-stream circulation (helical flow) fundamentally modifies the characteristics of the turbulent coherent structures, and thus of the turbulence dynamics in general. The characteristics of turbulent coherent structures in open-channel bends and their relation with the cross-stream circulation will be presented and analysed in more detail in a forthcoming paper.

5. CONCLUSIONS

This paper highlights the unique capabilities of an Acoustic Doppler Velocity Profiler (ADVP) in the investigation of coherent flow structures. Whereas most instruments measure point-wise, the ADVP simultaneously measures the quasi-instantaneous velocity vector along an entire profile. This allows a visualisation of the spatial flow structures. This paper illustrates ADVP measurements of two different kinds of coherent flow structures in open-channel bends, where the highly three-dimensional flow is characterized by the existence of cross-stream circulation (helical motion). Previous measurements were mostly limited to the case of straight uniform flow, and experimental data on coherent flow structures in three-dimensional flows are particularly scarce.

The first kind of coherent flow structure concerns the bulk-behaviour of the pattern of cross-stream circulation cells. The visualization of a horizontal flow plane indicates a turbulent oscillating behaviour of the entire pattern of circulation cells. Blanckaert and de Vriend (2002) have presented an in-depth analysis of these observations.

The second kind of coherent flow structure is associated with the turbulent bursting process. It is investigated by visualizing a vertical flow plane at the centreline of the flow. In the straight flow upstream of the bend, turbulent coherent structures are mainly found in the lower part of the water column. There, ejection and sweep events dominate over inward and outward interactions. At 150° in the bend, the turbulence signature is similar in the lower part of the water column. The upper part of the water column, however, is now characterized by the existence of significant turbulent coherent structures. There, inward and outward interactions are dominant, which is in agreement with the positive sign of the corresponding Reynolds stress. These observations indicate fundamental differences in the turbulence dynamics between curved flow and straight flow.

The presented results testify of the unique capabilities of our ADVP to illustrate and investigate coherent flow structures. Data of the presented kind are needed to improve our understanding and modelling of hydrodynamic processes in the river environment.

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