Instantaneous Flow Vector Measurement by a Pair of Ultrasound Doppler Instruments

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Ultrasound Doppler velocity profiling is an effective method for instantaneous fluid velocity measurement along a measurement line. However, measuring vector components in multiple dimensions requires the development of multiple transducers, with the exact number depending on numbers of required cross-sections. This study provides a technique to extract two-dimensional velocity data along the bisector between two transducers by using a reasonable correction of the time lag or progress between the transducers. The observed time differences arise from geometry of the set-up and depend on the distance from the crossing point, intersection angle, and representative velocity in the main flow direction. The developed methodology is applied to the measurement of a quartz-particle-laden turbidity current produced in a lock-gate flume. After opening the gate, the suspension intrudes into the ambient water and is transported downstream according to a density difference. A convex-shape velocity distribution in the direction of stream flow and the vertically generated instabilities along the interface with ambient water are observed using this simple and convenient velocity measurement technique, which can characterize flow structure and aid statistical analyses of parameters such as vorticity.

Keywords: Flow field monitoring, Vector field, Double-cast UVP system, Turbidity current, Particle-laden flow

1. Introduction

An ultrasound Doppler velocity profiler (UVP) is an ideal tool for measuring flow behavior along its beam axis [1], [2]. However, vector profiling in multiple dimensions requires multiple transducers (TDX) arranged to give cross-sections, with the exact amount depending on the required dimensionality of the results and number of observation points (e.g. [3], [4]). There are some difficulties when analyzing velocity fields by UVP with high temporal and spatial resolution, especially in unsteady flow. We developed a system to approximate the vector field based on a pair of TDXs along the bisector of their measurement lines. Using the representative velocity and geometry in the area, the time lag and progress are corrected according to the distance from the crossing point, and the vector field can be detected in high resolution.

To validate the method's applicability, we investigated the vector field of a turbidity current generated in a lock-gate-type flume. We observed not only the abrupt velocity increase in the direction of the stream after intrusion of the flow but also the vertical uplift flow due to shear with the ambient water. The provided method proved useful in estimating the vector map, even for an unsteady flow.

2. Velocity measurement

Fig. 1 outlines the vector field measurement. At the cross-section of the measurement lines of two individual UVPs, the velocity components in the stream direction and normal to the bed (i.e. u and v, respectively) are represented as follows [5].

$$u = \frac{u_1 - u_2}{2\sin\alpha} \tag{1}$$

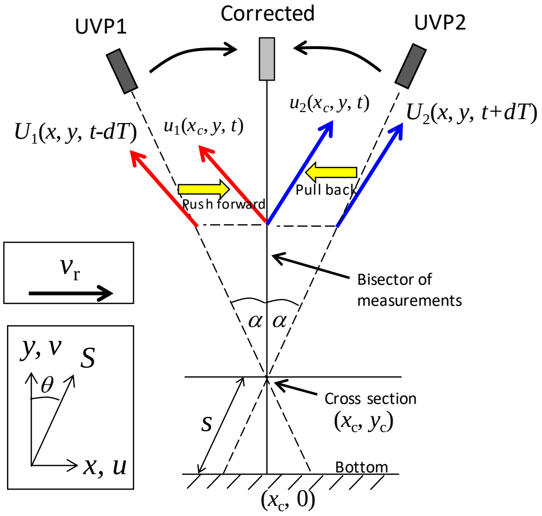

Figure 1: Overview of streamwise and bed-normal velocity measurement

$$v = \frac{u_1 + u_2}{2\cos\alpha} \tag{2}$$

where u_1 and u_2 are the respective velocities measured by an upstream and a downstream UVP in cross-section, and α is the acute angle from the y axis.

The original velocity (U_1 and U_2) can be advected assuming that the rate of change of velocity components during a certain short time is sufficiently small relative to the ratio of the inspection area to the representative flow velocity (v_r) and that velocity components are preserved in that period. The time lag or progress (dT) occurs owing to the inclination of the measurement lines from the bed-normal direction, and is corrected as follows:

$$dT = \frac{(S - s)\sin\alpha}{v_r} \tag{3}$$

where, s is the length from the bottom to the intersection (x_c, y_c) along the measurement line, and S is the length from the bottom to the target along the measurement line. The variables x, y and S are related as follows:

$$|x_c - x| = S\sin\alpha \tag{4}$$

$$y = S\cos\alpha \tag{5}$$

Based on equations (3) and (4), U_1 and U_2 are advected from the measurement lines to the bisector as

$$u_1(t, x_c, y) = U_1(t - dT, x, y) \tag{6}$$

$$u_2(t, x_c, y) = U_2(t + dT, x, y) \tag{7}$$

Applying equation (6) and (7) to (1) and (2) allows approximations of u and v at any t in $x = x_c$.

3. Results

3.1 Experimental setup

To validate the efficiency of the provided equations, we investigated the flow of a turbidity current produced in a lock-gate-type straight channel at the Laboratory of Hydraulic Constructions, EPFL. The experimental setup, coordinate definitions, and flow image are shown in Fig.2. The coordinate origin is set to be at the bottom of the gate. The flume is tilted at a slope of 1.38°, it is 4550 mm long, 210 mm high, and 143 mm wide. The gate was installed 2258 mm downstream from the beginning of the flume to divide the area into two. Before the experiment, the upstream reach was filled with the denser suspension with density ρ_1 = 1032 kg m^{-3}, whereas the downstream reach was filled with water with density ρ_0 = 1000 kg m^{-3} < ρ_1. Once the suspension had been well mixed and reached to predetermined density in the upstream reach, the gate was removed suddenly, and the denser suspension flowed under the ambient water with front velocity v_f. The sediment material for the turbidity current was quartz flour composed of SiO_2 with a mass density ρ_s = 2650 kg m^{-3}. Its grain size at D_{50} was 12.2 µm, and the settling velocity (v_s) for this size, based on Stokes' law, is 0.133 mm s^{-1}.

For the velocity measurement, a pair of 4-MHz UVP transducers which was synchronized using the external trigger of two UVP-Duo devices (Met-Flow, Switzerland) to start measurement, was installed at (x, y) = (951, 130) and (1059, 130) in mm at an inclination of 25° from the bed-normal (Fig. 2). The individual UVP measurements were continued before the head front had reached the end

Table 1: Parameters of UVP measurement

Parameter	Value
Ultrasound frequency (MHz)	4
Speed of sound (m/s)	1480
Maximum velocity range (mm/s)	179.1
Velocity resolution (mm/s)	1.399
Maximum measurement length (mm)	382.5
Number of channels	285
Number of profiles	4096
Sampling period for each profile (ms)	50
Window start (mm)	8.88
Window end (mm)	219.04
Channel distance(mm)	0.74
Channel width (mm)	0.74
Pulse repetition frequency (kHz)	1.936
Sampling rate (Hz)	20.0

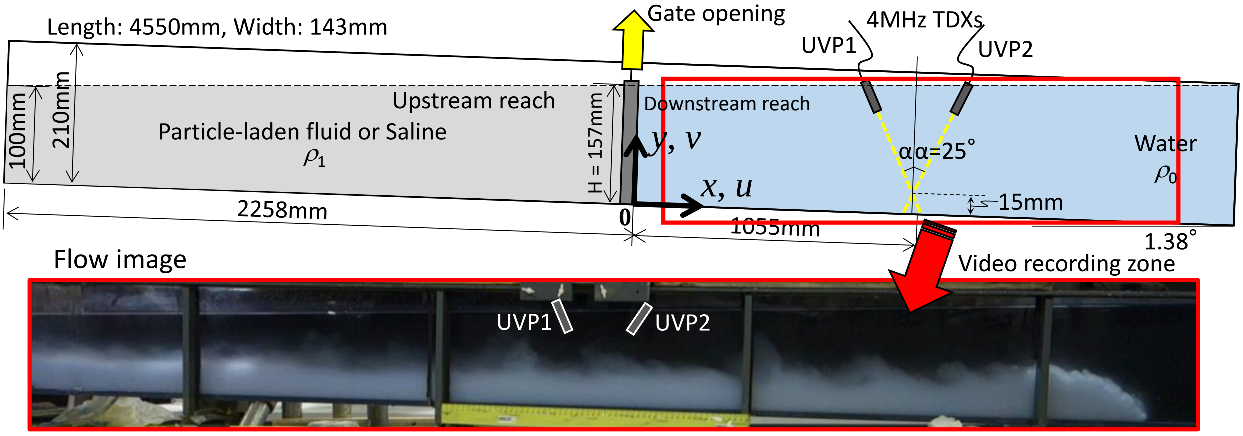

Figure 2: Experimental setup, coordinate definition, and flow image in downstream reach

of the flume. The UVP measurement parameters are listed in Table 1. The measurement lines of the pair of transducers crossed at (x_c, y_c) = (1055, 15) [mm], which was almost half the height of the produced flow.

3.2 Measurement Result

Fig. 3 shows the measurement of data by UVP1 and UVP2 after eliminating noise by a median filter in 3 × 3 velocity recording plots. A positive value denotes flow away from the TDX, and vice versa. Although both figures represent almost inverse values derived from the opposite measurement angles from the bed-normal, the presence of a vertical velocity leads to discrepancies in their distributions. Here the dashed lines at the height of 16.5 mm correspond to the position of the cross-section.

3.3 Streamwise and bed-normal velocity

Fig. 4 shows streamwise and bed-normal velocities (i.e. u and v) converted from Fig. 3 by equations (1) - (7). The front velocity (v_f = 76.4 mm/s) found from image analysis is a suitable representative velocity we confirmed that it remains constant in the measuring section owing to a suspension supply [6]. Here the absolute values of dT at y = 0 and 40 mm are 83 and 138 ms, respectively, which are less than the duration of three profiles and thus small enough to conclude that u and v can be transformed in the present experimental setup. Correcting the inclination of measurement lines improves the spatial resolution from 0.74 to 0.67 mm.

The abrupt intrusion of the turbidity current results in a specific rising slope along the interface with the ambient water in the streamwise direction. Simultaneously, a vertically lifting-up flow develops, as shown in Fig. 4. After reaching a maximum, streamwise velocity sharply decreases in the upper flow area, and a vertically downward flow develops, which indicates that the suspension is lifted by the shear with the ambient water and is entrained by the flow. This unsteady process due to flow arrival and passing is the typical for the head of a turbidity current [7]. After the passing of the head, we observe quasi-steady body area from t = 20 s. Due to shear with the bottom, the streamwise velocity there converges to zero; it initially increases in the vertical direction, but later decreases with height due to shear with the upper ambient water. As a result, the velocity maximum in the streamwise direction occurs at a specific height. To satisfy continuity in the area, a negative streamwise velocity develops in the upper area as a counterflow. A pair of positive and negative v layers is observed at the upper and lower zones relative to the height of the velocity maximum, implying that the suspended sediments are vertically separated due to the intrusion of the high velocity suspension in the streamwise direction, as reported by [8], [9].

4. Discussion

Fig. 5 shows the absolute and relative vector fields. Here, the velocity magnitude is normalized by its maximum value. In the relative velocity fields, the averaged velocities from 30 to 40 s (i.e. u = 21.8 and v = 1.2 mm/s) are extracted from absolute values. The relative vector field clearly shows the upward and backward flow after the flow arrival. There is evidently strong shear at the bottom and at the interface between the turbidity current and the ambient water.

To evaluate the flow structure in the turbidity current, normalized vorticity distributions are depicted in Fig. 6 according to the following equation:

$$\omega \approx \frac{\Delta v}{\Delta x} - \frac{\Delta u}{\Delta y} \tag{8}$$

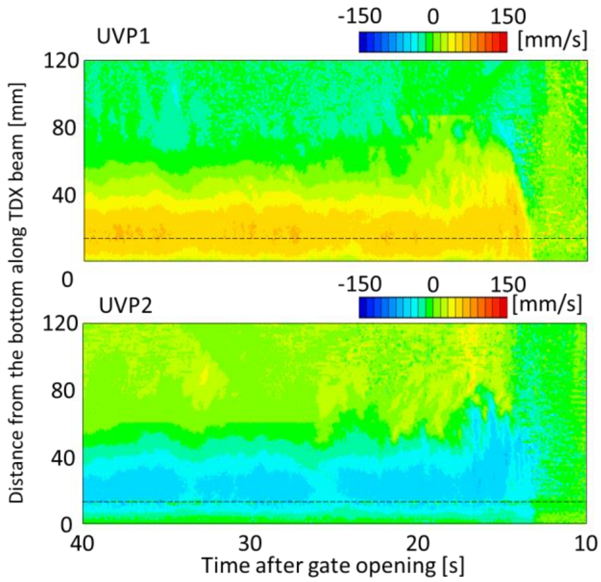

Figure 3: Data measured by UVP1 (upper) and UVP2 (lower). Dashed lines indicate the cross-section height

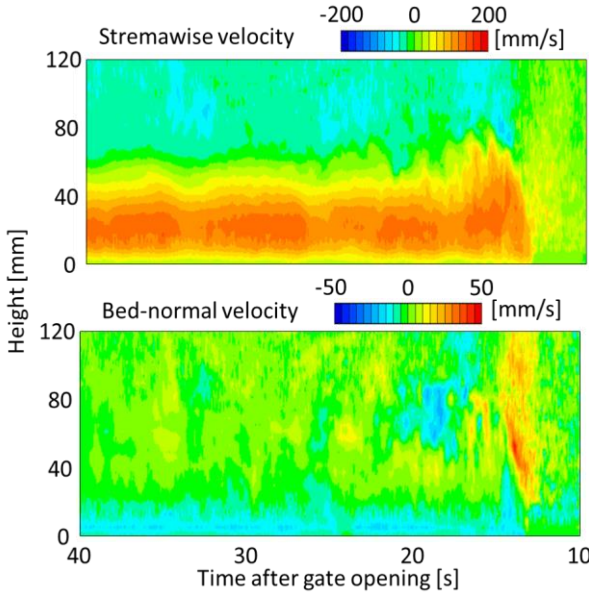

Figure 4: Streamwise (upper) and bed-normal (lower) velocity distribution

Where, ω is vorticity, Δx is the product of Δt and v_f (i.e., $dx = dt\ v_f = 3.8$ mm), and dy is fixed to six times the channel width (i.e., $dy = 4.0$ mm). After the flow arrival, positive vorticity develops along the sloping interface with the ambient water. This indicates that an anti-clockwise flow develops due to unsteady shear process. The body part shows negative and positive layers. As discussed in section 3.3, the turbidity current held back by the rigid bottom and static ambient water in the upper area. Because of the instabilities that results from these factors, the velocity maximum is located at a specific height and the velocity distribution becomes layered. While the vorticity is high at the bottom, its distribution is narrower than that in the upper area, indicating that the material characteristics at the boundaries cause such discrepancies and influence the disturbances.

5. Summary

We developed a method for instantaneous flow vector measurement using a pair of ultrasound Doppler instruments. By correcting the time lag and progress owing to the different positions of the measurement lines, we succeeded in approximating velocity components with high temporal and spatial resolution. The developed method is applied to investigate the dynamics of an experimentally produced turbidity current. In addition to the typical flow structure in the current such as an unsteady uplift flow in the head and a quasi-steady flow in the body, we observe some noteworthy flow dynamics such as entrainment after the passing of the upper head part, vertical separation around the velocity maximum, and other finer instabilities in the flow. Overall, the proposed method can effectively observe the 2-D velocity structure. Although it is relatively simple and only in the validation phase, the method may be applicable to a wide range of measurements. Extending the set-up to observe the 3-D structure would be possible using a triple-cast UVP system and applying the same proposed system to correct the time lag or progress.

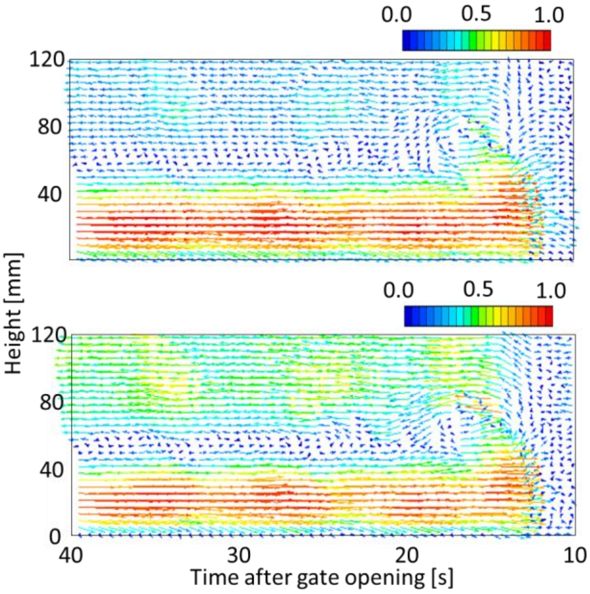

Figure 5: Normalized absolute (upper) and relative (lower) velocity vector

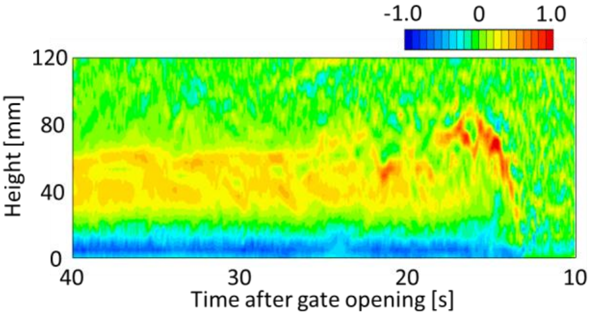

Figure 6: Normalized vorticity distribution

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