3D interpolation in a velocity field in sewers

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In order to propose a new sewer inspection method, a velocity/turbidity profiler (Ubertone, UB Flow) has been tested in a laboratory. A 50 m glass flume has been adapted with several lateral connections (with a arnge of diameter, angle, intrusions, cracks), supplied by a 1 m^3 tank. Placed just below the free surface on a rotating (to scan the wet section) and translating (along the main axe of the flume) structure, velocity profiles have been recorded and accurately positioned along the reach (with data from three laser distance meters and a 3 Mpix camera): a 3D cloud of raw velocities is created. After raw data pretreatment (deduction of translation velocity, Nyquist jumps correction, low quality data removal *i.e.* with low SNR threshold and vector projection corrections), five step-interpolation (adapted from [1]) methods have been implemented and tested: *i)* data filtering, *ii)* transformation to flume coordinates velocities, *iii)* isotropic gridding, *iv)* anisotropic gridding and *v)* continuity correction. These methods aim to produce contour lines and the quantification of different streamlines in the reach.

Keywords: 3D interpolation, Lateral connection, Data treatment

1. Introduction

Sewer rehabilitation decisions are mainly taken based on data obtained from CCTV inspection, it has been shown however [1] that information from this source is subjective and not very accurate. Therefore there is a need for techniques that result in objective information on the status and/or functionality of sewer. An important defect in sewers is leakage, be it infiltration, be it exfiltration or misconnection. In this article results from lab-experiments are presented, using a velocity/turbidity profiler for detecting anomalies in the flow field due to infiltrating flows.

In order to develop a new inspection technique, the FOULC project (Fast Over-scanning of Underground and Linear Constructions) aims at the development of an amphibious drone to inspect sewers without creating disruption in the sewage service. Several sensors will be set up on this platform: laser scanning devices, infrared camera, sonar and a velocity profiler.

The velocity/turbidity profiler (Ubertone, UB Flow [2]) might be a part of the monitoring platform to construct a 3D velocity field of the inspected reach (identification of the streamlines, quantification of the lateral connections). Such a use of this probe is quite challenging: positioning, control of the moving and angular velocities, construction of the 3D velocity vector field, *etc.* This sensor has been set up on a rotating (around the horizontal axis in order to scan the full wet section) laboratory facility and tested: the present paper describes the experiments, the methods used to convert raw data to a 3D velocity distribution along a flume.

2. Materials, laboratory experiments and method

2.1 Materials

Based on a system previously designed [4], built and tested for a laser profiler, the profiler has been fixed on a rotating platform and its position and spatial orientation (x,y,z, shift, pitch, yaw and roll angles) is calculated based on measurements from three laser distance meters (Dimetix, FLS-C10) and a 3 MPix camera (Allied Vision Technology, Manta GC282C).

Figure 1: Rotation structure (up), the flume (down left) and a window with lateral connection (down right) along the flume.

This system (Fig. 1, up) has been installed on a moving platform, guided along a hydraulic flume of 50 m long (Fig. lateral connections (Fig 1, down right). The exact position (distance from the reference point, pitch, yaw and roll angles) of the profiler can be derived from the three positions of the laser dots (recorded by the camera) and the three distances (from the laser distance meters) [4].

UB-Flow is a 2D velocity vector profiler (UVP) equipped with two transducers. The velocity estimation is based on the Doppler coherent method that allows high resolution measurements. The device switches alternatively from one transducer to the other. At each switch, the instrument provides a set of space-time matrix including velocity, SNR (Signal Noise Ratio) and echo data measured on the given transducer.

2.2 Laboratory experiments

Lateral connections were supplied with tap water (cold or warm) coming from a 1 m^3 tank, located just above the flume. The flow was manually controlled with a valve. The lateral connection flow was derived from the water levels (before and after the experiment), the section of the tank and the duration of the constant opening of the valve. The flow in the flume was controlled by the supply frequency of the main pump and recorded by a 600 mm diameter flow meter. Two discharges were tested in the flume: 120 and 520 l/s. In total 41 different experiments were carried out with different flume discharges, lateral connection types and discharges. Measurement have been done under stationary conditions.

2.3 Methods for data analysis

The method is divided in two parts.

The first part is devoted to the construction of a 3D velocity field from the UB Flow data and its position. With the recorded position and rotation of the profiler [3], its characteristics [2] (beam angles) and its adjustments (cell positions along the beam), measured velocities along the beams (V_1 and V_3) (coordinates of measured volume) can be placed in a 3D field. The cloud of raw data is created with velocities measured by both cells.

This second part is mainly based on the five steps method proposed by [4]: *1)* data filtering to remove artefacts in raw data, *2)* transformation of the velocities into the flume coordinates, *3)* isotropic gridding, *4)* anisotropic gridding and *5)* continuity correction. Only the step 1 (data filtering) and step 5 (continuity correction) differ slightly from the one proposed by [4] (moving average). The step 2 is new, due to the specifications of the UB Flow.

Initially done with a moving average, the values of each profile have been corrected for Nyquist jumps and noisy data (low SNR) have been removed.

The SNR threshold was fixed as 0.25 and the Nyquist correction was done for the velocities outside of the range (defined by the frequencies) with Eq. 1 [3].

$$V_{k,CORR} = V_k - \frac{c \times PRF}{2 \times f_{0,k}} \tag{1}$$

1, down left), specially prepared (windows with windows including lateral

where V_k ($V_{k,CORR}$) is the velocity in m/s (corrected) for the transducer k (1 or 3), c is the speed of sound in water (1480 m/s), $f_{0,k}$ is the emission frequency for a specific transducer k (in Hz) and PRF (in Hz) is the Pulse Repetition Frequency.

The step 2 consists to the transformation (V_1, V_3) to (V_z, V_y). For this step, a 3D grid is created: measured V_1 and V_3 are calculated by the means of the measurement contained in a cell. Empty cells are fill in with the nearest neighbor interpolation method. A regular grid of $V_{1,INTER}$ and $V_{3,INTER}$ is created. V_z and V_y are calculated with equations 2 [3].

$$\begin{cases} V_z = 1.873 \times V_{1,INTER} - 1.73 \times V_{3,INTER} \\ V_y = -0.23 \times V_{1,INTER} - 0.7975 \times V_{3,INTER} \end{cases} \tag{2}$$

Those velocities (given for the coordinated system attached to the rotating UB Flow) are then converted to velocities in the flume coordinate system (V_X, V_Y and V_Z).

The continuity correction (Step 4) is done trough an iterative process solving two equations (Eqs. 3 and 4)

$$\nabla^2 P = \rho \frac{\nabla U}{\Delta t} \tag{3}$$

$$U_{CORR} = U - \frac{\Delta t}{\rho} \nabla P \tag{4}$$

where P is the 3D pressure field (in Pa), $\boldsymbol{\rho}$ is the water density (in kg/m^3), U in the 3D velocity field (in m/s), Δt is the time step (in s), U_{CORR} is the corrected 3D velocity field (in m/s) and ∇ is the Nabla operator.

The equation system was solved with a finite difference method [5], using the scheme proposed by [6] and taking into account the Neumann boundary conditions [7]: equations (3) and (4) become (5) and (6) in a 1D scheme.

$$\frac{P^{i+2} - 2P^{i} + P^{i-2}}{4 \times \Delta x^2} = \frac{\rho}{\Delta t} \times \frac{U^{i+1/2} - U^{i-1/2}}{\Delta x} \tag{5}$$

$$U_{CORR,i} = U_i - \frac{\Delta t}{\rho} \times \frac{P_{i+1} - P_{i-1}}{2\Delta x} \tag{6}$$

3. Results and discussion

3.1 Construction of the 3D cloud

Figure 2 presents a 3D cloud of the raw velocities recorded in the flume.

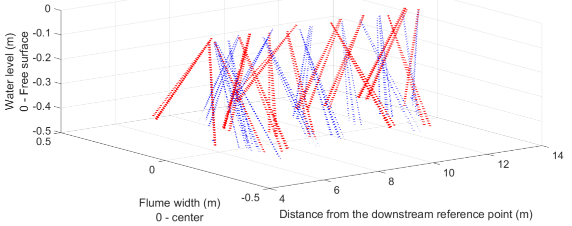

Figure 2: 3D cloud of the measurement cells (transducer 1 in blue, transducer 3 in red – both continuously moving along the virtual crest - top of each beams).

Figure 3 shows the effect of the switch [3] from transducer 1 (blue) to transducer 3 (red) during the measurement along the flume. The flow, roughly estimated by integrating basically interpolated velocity over the wet section, seems to be non-constant: from 70 to 150 l/s instead of 120 l/s: average measured flow (125 l/s).

The fluctuations in the raw data don't seem to come from the rotation of the UB Flow or the measurement sequence on the transducer 1 and the transducer 3.

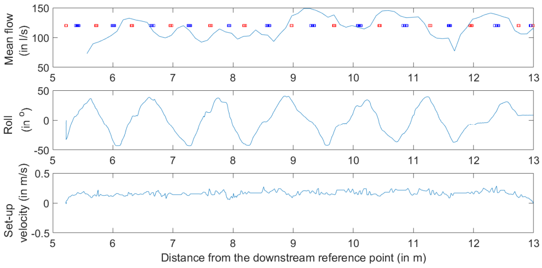

Figure 3: Fluctuations in the raw velocities (top) along the flume. Velocities (m/s) with transducer 1 (blue) and transducer 3 (red). Roll angle (middle) and set-up translation velocity (bottom).

3.2 Interpolation

Step 1. Correction of V_1 and V_3 profiles with Nyquist (if needed) and removal of low SNR value (Fig. 4).

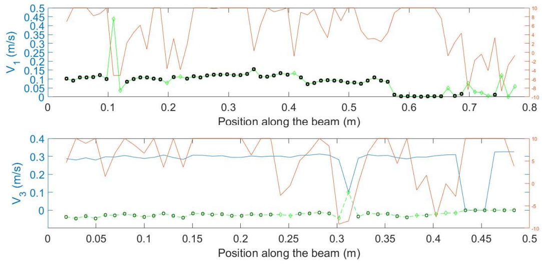

Figure 4: Raw and corrected profiles (V_1 - up, V_3 - down).

Step 2. Creation of the interpolated cloud of V (Fig. 5)$_z$ (main axis), V_y (along the width of the flume) and V_Y (along the vertical).

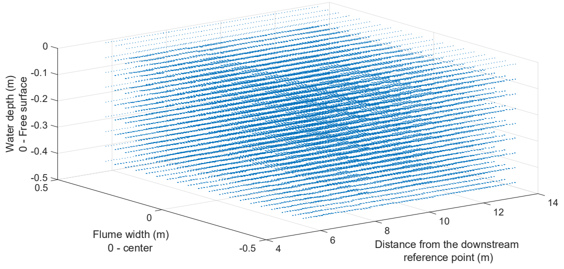

Figure 5: Quiver of velocities according to the flume coordinate system.

Step 3. The isotropic (i.e. rectangular) gridding proposed by [4] was not changed. The Figure 6-left illustrates the isotropic gridding.

Step 4. The anisotropic gridding step was not changed (Fig. 6 - right).

Step 5. The implementation of the 3D method proposed by [4] is done in three steps, in order to check step by step the CFD code: 1D, 2D and 3D.

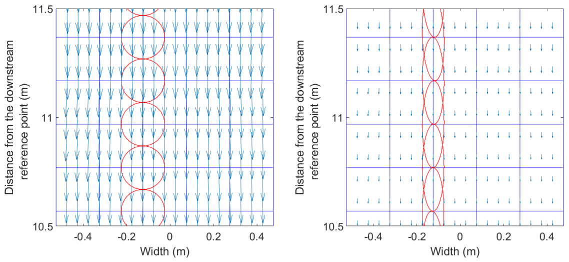

Figure 6: Gridding: isotropic (left), anisotropic (right).

For a discharge in the flume of 120 l/s, the average velocity is the wet section is supposed to be equal to 0.26 m/s (Fig. 7).

The method (in 1D) is converging (Fig. 6 bottom) but with some small instabilities (Fig.6 top).

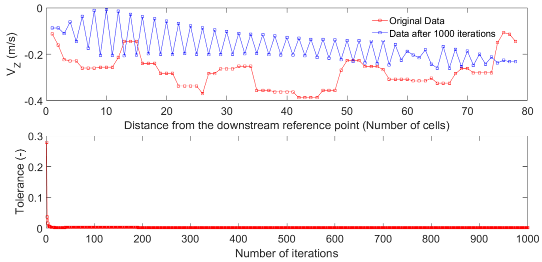

Figure 7: Effect of velocity artifacts on the convergence of the method. Top: existing data (red) and interpolated after 1000 iterations (blue). Bottom: tolerance.

The extension to the 2D methods shows the same results: the system is converging but with some punctual instabilities (Fig. 8).

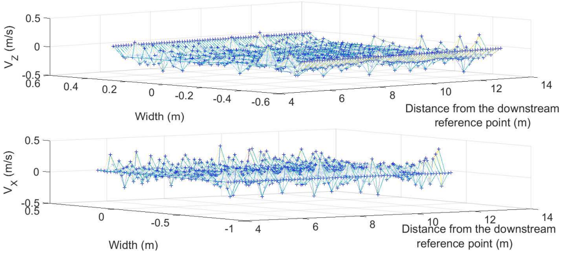

Figure 8: Result of 2D interpolation method. Top: V_Z velocities. Bottom: V_X velocities.

The method will be extended in 3D in order to validate (or not) the results the preliminary conclusions and applied on data issue of CFD simulation (Coming from [8]).

4. Conclusions and perspectives

The initial goal (*i.e.* the reconstruction of 3D velocity fields in a sewer with a UB Flow sensor) has been realized, despite some difficulties: adjustment of the profiler (emitting frequency), no simultaneous measurement of V_1 and V_3 and the coding complexity of the fifth step.

The probe seems to deliver velocity data that are consistent with the expected average velocity in the flume. The figure

9 shows a relative small noise in the data and highlights the rotation of the UB Flow (red vertical wave on the right part of the top figure).

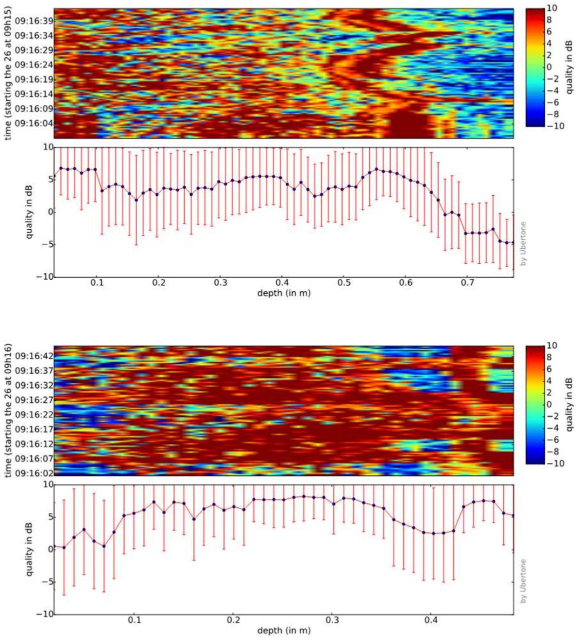

Figure 9: SNR ratios of the recorded data for the Transducer 1 (top) and the Transducer 3 (down).

Some weaknesses of the proposed method need to be highlighted. The first one is the construction of the 3D velocity clouds. The probe doesn't measure at the mean time on both beams: V_1 and V_3 need to be interpolation of the same grid to derive V_Z and V_Y. Secondly, there are few gaps in the data due to the switch between the beams: the data density (according to [4]) is around 1, instead of 3 as advised by the authors.

The UB-Flow, in it's actual setting, may not be adapted for this application. In order to achieve the initial goal, improvements of the current settings have to be done in order to obtain simultaneous and continuous measurements over the two beams.

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