Instrumental development and characterization for loaded liquid flow measurement

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Real-time sewer networks survey becomes a major key in wastewater regulation. Needs for continuous and precise information, especially in wastewater discharge, increase in importance. In the frame of a technological research and innovation network in water and environment technologies (RITEAU), our research group, in collaboration with industrial partners and other research institutions, has been in charge of the development of a suitable flowmeter: an ultrasonic device measuring simultaneously water flow and concentration of size classes of suspended particles. This paper will focus on velocity. After the description of the instrument and the utilized velocity principle, representative experimental results obtained in an experimental laboratory channel will be shown. Velocity profiles will be given and analysed, correspondance with theory and quality criterions will be discussed.

Keywords: Acoustic, velocity, estimator, profile.

1 INTRODUCTION

There are several methods for flow velocity profile evaluation. One of the commonly used is the pulsed ultrasound technique: the estimation of the flow velocity at different depths along a profile can be obtained by Doppler evaluation from the backscattered acoustic signal. The measured ultrasonic signal at each depth is the result of the reflection of the emitted beam by moving scatterers in a volume defined by the ultrasonic beam geometry and the range-gated echo duration [1].

Also several techniques can be used to extract Doppler information from the volumes [2]. They are classified in two main categories, the incoherent and the coherent Doppler methods. Incoherent Doppler is a narrowband method and consists in estimating the Doppler shift from echoes of single-pulse pings. Every ping generates a single estimation of velocity profile. This method is robust and allows long measurement ranges, but the velocity resolution error requires long averaging times. Coherent Doppler includes narrowband and broadband methods. For this technique, phase changes from successive pings are observed for each insonified volume [3]. Good spatial resolution and low variance are obtained with this method, but its main disadvantage consists in the well-known “range-velocity” limit.

Our research group has developed an acoustic device, designed for real time sewage supervision, which allows simultaneous measurement of velocity profile based on pulsed Doppler coherent method in monostatic mode, and concentration of different size classes of suspended particles. The current instrument’s prototype is made of two distinct parts: a submersible part containing transducers and acquisition electronics and an external processing part in charge of data analysis and storage.

After the description of the developed device, the paper will focus on velocity profiles estimations obtained on a hydraulic channel in the laboratory. The instrument’s velocity profile measurements will be discussed in order to evaluate the influence of secondary flows on discharge calculation [4]. Finally, a criterion to evaluate quality of the measurements will be discussed. Aim is to increase the precision of the instrument.

2 INSTRUMENT DESCRIPTION

The initially required specifications of our instrumental development were the combined possibility of flow rate measurements in open channels with diameters going from 0.3 to 1 m and velocities up to 3 m/s and concentration measurements of suspended solids with granulometric estimation.

From the design point of view, the instrument is split in two distinct parts: an immersed frame which is placed in the flow and a data management platform which remains on shore. Its schematic representation is shown figure 1.

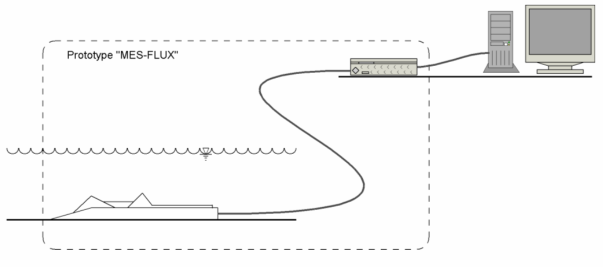

Figure 1: Schematic layout of the MES-FLUX.

Both parts are connected by a power supply and communication wire. The immersed frame contains the transducers and electronics for emission-reception sequencing and digitalisation. The management platform, in charge of data treatment and storage can be accessed by a personal computer or can be directly connected to a network.

Figure 2 shows the open data management platform with the frame on the right. Global dimensions of the frame are about 260x75x45 mm^3. The 3 specifically oriented transducers are used for velocity, water height and suspended solids concentrations measurements on the well known pulsed ultrasound principle.

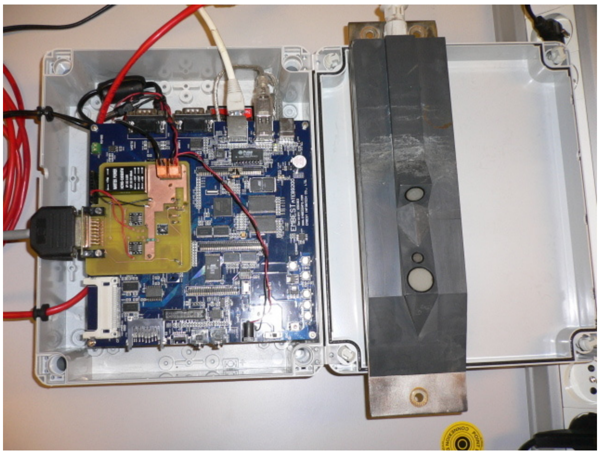

Figure 2: Picture of frame and open data management platform.

The biggest broadband transducer of mean frequency 1.8 MHz is used for velocity and water height measurements. When the instrument is placed on the channel bottom, which is its conventional position, this transducer makes a 75° angle with the flow direction. This transducer orientation allows higher velocity values for a given Doppler frequency. This first transducer and a second one, equally oriented, of mean frequency 9.2 MHz, are also used for suspended solids concentration measurements. The third and last transducer, centred on 4.5 MHz, makes an angle of 70° with the direction of the other transducers. It is used for collecting complementary data at another diffusion angle for granulometric measurements. Concentration measurements are made on frequencies ranging from 1 to 14 MHz and carrier frequency for velocity can be chosen between 0.9 and 2.3 MHz.

3 VELOCITY PROFILE ESTIMATION

3.1 Pulsed ultrasound principle

Instruments working on pulsed principle potentially provide measurement profiles. Their working principle allows precise knowledge of position in the flow of a given data at a given time stamp. Periodically an ultrasonic pulse is emitted in the medium. This signal is backscattered by the particles suspended in the flow (figure 3). Received by the transducer, the signal is conditioned, amplified and sampled in order to extract the information on velocity and concentration of suspended solids. Values are estimated on a succession of measurement volumes by windowing the backscattered signal in several blocs related to several measurement depths.

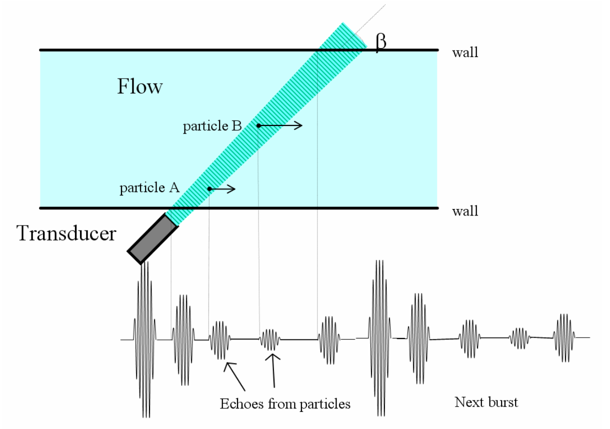

Figure 3: Pulsed ultrasound principle.

The Doppler signal frequency only depends on the particles velocity. Several methods are used to extract the Doppler information from the volume's signature. Our instrument uses the coherent Doppler method. This method uses the observed phase shift of the acoustic signal in a same volume during consecutive emission-reception cycles [3]. Each cycle generates a data sample by volume. This method allows good spatial resolution with low variance. Its major disadvantage is the "range-velocity" limit due to the signal sampling.

An estimator allows the calculation of mean Doppler frequency f_D, thus the flow velocity v in the corresponding volume according to:

$$v = \frac{c \cdot f_D}{2 f_0 \cdot \cos\beta} \qquad (1)$$

where c is the speed of sound in the medium, f_0 the carrier frequency and β the angle between flow and ultrasonic beam. Thus, velocity profile is obtained along the ultrasonic beam and its integration over the flow section gives the flow rate.

3.2 Doppler frequency estimation

Calculation of the first order moment of the signal (samples of the complex envelope with in-phase and quadrature components) gives the Doppler frequency in a given volume. Several methods may be used for Doppler frequency estimation. The Pulse-Pair method is commonly used [5]; another approach may be spectral analysis of the signal [6]. With the Pulse-Pair method, the estimated value of Doppler frequency is given by:

$$f_D = \frac{1}{2\pi T_{PRF}} \arctan \frac{\mathrm{Im}(R(T_{PRF}))}{\mathrm{Re}(R(T_{PRF}))} \qquad (2)$$

$R(\tau)$: Autocorrelation function, T_{PRF}: sampling repetition period.

The Coherent Pulsed Doppler method ensures good temporal and spatial resolution and low variance on velocity estimation. Unfortunately this method is limited by its sampling principle (so called "range-velocity" limit):

$$v_{\max} P_{\max} = \frac{c^2}{8 f_0} \tag{4}$$

$v_{\max}$: maximum detectable velocity, $P_{\max}$: maximum depth, f_0: carrier frequency.

To override this limit, several methods have been tested. Among them, the most popular ones uses interlaced pulse repetition frequencies [7] or relies on several carrier frequencies [8]. Thus, a factor 3 might be gained on the « range-velocity » limit.

3.3 Estimation of variance and S/N ratio

The second order moment of the signal gives access to the variance of the Doppler spectrum. Good representation of various turbulent media is given by a Gaussian shaped power spectrum [7]. Assuming that the signal is hidden in white noise, the evaluation of Doppler signal variance is given by [9]:

$$\sigma_S^2 = \frac{\ln\left(\left|R(T_{PRF})\right| / \left|R(2T_{PRF})\right|\right)}{2\pi^2\left((2T_{PRF})^2 - T_{PRF}^2\right)} \tag{5}$$

σ_S : standard deviation of the Doppler signal

In case of large signal to noise ratios, the variance of the Doppler signal can be related to the standard deviation of mean Doppler frequency [7]:

$$\sigma_{f_D} = \frac{1}{2\pi^{\frac{1}{4}}} \sqrt{\frac{\sigma_S}{M T_{PRF}}} \tag{3}$$

σ_{f_D} : standard deviation on Doppler frequency estimation; σ_S: Doppler spectrum width, T_{PRF} : pulse repetition period; *M* : number of samples used for a velocity estimation in a bloc.

Note that the signal-to-noise ratio related to this approach is given by [9]:

$$SNR = \frac{\left|R(T_{PRF})\right|}{\left|R(0)\right| e^{\left(-2\pi^2\sigma_S^2 T_{PRF}^2\right)} - \left|R(T_{PRF})\right|} \tag{6}$$

4 EXPERIMENTAL RESULTS

4.1 Open Channel setup

Measurements were done on the canal of the hydrologic platform of Alsace. This canal has a length of 16m, a width of 60 cm and a maximum water height of 80 cm. Its slope is adjustable. The instrument is centred in the flow, put in a zone where the hydraulic regime is well established. Its measurement beam goes from canal bottom to water surface (figure 4).

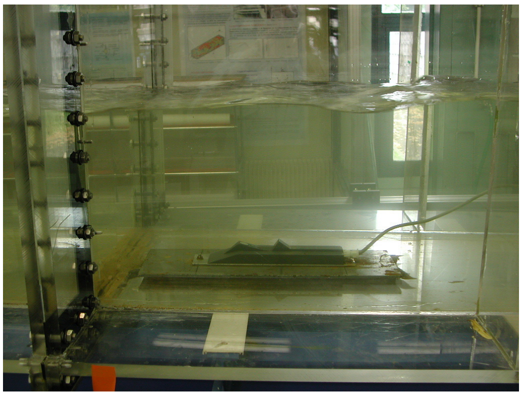

Figure 4: Experimental setup.

4.2 Doppler mean and variance measurement

The results shown below were obtained in a channel configuration with a flow of 253 m^3/h. The instrument's configuration is given in Tab.1. Several estimations of instantaneous profiles are depicted on figure 5. This figure represents the velocity profile and the standard deviation of the Doppler spectrum converted to velocity dimension. Water height is situated at 0.29m.

Each instantaneous profile corresponds to a estimation performed on a single data bloc, i.e. for a temporal resolution of 100 ms, giving the possibility to observe a turbulence phenomenon along the profile. Velocity profile observed beyond the water surface corresponds to multiple echoes and is not representative.

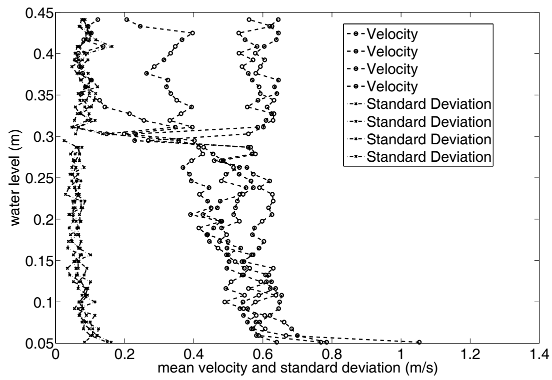

Figure 5: Instantaneous velocity profiles.

4.3 Distorsion in the profile

Figure 6 represents a mean profile scaled with its standard deviation. Water height level is characterized by a strong increase in standard deviation, because of the velocity gradient and turbulence in this volume. Good agreement between spectral variance and velocity standard deviation leads to the conclusion that the instrument brings weak electronic noise.

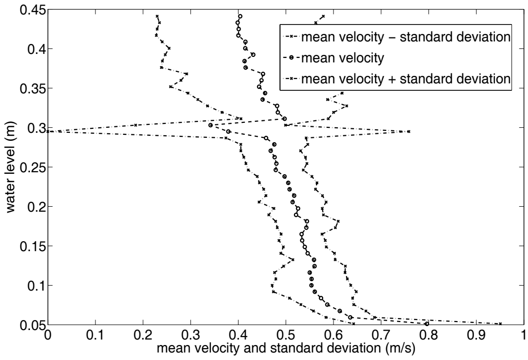

Figure 6: Mean profile with standard deviation.

Increase in velocity can be observed near to the transducer. This phenomenon is due to the velocity vector projection on the ultrasonic beam. Indeed, the instrument's topology induces changes in the velocity field in his near environment.

4.4 Measurement performance

Figure 7 represents the correlation coefficient, proportional to the ratio between mean Doppler frequency and spectral standard deviation, and the signal to noise ratio (SNR) for the whole profile.

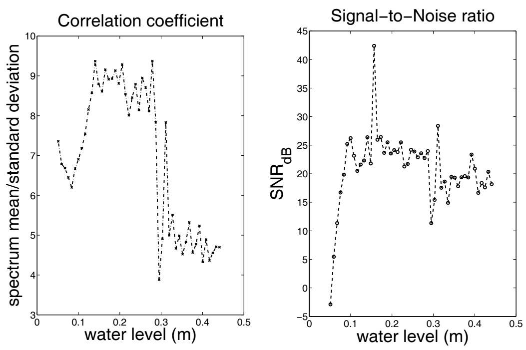

Figure 7: Correlation coefficient and SNR.

The correlation coefficient gives an estimation of the quality of the correlation, which can be decreased by turbulence, velocity gradient or presence of bubbles. Low correlation coefficient increases the variance of the Doppler estimates, but doesn't introduce bias.

We can observe a good signal to noise ratio all along the profile and a good correlation coefficient from bottom to water height. This coefficient decreases strongly after this level, indicating a loss in measurement quality. Combination of the two variables might be an interesting validation criterion for the quality of the measurement and might allow the filtering out of degraded data in measurement campaigns.

Table 1: Instrument configuration.

Variable	Symbol	Value
Carrier frequency	f_0 (MHz)	1.56
Number of periods/pulse	N_P	14
Pulse repetition frequency	PRF (Hz)	650
Number of volumes	N_{vol}	60
Distance between volumes	Δt (μs)	9.6
Number of samples/bloc	M	64
Number of blocs	N_{blocs}	24

5 CONCLUSIONS

Two prototypes of the described instrument exist. Both are used for various laboratory and in situ measurement campaigns. They showed good coherence for velocity measurements versus imposed flow. The influence of velocity field perturbation due to presence of the frame has still to be evaluated by comparison between the instrument's velocity profile measurement and its scanning obtained with a single-point Acoustic Doppler Velocimeter. A second investigation point would be Dual-PRF measurements and the evaluation of the possible quality criterion in these conditions.

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