DEVELOPMENT OF TESTING PROCEDURES FOR ACOUSTIC DOPPLER FLOW-METERS.

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Abstract

Les débitmètres ultrasonores à effet Doppler fournissent un mesurande supposé représentatif de la vitesse moyenne de l’écoulement. Connaître la relation entre ces deux données est nécessaire puisque ces capteurs sont très utilisés pour suivre en continu l’évolution les débits transitant dans des réseaux d’assainissement. Or la plupart de ces appareils mettent en œuvre une mesure indirecte de la vitesse à partir de paramètres caractéristiques (volume de mesure, pondération des échos) mal documentés pour l’utilisateur. Une procédure d’essais de laboratoire a été développée et testée pour déterminer ces paramètres.

Acoustic Doppler flow-meters rely on velocity sensors which provide data supposed to be representative of the mean velocity of the flow. Assessing the relation between these two data is necessary to obtain flow rate measurements because these sensors are commonly used to continuously measure flow rate in sewer networks. But those sensors used an non direct velocity measurement based on characteristic parameters (sampling volume, echoes ponderation) not properly documented. This paper presents testing procedures which have been developed in order to assess the intrinsic parameters of acoustic Doppler velocity sensors.

Introduction

Acoustic Doppler flow-meters are measuring devices commonly used in urban hydrology. Rather small, autonomous, easy to set up and not expensive, they are suited to many situations, like temporary measurement campaigns in a sewer network (Figure 1) or on a combined sewer overflow as well as continuous monitoring or legal control of the wastewater depollution process.

The space domain investigated by a Doppler flow-meter is a cone shaped volume. The value of interest is the mean value of velocity in a 2D sewer cross section. This value must be extrapolated from the values measured in the sampled 3D volume (Figure 2). This extrapolation is performed by the software embedded in any Doppler flow-meter, which assumes a standard set up of the sensor and a regular distribution of velocities over a section. As a matter of fact, these assumptions are not fulfilled in many situation. As the sampled volume is rather narrow, with a somewhat limited range, problems may arise, especially when a Doppler flow-meter is used in a large sewer [1]. These problems might be overcome with a proper knowledge of the actual sampled volume.

Figure 1: Sensor being implemented in a separative sewer

Figure 2: A Doppler velocity sensor and its sampled volume.

Unfortunately, the intrinsic performances of the velocity sensor are usually poorly documented, and important items like the sampled volume are not clearly described. The ISO/TS 15769 Technical specification [2] provides some useful guidelines about parameters of interest, but it does not give precise procedures to assess these parameters. Anyway this Technical Specification is still to be turned into a real standard.
This paper presents testing procedures which have been developed in order to assess the intrinsic parameters of acoustic Doppler velocity sensors.

**Theoretical background of Doppler sensors**

**Principle**

An acoustic Doppler velocimeter generates an ultrasonic beam at the frequency $f_s$ (commonly between 0.5 and 1 Mhz). When the beam encounters a solid particle or a bubble (indeed any change of density), the wave is reflected with a new frequency $f_{s,n}$ where $f_{D,n}$ is proportional to the particle velocity.

Using an acoustic velocimeter to measure the velocity of the effluent consists in making the fundamental hypothesis that the particles carried by the fluid are moving at the same velocity than the flow. Then the sensor measures the radial component:

$$V_n \times \cos \theta_n = \frac{c \times f_{D,n}}{2 \times f_s}$$

reflected in its direction by the particle $n$, where $c$ is the acoustic beam celerity, $f_s$ the emitted frequency, $f_{D,n}$ the Doppler frequency shift produced by reflector $n$, that is the difference between the emitted and reflected frequencies, and $\theta_n$ the angle between the beam and the direction of motion of the particle (Figure 2). In most applications, $\theta_n$ is considered as equal to the ultrasonic beam angle $\theta$ of the acoustic beam.

A Doppler velocimeter measures the frequency shift produced by a large number of particles $n$ in the sampled volume, providing a frequency spectrum. From this spectrum is derived either a mean velocity $V_m$ or a maximum velocity $V_{max}$ in the sampled volume.

**Investigated parameters**

The parameters presented hereafter are defined in conformity with the ISO/TS 15769 Technical specification.

**Ultrasonic beam angle and beam width**

The ultrasonic beam angle $\theta$ (Figure 3) is the angle between the cone axis and the flow direction. Together with the range, this parameter gives important information about the region in which velocities are investigated by the sensor. For example Figure 2 shows that, for a same range, the emission angle $\theta_1$ does not allow to attain the particles located close to the free surface.

The beam width $\theta_w$ indicates the spread of the beam. This is an important parameter: the wider the beam width is, the greater the “envelope” is (Figure 3). Thus, for a same concentration of particles, the number of particles that send ultrasonic signals back to the sensor increases, but as $\theta_n$ varies for each particle, the accurateness of the measurement can be affected.

![Figure 3: Influence of the emission angle on the "envelope"

**Range**

It is the maximum distance that can be reached by the ultrasonic beam with a sufficient return signal for assessing the Doppler frequency shift. Associated with the ultrasonic beam angle and beam width, it controls the "envelope" of ultrasonic beam that is the volume including the particles used to measure the velocity (Figure 4).

![Figure 4: Influence of range on the capacity to measure $V_{max}$

**Signal processing (weighting of echoes)**

This may sound as a tough job! But in the measuring volumes, all local velocities are not “seen” with the same acuteness by a sensor: the closer to the sensor the particles are, the more energetic the reflected signal is. So the flowmeter has to achieve some kind of balance among reflected echoes. But [3] has reported that the position of the reflector is a major source of uncertainties. Thus the balance is of great influence on the ability of the sensor to actually provide the maximum or the mean velocity of the flow. This balance is controlled by the electronic part of the sensor which analyses all the weighted signals. It has to be pointed out that the technical documents of the sensors do not give any information on the way the signals are weighted.

Users have no direct access to the electronic processing of the signals. It is however possible to assess indirectly how the sensor makes a balance between several different signals. This has been achieved by using two targets. In a first step, a flow circulates in the pipe $P_1$ and no flow in the pipe $P_2$, and the sensor records a velocity $V_1$. In a second step, a different flow circulates in the pipe $P_2$ and no flow in
the pipe P1, and the sensor records a velocity V2. Finally both flows are circulating and the sensor records a velocity V that is compared to V1 and V2 (Figure 5).

**Experimental setup**

**Flow-meters**

In order to check the versatility of the testing procedure, the experiments have been made with commercial flow-meters, the emission frequency f and the velocity parameter of which are given in Table 1. The velocity parameter is either the maximal or the mean velocity of the flow, and it is specific to each sensor.

**Laboratory setup**

The characterization of a sensor requires controlled experimental conditions that can not be achieved in a real network. The typical real situation of a sensor implemented at the bottom of a sewer and emitting an ultrasonic beam to the free surface of a flow has been modeled with an experimental setup (Figure 6). The sensor is immersed in a tank containing quiet water. Water streams, loaded with polystyrol beads, are pumped with controlled flow-rates through PCV pipes, 10 mm in diameter. PCV has been selected because it is transparent for ultrasonic waves. In order to delimit precise “targets” for the velocity sensors to detect, the pipes are covered by an insulating coating, except on adjustable “windows”.

Table 1: Characteristics of the flow-meters

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Trade mark and type</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Isco 4250</td>
<td>f : 0.5 Mhz, velocity parameter: V_mean</td>
</tr>
<tr>
<td>D</td>
<td>Mainstream</td>
<td>f : 1 Mhz, velocity parameter : V_max</td>
</tr>
</tbody>
</table>

This experimental set-up is a rather rough model of the real situation: it provides reproducible testing conditions, which will have to be compared with field surveys to assess their representativeness.

**Results**

**Ultrasonic beam angle and beam width**

The measurement of the beam width comes from the observation of the intersection of plane of the target with the sampled cone that gives an ellipse (Figures 7 and 8).

The geometry (Figure 8) shows that:

\[ \tan(\theta) = \frac{d_2}{R_3} \]

this is a way to determine the beam angle \( \theta \) but it is quite fastidious to precisely determine \( R_3 \). Another way is by turning the sensor by a pitching angle \( \psi_y = \pm 45^\circ \).
Figure 8: the sampled ellipse and its projection on a vertical symmetry plane

Let

\[ V_2 = V \times \cos(\theta + 45^\circ) = \frac{c \times f_\theta (\theta + 45^\circ)}{2 \times f_s}, \]

\[ V_3 = V \times \cos(\theta - 45^\circ) = \frac{c \times f_\theta (\theta - 45^\circ)}{2 \times f_s}, \]

then:

\[ \tan \bar{\theta} = \frac{V_2 - V_3}{V_2 + V_3} \]

In fact for the assessment of the velocity with the angle \((\theta + 45^\circ)\) the beam could be almost perpendicular with the flow, giving measures near to 0.

It is also possible to calculate the beam width \(\theta_w\) as

\[ R_1 = d_e l = \frac{1}{\tan \left( \frac{\theta - \theta_w}{2} \right)} - \frac{1}{\tan \left( \frac{\theta + \theta_w}{2} \right)} \]

that is equivalent to :

\[ R_1 = d_e l = \frac{2 \sin(\theta_w)}{\cos(\theta_w) - \cos(2\bar{\theta})} \]

The equation allows the result :

\[ \cos(2\bar{\theta}) + \left( \frac{2d_e l}{R_1} \right) \sin^2(2\bar{\theta}) + \left( \frac{2d_e l}{R_1} \right)^2 \]

\[ \cos(\theta_w) = \frac{1 + \left( \frac{2d_e l}{R_1} \right)^2}{1 + \left( \frac{2d_e l}{R_1} \right)^2} \]

Table 2 shows the results of such experiments. It is interesting to notice that the beam width are similar but the beam angle very different. That implies that the envelope of each sensor is not screening the same part of the flow.

### Table 2: Beam angle and beam width

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Beam angle (°)</th>
<th>Beam width (\theta_w) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>31</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>14</td>
<td>24</td>
</tr>
</tbody>
</table>

**Range**

The range of a sensor is investigated by moving the sensor away from a fixed target. The determination of the range is not an easy task, because the behavior of different sensors differs from one to another as the target approaches their maximum range. Some sensors assess the quality of the signal and stop giving any value when the quality is regarded as too low (sensor C on Figure 9). In this case the range is quite obviously defined. Other sensors provide a value whatever the quality of the signal (sensor D on Figure 8). In this case, a threshold value must be chosen, which defines the range on a somewhat arbitrary basis: we have defined the range as the distance where the velocity fall beyond 80% of the maximum values obtained at 20 cm of the target. Figure 9 shows that difference of behaviors. An other question is the influence of the pipe, we did comparison with the 4 mm thick PVC pipe and a very thin and fragile 100 microns target and no difference could be noticed.

Figure 9: Ranges of the sensors.

Table 3 shows that the sensor D has a range 25% greater than sensor C. This aspect might be considered in comparison with the water levels expected in the measuring area.

### Table 3: Range

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>80</td>
</tr>
<tr>
<td>D</td>
<td>100</td>
</tr>
</tbody>
</table>

**Signal processing**

As explained earlier, it is possible to assess indirectly how the sensor makes a balance between several different signals. Table 4 shows that the sensor D measures (at least with 2 different velocities located in the envelope of the beam and at the same distance of the sensor) the maximum velocity, as announced by the builder. This is not the case of the sensor C which should measure a mean value, and actually provides a value greater that the expected one.

### Table 4: Signal processing

<table>
<thead>
<tr>
<th>Sensor</th>
<th>searched velocity</th>
<th>Result of the weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Vmean</td>
<td>aVmin + bVmax with a+b=1</td>
</tr>
<tr>
<td>D</td>
<td>Vmax</td>
<td>Vmax</td>
</tr>
</tbody>
</table>

**Uncertainties evaluation**

This testing procedure requires a lot of measurements thus we tried to evaluate the uncertainties associated. If we consider a variable \(Y\) defines as a function of \(n\) parameters \(X_i\), we can write that \(Y = f(X_1, X_2, ..., X_n)\) and the associated uncertainty \(u_Y\) can be calculated with the generic formula:

\[ u_Y = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial f}{\partial X_i} \right)^2 u_{X_i}^2} \]

where \(u_{X_i}\) is the uncertainty associated with the parameter \(X_i\).
Using the measurement protocol described before, the emission angle can be defined as \( \bar{\theta} = f(d_{el}, R_1, V_2, V_3) \). But it is extremely difficult to evaluate the uncertainties \( u_{\bar{\theta}} \), then we could not properly evaluate \( u_{V_i} \). The beam width can be defined as \( \theta_w = f(\bar{\theta}, R_1, d_{el}) \) where \( \bar{\theta} \) is the beam angle, \( R_1 \) and \( d_{el} \) are geometric parameters defined on Figure 8. Figure 10a shows that the relative error \( \frac{u_{\theta_w}}{\theta_w} \) on the beam width is not affected by the distance \( d_{el} \) between the sensor and the pipe containing the target for the beam angles of the sensors C and D used on the experiments. Figure 10b shows the relative error on the beam width as a function of that angle for beam angle between 10 and 70 when the measurement uncertainties are evaluated at \( u_{R_1} = 0.5 \) mm and \( u_{del} = 0.5 \) mm. It can be noticed that the relative error is greater than 12% for a beam with of 15°, that is similar to the beam angle of the sensor D. The positive point is that, for the two sensors used here, the relative error is smaller than 6%.

**Conclusion**

The main intrinsic parameters of the sensor (emission angle, beam width, range) can be investigated with a laboratory setup quite easy to manage. The results allow to avoid any problems with sensors which emit with 45° beam angle. With such results, the users could be receptive with the using conditions. The two sensors tested here show deep differences. In relation to the exploitation of the mean or the max velocities, the knowledge of the measuring volume has to be taken into account, for sites which present variable conditions.

**Acknowledgements**

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**References**

