Cross correlation – the better Ultra Sonic Doppler – technique

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The acoustic Doppler effect is used since years to carry out velocity and flow rate measurements in liquids and gases. To determine the flow rate in waste water first versions were realized with continuously working (cw) acoustic sources and separate detectors. Stochastic considerations together with assumptions of the velocity profile allow the determination of the mean velocity, but with usually quite poor accuracy for the volume flow rate . To improve the accuracy the required spatial resolution was realised with Pulse Doppler technique. This ADCP technique offers the determination of velocity profiles with spatial resolutions of some decimetres as minimal dimensions. Therefore it is mainly used in larger dimensions such as oceanographic investigations. The cross correlation technique offers much higher accuracy for the velocity determination and also for the spatial resolution, resulting in an accurate flow profile estimation. It can be used for small dimensions as well, for the spatial resolution may be as small as 1-2 cm. To measure in larger dimensions too, chirp coded pulse can be used. This technique is therefore used for applications with a demand of high accuracy for open channel flows. Some of this applications will be described.

Keywords: flow rate measurement, velocity profile, cross correlation technique, float system

1 INTRODUCTION

Since years ultra sound is used for velocity and flow rate measurements of water and waste water in pipes, open channels and water courses. There are mainly two techniques; transit time and Doppler. Here only Doppler technology is considered. A minimum of pollution is required to use this Doppler echo technique due to the fact, that the velocity of small particles or air bubbles is measured. Generally this is a very good approach as this velocity is approximately the same as the real flow velocity. Signals can be evaluated in the time or the frequency domain; usually Doppler and Puls Doppler devices work in the frequency domain; they are described in section 2.1. Evaluation in the time domain by cross correlation is explained in section 2.2.; also a brief comparison is given there. Section 3 describes some applications.

2 ULTRASONIC ECHO DEVICES

2.1 Doppler technology

There are many simple ultrasonic devices on the market for flow rate measurements. These normally use continuously working piezo-ceramic electric sensors and separate detectors [2]. The detector measures the flow velocity by use of the reflected and Doppler shifted ultrasonic echoes of scattering particles; i.e. air bubbles or any solid particles. The flow rate is than calculated from this velocity. With no spatial resolution the accuracy of this instruments as flow rate meter is quite poor.

To obtain a spatial resolution, too, the pulse Doppler technology is used. Here short pulse bundles are sent into the medium. This kind of sensor does not require a separate detector; normally only one ceramic is used as sending and receiving unit. Knowing the sound velocity *c,* it is easy to determine a spatial resolution (*l* = distance to the detector) by measuring the time *T* between sending and receiving the echo. This can be seen in figure 1.

$$l = \frac{c \cdot T}{2} \tag{1}$$

Usually the echoes are collected in time frames resulting in spatial windows which are used to determine the velocity; see figure 1.

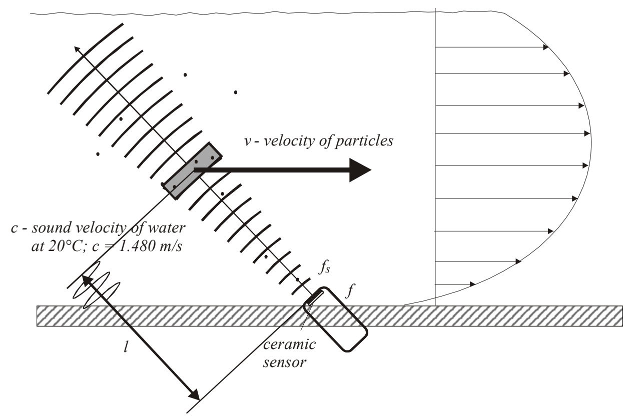


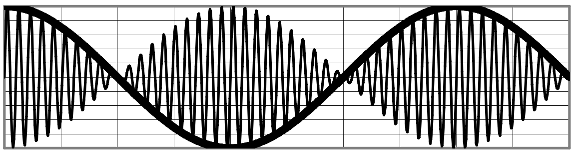
Figure1: Doppler system

The direct measurement of the Doppler shifted frequency f_s with v as particle velocity is difficult:

$$f_s = \frac{f \cdot c}{c - 2 \cdot v \cdot \cos\alpha} \tag{2}$$

Some numbers may explain this; for a sending frequency of 1,000,000 Hz the typical shift is about 100 to 1,000 Hz. It is more difficult to determine this frequency directly than overlapping the echo frequency with the basic frequency and determining the beat frequency $\Delta f = (f_s - f)$. Figure 2 shows the beat frequency. The resulting formula is:

$$v = \frac{(f_s - f) \cdot c}{2 \cdot f \cdot \cos\alpha} \qquad (3)$$



Picture 2: Beat frequency

The determination of the beat frequency is possible only if there are enough cycles of the basic frequency within the beat frequency. Due to this, the spatial resolution of this Doppler devices is restricted to a minimum of typically 0.30 to 0.40 m. Usually an easy frequency determination is implemented; it is indirectly calculated by measuring the time between the zero crossings of the beat frequency. This measurement fails at low velocities and it becomes impossible at 0 m/s, where the corresponding frequency is 0 Hz, too ($1/T \to \infty$).

2.2 Cross correlation technology

Correlation is more and more used as a mathematical tool for flow rate measuring especially for signal evaluation since fast and powerful microprocessors have become available. Used in stand-alone flow rate meters, it is meanwhile used for measurements in two-phase fluids, too.

The figure 3 shows the acoustic cross correlation sensor OCM *Pro* CF of the NIVUS [3]. The sensor at the bottom sends a short ultrasonic pulse into the water with an angle of 45° towards the flow direction. The echoes are than collected in time frames. Than a second pulse is send into the water and the echoes of this sensor are collected in the same time frames. The correlation of both echoes enables the calculation of the temporal movement in each frame/window; the velocity profile can be calculated. The method offers a spatial resolution of the length of a single oscillation, but to achieve a better mean the minimal window length is set to about 0.01 m. The maximal size is variable and may reach up to 0.10 m.

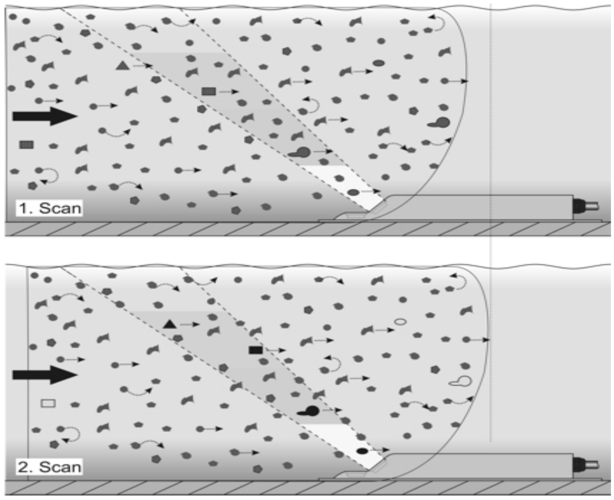


Figure 3: Acoustic cross correlation method

The formula 4 gives the mathematic expression:

$$\varphi_{f,g}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} f(t) \cdot g(t+\tau)\, dt \qquad (4)$$

or as digital expression:

$$\varphi(\Delta T) = \frac{\sum_{i=1}^{N} f_i \cdot g_i(\Delta T)}{\sqrt{\sum_{i=1}^{N} f_i^2 \sum_{i=1}^{N} g_i^2}} = \frac{\sum_{i=1}^{N} f_i \cdot g_i(\Delta T)}{N^2} \qquad (5)$$

with
f = echo function of digital picture 1
g = echo function of digital picture 2

The velocity is calculated in maximal 16 windows (time frames) and can be used to determine a velocity profile. The velocity values and the profile can be used to calculate the flow rate in full pipes and open channels as well. The velocity profiles in full filled pipes are well known and the flow rate determination is straightforward [1].

For part filled open channel flows an additional height measurement is required. Therefore an ultrasonic height sensor as well as a hydrostatic sensor are integrated. Using an external sensors is possible, too. The height fixes the position of the 16 velocities. The calculation of the flow rate from this velocities will not be discussed here, some information about this topic can be found in [3].

There is one major limitation for cross correlation used by the OCM *Pro* CF. The maximum height in which velocities are measured is 1.00 m or 1.5 m along the ultra sonic beam. For larger distances only empirical or numerical calculations can be used taking into account the measurements along the first meter.

This limitation is caused by a de-correlation between the 2 pulses. Before the second pulse is sent into the water, all echoes from the first echo need to be collected in advance. Therefore the time between the 2 pulses is getting longer while the distance to the sensor increases. As the distance to the ceramics is growing, the ultra sonic intensity of the reflected echoes decreases due to the normal propagation of waves; this two effects lead to a poorer correlation.

The OCM *Pro* LR overcomes both problems. It uses ceramics with a larger diameter. As a result the lower spreading angle keeps the intensity of the ultrasonic beam higher. This first step neglects explosion requirements (ATEX), too; with more ultrasonic power the intensity problem of the echoes could be ignored.

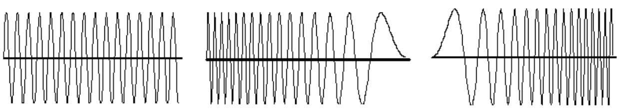
Reducing the time between the two pulses was done by using a chirp coding of the “normal” ultra sonic burst:

$$U = U_0 \cdot \sin(\omega \cdot t) \quad (6)$$

where U is the amplitude of the ultrasonic wave, ω the frequency and t the time. For chirp coded signals ω is not longer a constant but depending on time. A linear chirp e.g. utilizes

$$\omega = \omega_0 + k \cdot t \quad (7)$$

with k as a constant. We did not consider other chirps, thus as exponential. Picture 4 shows linear up and down chirp coded pulses in comparison to a “normal” pulse:



Picture 4: “Normal” burst, up-burst, down-burst

To use chirps ceramic oscillators are required that can be excited in a larger frequency range. Under ideal conditions the 2 bursts are orthogonal and do not interfere with each other. The ideal orthogonally is not possible and also disturbed due to the interaction of the ultra sonic pulse in the $3/4 \cdot \lambda$ coupling plate and in the water. Beside the good correlation of this pulses a higher energy can be involved with larger bursts. This results in larger distances that can be measured.

3. Applications

Meanwhile the OCM *Pro* is used for many different applications. In the following there will be three different ones.

Flow rate measurements are difficult in the sludge return with up to 3-5% solid content. If there is fat as well magnetic inductive instruments cant be used. Figure 5 shows the sludge pipe from the digestion tank to the sludge incineration.

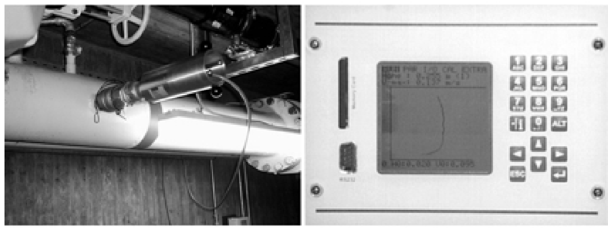


Figure 5: Flow rate meter in the sludge return

The right picture shows at the display of the transmitter a well developed velocity profile; therefore a good accuracy can be assumed. A fast removal of the pipe sensor during cleaning is realised with a special fitting.

Especially in the influent to the waste water plants you may have sedimentation in the channel. The sensor may still work at low sedimentation, but it will fail finally. Secondly usually a wrong cross section, the complete big one is taken to calculate the flow rate. A float system (figure 6) can help to solve this problem. A wedge sensor is mounted below the float.

Figure 6: Float system by use of surf boards

A ultra sonic height sensor measures the sludge level to calculate the correct cross section. The velocity sensor measures from the surf boards to the bottom; there is no need to consider a sedimentation, but fat is removed from time to time.

Flow monitoring is a significant part of operating of a sewer system. The presented example comes from Prague sewer network, where a system of permanent flow monitoring includes all main collectors, which collect waste water for the CWWTP (Central Waste Water Treatment Plant), and also at important CSO structures.

In 2006 one of the most complicated permanent flow sites, called “ACK”, was equipped with an OCM Pro flow meter. It replaced the former Doppler device with a Correlation system. The data measured by OCM PRO are implemented into the telemetry system to enable remote access to them. Figure 7 shows a sketch of the site

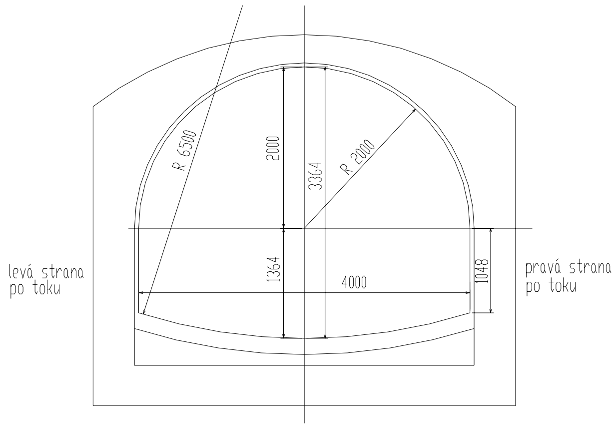


Figure 7: Sketch of “ACK”

The shape is a mouth profile made of reinforced concrete; channel height is 3.35 m, the width 4.0 m. With a slope of 0.2 % there is no sedimentation. To mount this devices in the channel special brackets were used that can be seen in figure 8. Also the ultra sonic level meter is visible at the ceiling.

To reach high accuracy a calibration was carried out. The calibration was performed with a grid measurement with a hydrometric propeller; the uncertainty of the calibration was within about 5%. The analysis of the measured data show very stable readings of the flow meter.

After two years of operation it is obvious, that that the flow meter OCM *Pro* has brought a significant improvement of the flow measurement at this site. Based on this experience two other permanent measurement profiles “F1” and “K1” were equipped by the same technology in 2007.

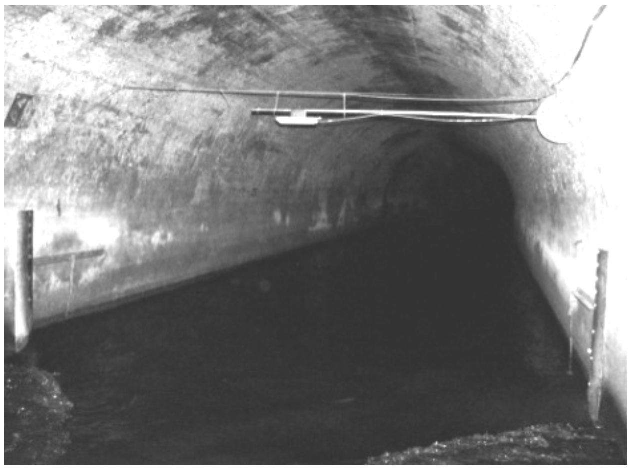


Figure 8: Measuring site “ACK”

4 CONCLUSIONS

Other successful applications meanwhile indicate the potential of the cross correlation instrument. The applicability in different degrees of pollution covers a range from very high pollution (see above) up to very clean water in the effluent of waste water treatment plants with nearly drinking water quality. The dimension rage from 0.1 m up to several meters; resulting in flow rates from about 1 l/s to about 1000 m³/s

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Beside the theory here the complete application know how of the company NIVUS is involved. The description of more applications can of course be found in other documentations of NIVUS.

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