Ultra Sonic Flow Rate Measurements in Large Pipes and open Channels

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I Summary

Correlation is a mathematical tool which, enabled by developments of fast and powerful microprocessors in last few years, has found its way into the signal evaluation in the field of flow rate measurement. Within the various flow measurement methods it is especially applied as a non contacting technology in multiphase flows. In this connection the correlation is used with various signal transmitters, this report is confined to an acoustic signal transmitter and a receiver though. To portray the correlation in simplified terms it can be considered as the consistent development of simple CW Doppler systems and Pulse Doppler systems. To point out the differences these technologies will be discussed as well.

The acoustic Doppler effect is a well known to be used for velocity or flow measurement in fluids and gases. First applications in this field worked with continuously operating sound generators and separate receivers (CW - Doppler) determining the Doppler shifted frequency of scatters in the liquid. The velocity of the reflecting particles in the fluid (gas bubbles, solid substances or similar) can be calculated from the difference between transmitted and received frequency. Intelligent evaluation procedures enable plausible profile assumption, so the Doppler velocity measurement method can be used as flow measurement in connection with level measurement.

The Pulse Doppler method represents a further development of the continuous Doppler method and provides an additionally spatial resolution of the measured particle velocity. This positioning of a spatial measurement window is gained from measuring the transit time of a short ultrasonic pulse. So the maximum velocity is measured that is converted into the mean velocity and using this, the flow rate is calculated. Additionally the pulse method allows the transmitter and receiver to be identical.

The cross correlation method provides much higher accuracy for the velocity measurement – due to the turbulent velocity fluctuations a further improvement will not offer additional information. The spatial resolution is more than 10 times lower than for a Pulse Doppler system. Though the current velocity profile can be determined. In combination with an integrated level measurement an accurate calculation into the flow rate is feasible. This opens up measurement ranges in partially and full filled pipes with large diameters and in applications with open channels and flumes. Such applications could not be covered sufficiently in the past or caused extremely high expenses.

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1.) Introduction

Flow measurement in full filled pipes mostly attains very high accuracy, particularly in pipes with diameters < 200 mm. Many suppliers and many various measurement methods normally guarantee inexpensive measurement devices here. The situation changes as soon as large partially or full filled pipes and open channels with irregular velocity profiles, backwater, low filling levels and low flow velocities are considered. Here generally the attained accuracy is not comparable, but nevertheless prices increase often very clearly in connection with the channel dimensions.

It is plain to see the increasing need for accurate and inexpensive measurement methods in this area.

Ultrasonic meters for flow measurement have been practically used for some time. Initial stages are operated with a continuous ultrasound – Doppler method which is used in connection with level measurement. This procedure is briefly described in chapter 2.

Chapter 3 outlines improvements which come in use especially in full filled pipes. Here, using the Pulse – Doppler method enables the spatial allocation of measured velocities.

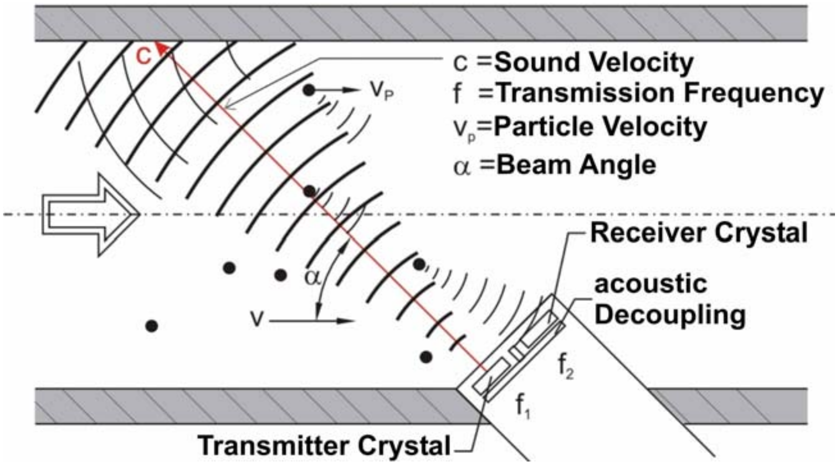
The measurement accuracy is than be improved by using the cross correlation. This method is described in chapter 4. By using the latest developments in the field of electronics measurement devices a new sensor could be developed that provides very high accuracy in velocity measurement as well as high spatial resolution. This enables a reliable velocity profile determination. Hence, in combination with an integrated level measurement within our compact sensor, reliable flow rate measurements are feasible.

Chapter 5 points out several applications.

2.) Doppler Method

When a car passes by it emits a sound signal that is changing its frequency. As long as the car is approaching us, the frequency is higher as if it is moving away from us. In simple words: if the vehicle comes towards us, the sound waves are "compressed" causing a higher pitch. If the car moves away the sound waves are „stretched" causing a lower pitch. This frequency shift is a perceptive effect only: for the driver the sound is the same all the time. This effect (described by Christian Doppler in 1842) is practically used in the fields of astronomy, medicine and industrial applications. The following explanations describe how the Doppler effect can be used for flow rate measurements if transmitter and receiver are firmly fixed with a flowing medium and moving and reflecting particles.

As depicted in Fig. 1 there are two piezo crystals integrated within the Doppler sensor. One of them is operating as continuous transmitter, the other one as continuous receiver. Both crystals are acoustically decoupled against each other on their rears. Towards the medium (due to mechanical and chemical protection) they are isolated with a cast resin layer that has good acoustic coupling and transmission capacities.



Sound Velocity c:
(at 20°C)

Water	= 1480 m/s
Air	= 330 m/s
Steel	= 5900 m/s
Meth. Alc.	= 1100 m/s

Fig. 1: Doppler Effect in Flow

The transmitter crystal continuously transmits sound waves with the defined frequency f_1 and a fixed angle α into the water (**c**ontinuous **w**ave operation). The waves hit particles or gas bubbles contained in the medium, which move through the acoustic area with the velocity v. The receiver crystal measures the Doppler shifted frequency f_2 that is reflected by the particles according to the formula:

$$f_2 = \frac{f_1 \cdot c}{c - 2 \cdot v \cdot \cos\alpha}$$

From this measured frequency f_2 the frequency shift can be calculated.

$$\Delta f = f_2 - f_1 = \frac{2 \cdot v \cdot f \cdot \cos\alpha}{c}$$

In practice the high frequency transmitter signal is heterodyned with the received frequency, than the envelope frequency is determined. This is to attain a higher resolution.

Example:	Transmitting Frequency:	1.000.000 Hz
	Receiving Frequency:	1.000.200 Hz
	Frequency Difference:	200 Hz

The frequency difference is a linear measurement for the particles' velocity in the medium and thus representative for the flow velocity of the medium itself, if the particles are small enough.

The determined Doppler difference frequency is converted into digital impulses. The used period duration measurement has, in comparison with the direct frequency measurement, the advantage to measure even very low frequencies (i.e. low flow velocities) quick and reliable. Accumulated data are saved and sent to the measurement transmitter's statistical data evaluation.

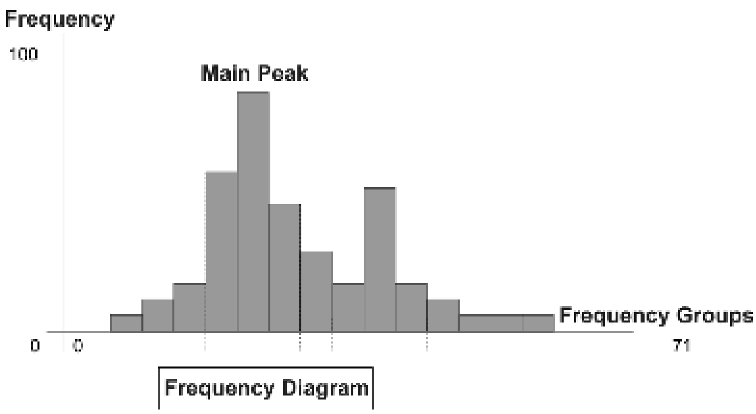


Fig. 2: Frequency Diagram

The statistical data evaluation subdivides the entire frequency spectrum into a number of frequency groups. For each of these groups the frequency of the measured single frequencies is determined. A defined number of single frequency measurements are sorted into this set of statistics. This is how the average value of the frequency groups and thus the resulting average velocity can be calculated from the determined frequency group maximum.

Depending on density and number of the particles in the medium as well as the used sound frequency the Doppler method enables intrusion depths from a few millimetres up to 5 m.

Unfortunately it is not possible to position or to limit the intrusion depth. This may possibly result in reflecting the sound waves from an uneven water surface if number or size of the particles in the medium are badly fluctuating. In this case the movement of the waves on the water surface may eventually be misinterpreted as particle velocity.

Above all this procedure is used in sewage treatment plants for influent and discharge measurements, to record recirculation and return sludge volumes as well as for discharge measurement and control in storm water and rain retention basins. Recording direct or indirect influent in feeding sewer systems or measurements and control in pump stations are widespread applications too.

3.) Pulse Doppler

The ultrasonic pulse Doppler method shows a further development of the known Doppler measurement technology described above. Figure 3 shows the setup.

Like the CW – Doppler method (continuously working transmitters) the pulse Doppler method emits short ultrasonic frequency bursts. Since the temperature compensated sound velocity in the medium and the beam angle of the ultrasonic signal are known the measurement point can be determined by precisely controlling the time duration between transmission and reception. This enables a defined measurement window in the medium to be assigned to the received signal. As described above the frequency shift of the received ultrasonic signal can be used to calculate the flow rate. Due to the used pulse tact between transmitting pulse and receiving the measured velocity can be located spatially. Echoes from particles in other areas do not affect the velocity measurement.

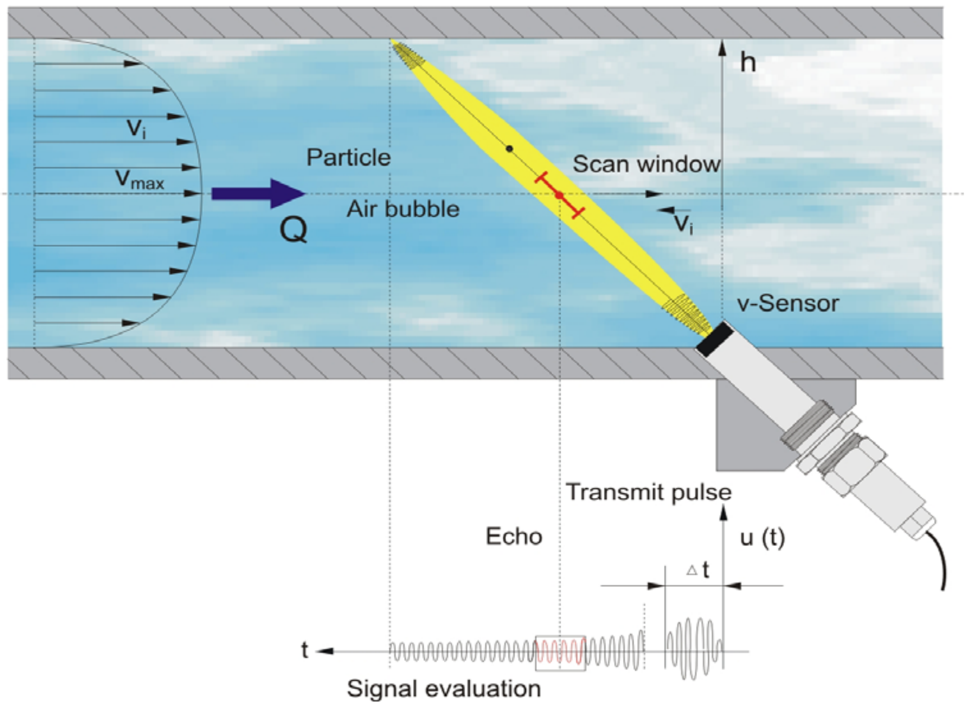


Fig. 3: Pulse - Doppler

This measurement method is restricted to be applied in full filled circular pipes due to the calculation procedure it is based on.

The pulse Doppler method with its spatially defined single – point - measurement offers two different options for evaluation and conversion of the measured flow velocity into the average flow velocity:

1. v_{max} (preferred method) The measurement window is positioned at the centre of the pipe ($r_m = 0$)

2. $v_{average}$ (more inaccurate method, used mostly in very large diameters) Measurement window is positioned to the point of average flow velocity ($r_m = 0{,}77 \times r$)

A next measurement pulse is sent out with an impulse repeat rate which results from signal intrusion depth, flow velocity and diameter (Table 1). The setting is made automatically, but can be fixed manually too.

Velocity [m/s]	**Max. Intrusion Depth at 750 kHz / [mm]**	**Max. Pipe Ø [DN]** v_{max} **Method / [mm]**	**Max. Pipe Ø [DN]** $v_{avg.}$ **Method / [mm]**	**Repeat Frequency [mm]**
0 – 1	340	680	2.800	1463
0 – 2	170	340	1.500	2927
0 – 4	85	170	750	5954

Table 1

4.) Cross Correlation

Correlation is a mathematical evaluation method which, enabled by the development of fast and powerful microprocessors, has found its way into the signal evaluation in the field of flow measurement technology.

Within the various flow measurement methods it is especially applied as a non-contacting technology in multiphase flows. In connection with ultrasonic technology it can be applied to cover measurement ranges in full or partially filled pipes with large diameters as well as in open channels, which otherwise cannot be covered sufficiently, with unsatisfactory accuracy only or by causing extremely high expenses.

Correlation is the „comparison“ between two ultrasonic records with a temporary offset. The prerequisite for its use are reflecting particles (solid and floating particles or gas bubbles) in the water.

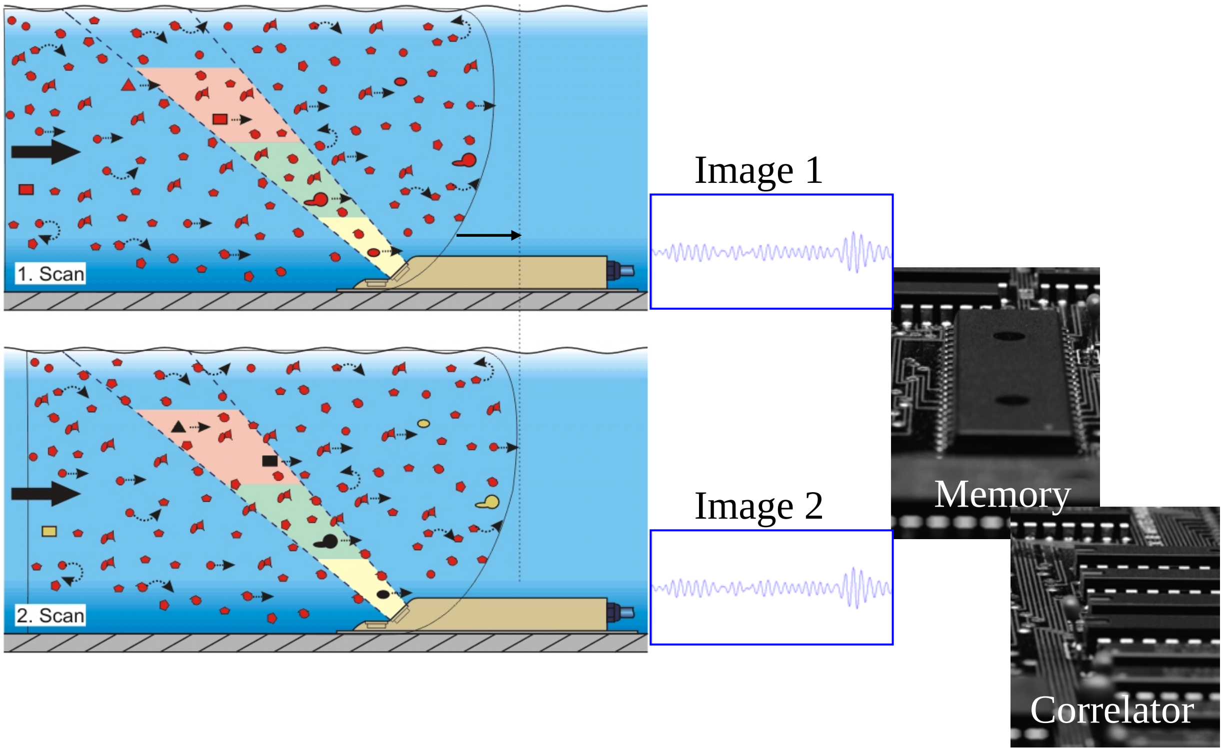


Fig. 4: Correlation

These particles are scanned by ultrasonic pulses with defined angle and their echoes are stored as image or echo patterns. Resulting from the pulses' travel time (or the echoes of these impulses) a spatially allocated measurement can be derived like using the Pulse Doppler method. Within about a milliseconds a second scan is taken whose echo pattern is stored as well. A travel time determination ensures the measurement has be taken in the same time/spatial window. The correlation of stored signals enables the determination of the time shift, that is directly converted into the flow velocity and the volume flow rate.

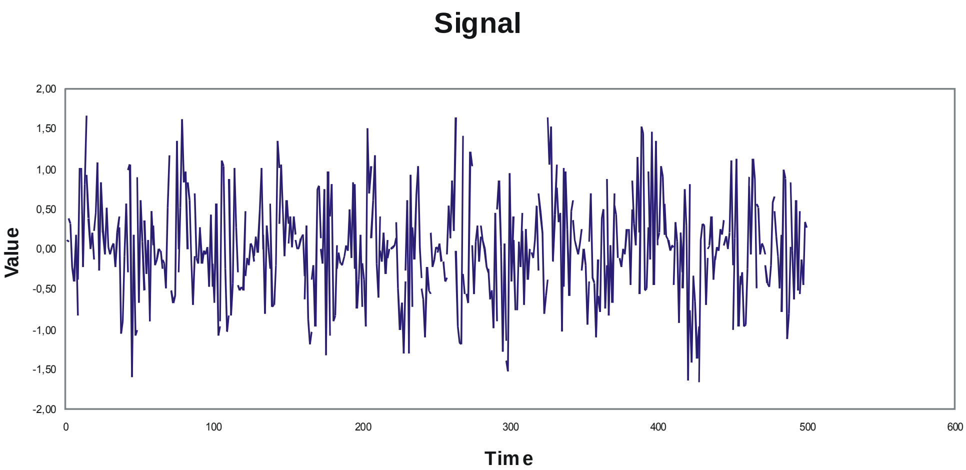


Fig. 5: Ultrasonic Echo Signal

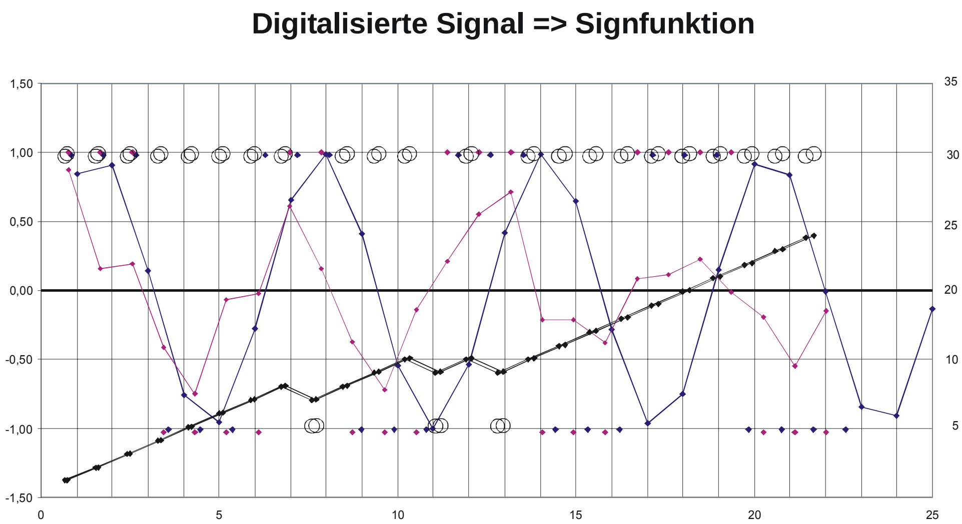


Fig. 6: Partial Ultrasonic Echo Signals, digitalized and correlated

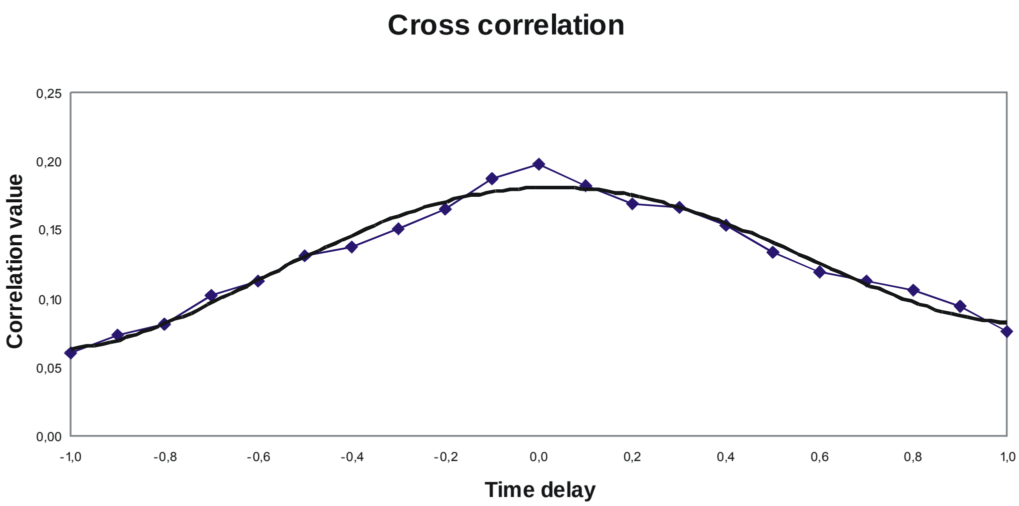
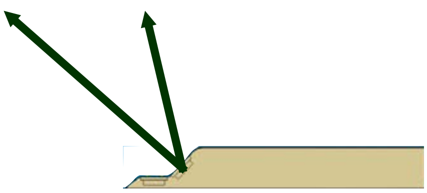


Fig. 7: Correlation Function

Here the basic correlation equation

$$f(t) \xrightarrow{\varphi_{f,g}(\tau)} g(t)$$



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

is digitally expressed as follows:

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

with

f = 1st digital „Image”
g = 2nd digital „Image“

The figures 5-7 outline the look of an ultrasonic echo signal and how a cross correlation can be digitalized and evaluated by using a simple sign function. This results in a maximum concerning the time shift which will be processed further.

This measurement setup enables velocity measurements in up to 16 „windows“ and hence the velocity profile can be determined. This can be used to determine the flow e.g. in full filled pipes (by using the usual average velocity calculation from the path velocity, as usual done for example for ultrasonic clamp-on measurement methods). It is advantageous to obtain in addition to the average path velocity a velocity profile measurement which can be used in simple cases to assess the „quality“ of a measurement place. Further it can be used for measurement value correction too.

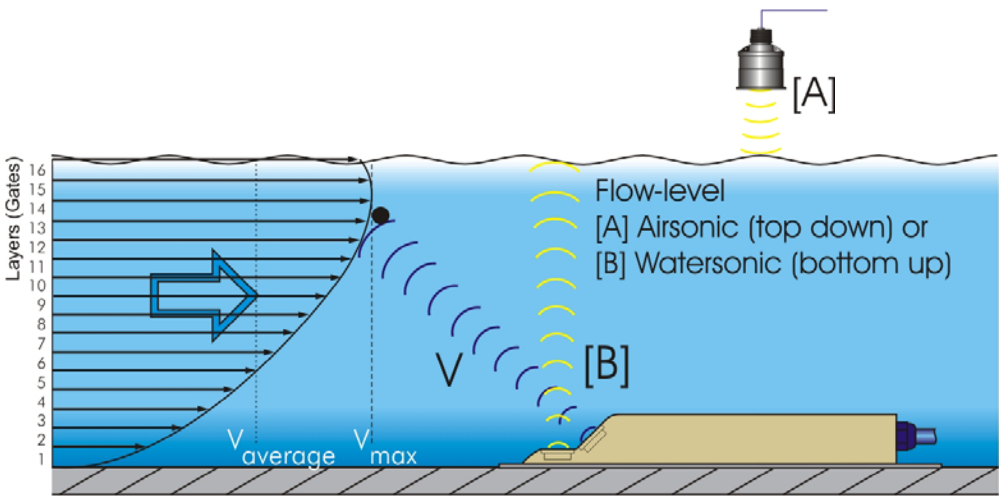


Fig. 8: Integrated and/or external Level Measurement

By using the velocity profile from 16 „windows“ above all flow measurement in partially filled pipes and channels is feasible. To achieve this, an additional level measurement is required which can be carried out by an integrated or an external sensor.

With a combination sensor in partial fillings besides the flow velocity the flow level is determined too. This is achieved by using a water ultrasonic sensor which determines the water level by evaluating the travel time of an ultrasonic pulse up to the fluid surface. Connecting an external level sensor it is possible too and even recommended under certain conditions, i.e. wavy surface or a lot of air bubbles in the water. Depending on the filling level the “windows“ are positioned variably and their size is adjusted. At low filling levels the number of the “windows” is decreasing.

Considering the accuracy we can see some errors effecting the total error according to the common quadratic error calculation:

f_1 = Time Meas. = Velocity Meas.	= 0,10 % of Measurement Value
f_2 = Installation Angle (5°)	= 0,75 %
f_3 = Velocity Profiles	= 0-10 % typically 1 %
f_4 = Length of Meas. Path in Velocity Profile	= 0-20 % typically 1 %
f_5 = Number of Measurement Windows	= $1/\sqrt{N}$ for 4 Gates 0,5 %
f_6 = Black Areas	= 0-50 % typically 1 %

$$\text{Total Error (typically)} = \sqrt{\sum_{i=1}^{6} f_i^2} = 1{,}96\ \%$$

The device is depicted in figure 9. In figure 10 some sensor variations can be seen which are to be used in various applications.

Fig. 9: OCM Pro

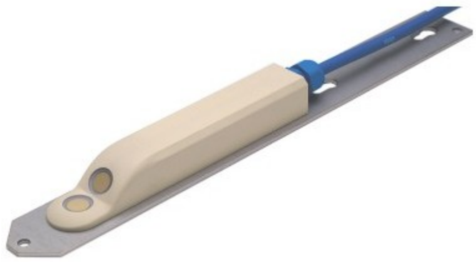


Fig. 10: wedge-shaped Sensor Immersion Sensor Pipe Sensor with Ball Pivot

5.) Applications

1.) Wastewater Treatment Plant: Influent, Discharge, Influent to Aeration Basins, Return Sludge, Recirculation, Surplus Sludge, Digester Discharge and Coagulant Dosage
2.) Stationary measurements at RÜB's
3.) Temporary Measurements in Sewer Systems
4.) Leakage investigation or investigation of extraneous water
5.) Direct feed control
6.) Industrial sewer channel systems
7.) Flow rate measurement in chemical industry
8.) Irrigation systems
9.) Cooling water influent, discharge and circulation
10.) Sluice stages in rivers
11.) Hydro power plants, thermal power stations