

# CROSS CORRELATION FLOWMETERS WITH AE SENSORS

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*Abstract: This paper is concerned on the new type of the sensing elements for a particle volume of flow rate measurements based on cross correlation flowmeters. The new type of sensing elements exploit the fact that the solid particles being carried by a flowing air and impacting a properly formed obstacle generate an acoustic surface wave (acoustic emission - AE). The acoustic signal is indicated by the aid of a high sensitive transducer, which converts the acoustic signal to an electric one. If we use two sensing elements in the flow channel with defined distance, we may use cross correlation technique for calculating transit time and then from time and distance of obstacles the speed of particles.*

*Keywords: Cross correlation flowmeters, acoustic emission, speed of particles*

## 1 INTRODUCTION

Flow measurements belong to the most difficult ones because the medium being measured can occur in various physical states, which complicate the measuring procedure. They are namely temperature, density, viscosity, pressure, multi-component media (liquid-gas, solid-gas), the type of flow, etc. The choice of the method is further directed by specific requirements for the flow meter, e.g. the measuring range, minimum loss of pressure, the shortest possible recovery section, a sensor without moving parts, continuous operation of the sensor, etc. That is why about 60 measuring methods have been developed to meet the increasing demands on laboratory and industrial measurements of flow of gases, liquids, vapours and solid particles in one-phase or multi-phase medias. The flow of fluid is often measured by orifice plates, venturis or vortex flowmeters, turbine flowmeters, thermal flowmeters, ultrasonic pulse transit flowmeters, magnetic flowmeters, Coriolis type flowmeters etc. [2]

Cross correlation flowmeters are one from the sensors for the volume flow rate measurement. The basic idea is simple. The cross correlation flowmeter measures flow by sensing the passage of some disturbance or tagging signal in the flow at one position, and measuring how long time (transit time) needs that disturbance to travel to the next point. Different types of sensing elements can detect tagging signals. The choice of the sensing elements should be principally based upon reliability and cost. The small change of the sensitivity or temperature gain unsuitability of the sensing elements (transducers) is not important, because we measure only time variations of the signal from the sensing elements. The standard sensing principles fall into three categories [1]:

- Modulation of radiation by the flowing fluid (modulation of acoustic radiation, modulation of light, modulation of gamma rays etc.)
- Emission of radiation by the flowing fluid (thermal radiation from the hot flowing gas, ionising radiation from the flow of highly radioactive liquor, etc.)
- Instantaneous measurement of electrical and thermal properties of the fluid (capacitance sensors for measuring the flow of gases with particles, electrodynamic sensors for measuring electrostatic charge accumulates on the particles – triboelectric effect, electrical conductivity sensors for liquid-solid mixtures, thermal sensors to detect turbulent eddies, thermal sensor to cross correlate injected heat pulses, etc.).

The cross correlation function is defined:

$$R_{xy}(\tau) = \frac{1}{T} \int_0^T x(t-\tau)y(t)dt \quad (1)$$

where  $x(t)$  and  $y(t)$  are signals from the sensing transducers.

A microprocessor computes the sampled data form of the above equation:

$$R_{xy}(j) = \frac{1}{N} \sum_{k=0}^{k=N} x(k-j)y(k) \quad (2)$$

A specific advantage of cross correlation is that any spurious signals present as interface on the measured output are strongly rejected. Function (1) reaches its maximum value when the cross correlation lag  $\tau$  is equal to the transit time  $\tau^*$  of the tagging signals, hence the flow velocity is given [1]:

$$v = \frac{l}{\tau^*} \quad (3)$$

where  $l$  is the distance between transducers. Optimal value is approximately 3 times of pipe diameter.

A measured flow  $Q$  is given:

$$Q = k \cdot v \cdot A \quad (4)$$

where  $k$  is calibration factor,  $v$  is flow velocity (eq. 3) and  $A$  is cross sectional area of pipe. The calibration factor  $k$  is mainly dependent on the non-uniformity of the flow velocity profile across a pipe.

My work is concerned on the new type of the sensing principles and I will be described it in the next chapter.

## 2 SENSING PARTICLES WITH UTILIZATION OF ACOUSTIC EMISION

The principle of the method using acoustic emission is that a carrier gas carries the particles. In the flow channel there is a partition against which the particles strike. The impacts generate a pressure deformation waves - an ultrasonic signal is emitted.

Collision of a particle with the surface of an obstacle generates a pressure wave. It is therefore a mechanical impact of two bodies. For an approximate description we can use the Hertz theory of impact. This theory truly defines the quasistatic character of impact at a relative velocity of a body before the impact duration of which is much shorter than the time needed by the deformation wave to penetrate through the body and return to the place of impact [4], [5]. Let us suppose a vertical elastic impact of a sphere and a massive flat plate. At the place of the impact both bodies are depressed for an instant. The time of depression  $x(t)$  follows from integral equation

$$t = \frac{1}{v} \int_0^x \frac{dx}{\sqrt{1 - \left(\frac{x}{x_{\max}}\right)^{\frac{5}{2}}}} \quad (5)$$

where  $v$  is mutual velocity of the bodies before the impact

$x_{\max}$  is the maximum value of depression, i.e. the value of depression at which the mutual velocity of the bodies dropped to zero. We can calculate it from the following equation:

$$x_{\max} = \left[ \frac{5}{4} \pi \rho (\alpha_1 + \alpha_2) \right]^{\frac{2}{5}} v^{\frac{4}{5}} r = 1,73 [\rho (\alpha_1 + \alpha_2)]^{\frac{2}{5}} v^{\frac{4}{5}} r \quad (6)$$

where  $\rho$  is the specific mass of the sphere material

$r$  - diameter of the sphere

$\alpha_1, \alpha_2$  - material constants of the sphere and plate.

From the integral equation shown above follows the time of impact

$$T = \frac{4}{5} \sqrt{\pi} \frac{\Gamma(0,4)}{\Gamma(0,9)} \left[ \frac{4}{3} \pi \rho (\alpha_1 + \alpha_2) \right]^{\frac{2}{5}} v^{-\frac{1}{5}} r = 5,1 [\rho (\alpha_1 + \alpha_2)]^{\frac{2}{5}} v^{-\frac{1}{5}} r \quad (7)$$

By solving the integral equation the time of depression  $x(t)$  during the impact can be defined, i.e. for  $0 < t < T$ . It can be approximately described by equation

$$x(t) = x_{\max} \sin \frac{\pi t}{T} \quad (8)$$

For impact force

$$F = \frac{4}{3} \frac{\sqrt{I}}{\alpha_1 + \alpha_2} x^{\frac{3}{2}} \quad (9)$$

The above analysis applies to theoretical determinations of the magnitude of force and length of deformation wave, which is in a transducer transformed into an electric signal.

If the particles are small, then the length of the deformation wave will be very short, and the frequency spectrum will have a wide range. The relationship between the length of the pulse on one hand and its frequency spectrum on the other hand serves as a basis for determining the parameters of the transducer and electrodes. For the pulse generated in the transducer by the deformation wave

$$u(t) = U \sin\left(\frac{\pi \cdot t}{T}\right) \quad (0 \leq t \leq T) \quad (10)$$

we get the frequency spectrum:

$$S(f) = \frac{2U \cdot d}{\pi} \frac{\cos(\pi \cdot f \cdot T)}{1 - (2 \cdot f \cdot T)^2} \quad (11)$$

By means of an ultrasonic emission transducer this signal is transformed into an electric signal. Piezoelectric sensors seem to be the best solution because they have low mass and high sensitivity. Important at this application is that these sensors can be constructed with a broad bandwidth. The basis of the piezoelectric sensor is a piezoceramic plate cut. As the signal from the transducer is rather weak, it must be first amplified and then further processed for evaluation. The signal has the shape of pulses. With a larger number of emission events a continuous signal rises.

Distance, position and shape of the partition are critical, because the first partition may create a shadow for the following transducer.

### 3 DESIGN OF CROSS CORRELATION FLOWMETERS

The block diagram of the cross correlation flowmeters is shown on Fig.1. The partition (incurion block) is inserted acoustically isolated in the flow channel with the piezoelectric AE sensor tightly attached to it. Electric signal from the sensor (S) is brought to amplifier (A) with gain 40 dB and further through filter (F). The filter suppresses strongly spurious signals under 40 kHz. The cross correlator with variable time delay  $\tau$  is connected to the output of the filters. The partition inside the flow channel is of the shape of rod, with cylindrical cross-section. Another shapes have been tested (inclined plate, bent pipe, etc.). Two-channel Signal Spectrum Analyser HP 89410A was used for the real time cross correlation measurement.

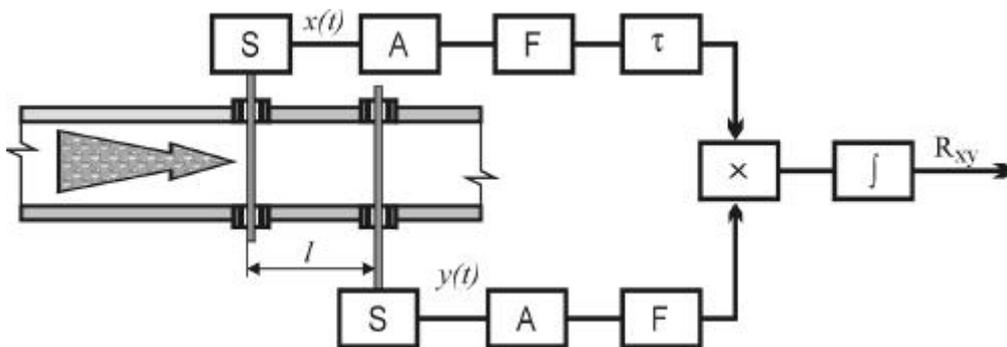


Fig.1: The basic block diagram of the cross-correlation flowmeter

Both ways of creation of the cross-correlation function have been tested. As first, the calculation of the cross-correlation function directly from the high-frequency ultrasonic signal and, as second, the calculation cross correlation from the RMS value of high frequency ultrasonic signal. Better results have been achieved in the second case.

The whole principle of the measuring must be treated as a statistical one. There is impractical to handle with unique impacts of particles on the obstacles, because there may exist particles, which impact only the first obstacle, but not the second one - and vice versa. For this reason there is more practical to inject into the pipe (on its input side) a group of particles. This group causes the rise of a

accumulated impulse on the AE sensor on the first obstacle and (later) a rise of a cumulated impulse on the AE sensor on the second obstacle. The number of particles which impact the first obstacle and the second obstacle need not be the same, but the delay between the cumulated impulses will contain the information of the speed of the carrying gas. This delay will be calculated from the cross-correlation function mentioned above.

The comparison of the volume flow, which has been measured by the cross-correlation flowmeter and by a reference turbine flowmeter, is shown on Fig. 2. The calibration factor  $k$  has been found as  $k = 0,87$ .

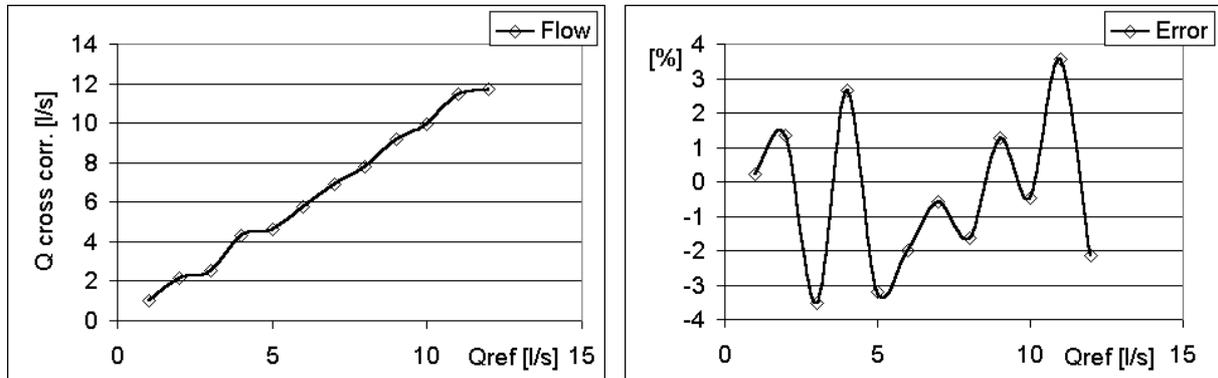


Fig.2: The basic characteristic of the cross-correlation flowmeter

#### 4 CONCLUSION

A cross correlation flowmeter for measuring of the speed of solid particles in a carrier gas using new type of transducers was described. The principle of the sensing method consists in that the particles hit the partition in which ultrasonic pulses (ultrasonic emissions) are generated. These pulses are in the sensor transformed into an electric signal and further processed via amplifiers, filter and cross correlator. The method has been experimentally tested.

The above-described method of measuring the speed of solid particles in a carrier gas represents a contribution to the usually used techniques. Measurements can be carried out even at high temperatures and the only restriction is the Curie temperature of the piezoelectric material of the sensor. The sensor is relative simple in its construction.

Powder technologies are the main area where this flowmeters may be used (also the hard chemistry, cement production, power engineering, pharmaceutical production, etc.). The particles have the dimension range from 10 to 100  $\mu\text{m}$  and bigger and the speed is in range 0,5 to 30 m/s.

#### ACKNOWLEDGMENTS

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