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Ultrasonic Flowmeter using Cross-Correlation Technique

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ABSTRACT

The correlation technique presented offers a good possibility for measuring the average rate of flow of fluids between the pipes. The physical parameter required for the measurement principle is the well known distance among the sensors. The new system described here consists of ultrasonic sensors, changing the natural pressure ,stochastic fluctuations of velocity and density into two signals with a real-time correlator and a delay time T and obtaining the delay time from the signals and calculating the average rate of flow of the fluid. In dissimilarityto established flow methods for measuring, no deceive bodies are essential and electrical conductivity of the fluid is not required. In this paper a detailed theoretical signal model describing the interaction of sound waves in random continuum and turbulent media will be presented. Measurements have been carried out with 27 mm pipe diameters for clamp-on transducers.

1. INTRODUCTION

Techniques for **c**ross correlation have been put into practice with several types of signal sources to a wide variety of engineering fields, which include communication systems, industrial pipeline installations, and medical instrumentation equipment.

The close mathematical relation between cross-correlation and frequency-response methods, such as power spectral density functions, makes cross correlation a well-suited tool for system identification dynamics, particularly for analyzing time invariant systems, where spurious signals or noise interfere with the output measured signal.

Generally, any signal disturbed by the flow can be used to cross correlate with another signal produced at some distance apart. By measuring the time difference between similar patterns produced by both signals and by knowing the actual distance between them, it is possible to calculate the flow rate. In performing this, the sensing setup usually employs two sensors for obtaining the transit time of tagged signals, from which the cross-correlation calculation is done.

2. MODELLING AND SYSTEM DESCRIPTION

Measuring the average velocity of flow is more difficult than is measuring that of solid surfaces because flow profiles are distributed about the pipe cross section and because there are velocity fluctuations of the main flow or different regions of turbulence intensities. The main advantage of the correlation principle is that only one parameter, the distance *l* between the sensors, is required and that the measurement, in contrast to measurements with time-of-flight flowmeters, is independent of physical constants such as the speed of sound, wall thickness and transmitting angle.

Moreover, gas bubbles increase the signal-to-noise ratio and do not cause signal losses. Correlation measurement systems for one-phase flow usually use tracers or bluff bodies in the pipe to effectuate stronger stochastic signals and better signal-tonoise ratios. In this paper a flow meter which exploits only the natural inhomgeneities, namely the fluctuations of velocity, pressure and density, is presented. In combination with sensors clamped onto the outside of the pipe, a flexible and robust flow meter is set up, which could be applied to the measurement of corrosive, abrasive and non-conductive fluids and in processes that must not be interrupted. Furthermore, such a flow meter would be very inexpensive and the same measurement system could be used for various pipe diameters.

2.1. The principle of transit time correlation

The ultrasonic transducers transmit continuous sound waves which are phase modulated by the inhomogeneities of the fluid. In the ideal case of a 'frozen flow pattern' the demodulated signals $S_1(t)$ and $S_2(t) = S_1(t - T)$of the receivers are identical, but mutually shifted by a delay time T . For real flow conditions, there is degradation of the flow pattern and the signals are only similar, with consequences for the correlation coefficient.

With increasing sensor distance, the normalized correlation coefficient decreases from unity (identical signals) to zero (no similarity between the signals). The cross correlation function of the signals $S_1(t)$ and $S_2(t)$ has its maximum at $\tau = T$ and the main task of the correlator is the estimation of this time and the calculation of the velocity v with the given sensor distance *l:*

$$v = l/T.$$

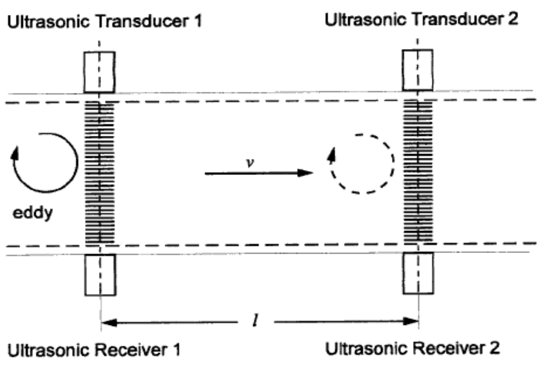

Figure 1. The measurement principle of transit time correlation

There are two fundamentally different methods to solve this problem. The first method, which is preferred in most of the literature, directly calculates the cross correlation function

$$\Phi_{s_1 s_2}(\tau) = E[s_1(t-\tau)s_2(t)] \approx \Phi_{s_1 s_1}(\tau - T)$$

and determines the position of its maximum by usual maximum-searching algorithms.

The second method interprets the process generating the signals as a linear system of the transport delay type with a delay time *T*. The first signal will be retarded by a model delay time $\mathcal{T}$ until the difference between the signals is minimal in the mean square sense . The delay time *T* is determined in a closed loop. This principle was realized by using a low-cost, one-bit real-time correlator and was applied to the measurements carried out.

The main advantage of this tracking principle is that the dynamic response does not depend on the arithmetic speed of the correlator and that the statistical errors are smaller than are those with an open-loop correlator.

However, with this method the correlator is not able to distinguish between a local and a global maximum. In a subsequent part of the paper a method to estimate the starting value of the model delay time $\mathcal{T}$in order to guide the correlator to the global maximum is proposed.

2.2. Beam Modulation

The ultrasonic beams are modulated by random changes of acoustic impedance throughout the volume of the field of interrogation. This can be due either to flow turbulence or to the passage of a second phase component. Demodulation of the received Carrier signal provides the two signals to be processed. In gases and multiphase liquids the beam is amplitude and phase modulated but, in low-velocity single-phase liquids phase modulation due to turbulent eddies predominates and amplitude data is usually so small as to be unusable.

2.3.Comparison with Pulsed Transit-Time Ultrasonic Flowmeters

Both ultrasonic pulse-transit-time and crosscorrelation flow meters derive their data from a line integral across the flow, although their method of measuring the flow velocity is fundamentally different. Both are influenced by the shape of the flow profile (for single beam versions). The advantage of the ultrasonic cross-correlation meter verses its pulsed-transit-time counterparts is its ability to withstand very large changes of acoustic attenuation in the beam.

The dynamic range of a continuous-wave crosscorrelation instrument is determined by the difference in acoustic energy transmitted around the pipe walls to that transmitted across the pipe with the pipe full of liquid. Typical values for this ratio are of the order of 8OdB and represents the upper limit of attenuation that can be tolerated by a crosscorrelation meters.

2.4.Sensor Geometry

The accuracy of the transit time measurement is dependent upon the ultrasonic beam geometry since these actas markers. Two accurately-spaced parallel ultrasonic beams must traverse the flow. For this reason clamp-on transducer arrangements cannot be guaranteed to since the beam spacing and orientation depends on acoustic transmission through the pipe walls where imperfections distort and refract the beams.

More importantly, the dynamic range of a clamp on flowmeter is severely restricted due to the pipe wall acoustic short circuits between ultrasonic transmitters and demodulator. For this reason, in a continuous wave cross correlation meter, the sensors must be acoustically isolated from the pipe walls to eliminate the above short-circuit effect which usually excludes the use of a clamp-on arrangement.

2.5.Correlation Signal Processor

The correlation signal processor used in all trials reported in this paper was a commercially available instrument specifically designed for accurate transit time determination and velocity tracking and is based on a multichannel design system5. The measurable transit time range was from 0.5ms to 400ms corresponding to a velocity range of 0.lm/s to 80m/s for a sensor spacing of 40mm.

This instrument can also process phase and amplitude modulation data simultaneously so that fluids varying from single phase to multiphase can be metered. The instrument is also naturally rejects any periodic interference.

2.6. System Description

The study of the cross correlation is considered. many parameters determine the flow of the liquid. One among the parameter includes the time delay which is measured by using ultrasonic flowmeter. Because some of the advantages of the ultrasonic flow measurement process over most of these classic measuring methods:

- Linear, accurate, wide measuring span,
- No wear, no maintenance, long-time stability,
- Assignment of better parameters for every measurement task fitting the nominal diameterof the process piping,
- Here the process product conveys additional information through parallel output of the sound velocity,
- No additional pressure drop,therefore, Lower cost of ownership.

2.7. Block Diagram

The cross-correlation ultrasonic flow measurement system, shown in figure 2 ,consists of an adjustable signal generator, two pairs of wideband ultrasonic transducers with a center frequency of *2* MHz, a phase demodulation unit, acorrelator and a recorder.

The transducer pairs were clamped on the pipe at a distance of 30 or 40 mm from each other. The phase demodulation was based on a phase-locked loop, which directly provides on output signal related to the phase modulation of the input signal and cuts off the carrier frequency.

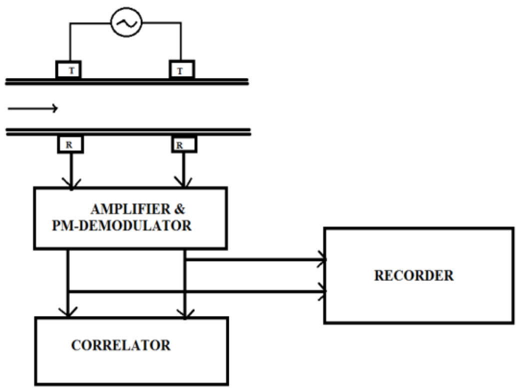

Fig 2.The block diagram of the ultrasonic cross-correlation flow measurement system

The demodulated signals were further filtered with 540 HZ low-pass filter and fed into a HP 3721 A correlator for real time monitoring of the cross-correlation function. The signals were also recorded on tape and the delay of the cross-correlation peak as well as the derivative of the phase function of the cross-power density spectrum were later analyzed by signal analyzer.

3. CROSS CORRELATOR DESIGN

Cross correlator is commonly used in signal processing and is defined as the correlation of a series against another series, which is shifted by a particular number of observations or samples.

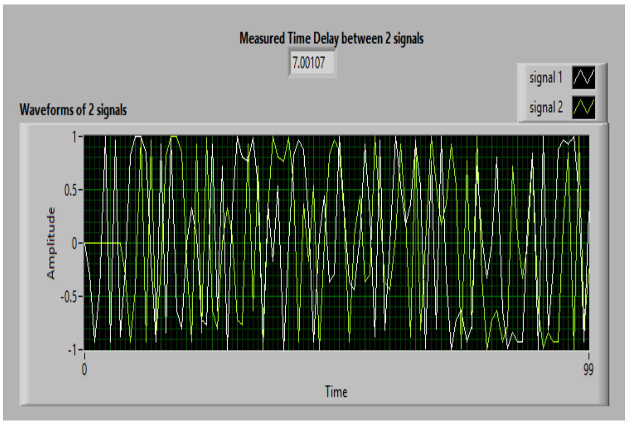

Figure 3. Signals recorded by two sensors

Suppose two time series (X_k, Y_k) having M samples each that are described as follows:

$$[x_k] = [x_0, x_1, x_2, \ldots, x_{M-1}]$$
$$[y_k] = [y_0, y_1, y_2, \ldots, y_{M-1}].$$

Then, cross-correlation function $\varphi_{yx}$is defined as

$$\phi_{yx}(\tau) = \sum_{t=0}^{M=1} x_t y_{t+\tau}.$$

In the case of the signals recorded by two sensors, which are placed at a known distance along a pipe, $X_t$is the function expressing the signal recorded at the upstream station at time t, $Y_{t+\tau}$is the function expressing the signal recorded at the downstream sensor at time $t + \tau$, and τ is the time delay (unknown) that elapsed between the two signals Figure 3.

To calculate the velocity, the time delay between the appearance of any event at the upstream sensor and the appearance of the same event at the downstream sensor is required. The time at which the maximum point of the cross-correlation function φ_{yx}occurs corresponds to the referred time delay.

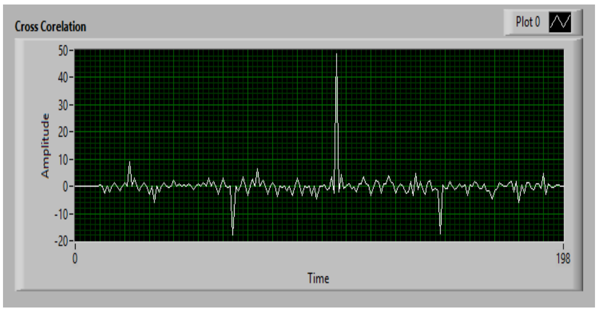

Fig. 4.Cross-correlation function of signals in Fig. 3.

4. CONCLUSION AND FUTURE WORK

The time delay between the two signals is calculated by giving known time delay to one of the two signals. It is designed for particular limit of samples only. One drawback is that for a valid estimate to the flow velocity the longer integration time or the better coherence is needed than with the crosscorrelation method. The cross-correlation method is faster, but when using phase modulation, a continuous monitoring and frequency adjustment is needed to eliminate the phase-error.

This project can be extended to developing a Cross correlation based Ultrasonic Flow meter to overcome the above mentioned drawbacks of the Cross correlation method. Because Ultrasonic flow meter mainly used for continuous process of flow measurement. This Cross correlator model will be done using LABVIEW Advanced signal processing unit.

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