Proc. Symposium on Advances in Nuclear and Allied Instrumentation 1997 (SANAI-97), BARC Mumbai

# SINGLE PHASE FLUID FLOW MEASUREMENT BY PULSED ULTRASOUND USING CROSS CORRELATION TECHNIQUE

H.B. NEMADE T. ANJANEYULU P.C. PANDEY

*Research Scholar* *Professor* *Professor*

*Department of Electrical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai 400 076*

*e-mail : harshal@ ee.iitb.ernet.in*

*Abstract* — **A new technique for sensing turbulence in single phase fluid flow by pulsed ultrasound is introduced. The velocity component of turbulence perpendicular to the flow axis is sensed by two ultrasonic transducers mounted diametrically opposite on the pipe. The technique facilitates detecting variations in time of flight of two ultrasonic pulses which are simultaneously transmitted in opposite directions and perpendicular to the flow axis. The flow velocity is obtained from the position of the peak in the cross correlation function of the turbulence signals sensed at two locations on the pipe. The paper presents the implementation details and the result obtained.**

## 1. INTRODUCTION

Flow measurement by cross correlation involves sensing tagging markers, like suspended particles or turbulence, in the flow at two locations on a pipe as shown in Fig. 1(a); and estimating the transit time of the tagging markers between the two locations, with the help of the cross correlation function of the signals [3]. If x(t) and y(t) are the two signals derived from the upstream and downstream sensors respectively, the cross correlation function $r_{xy}(\tau)$ relating these signals in terms of the time delay $\tau$ is given by the expression:

$$r_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t-\tau)\, y(t)\, dt \qquad (1)$$

where T is the integration period. The flow transit time $\tau_m$ is determined from the delay corresponding to the maximum cross correlation as shown in Fig. 1(b). The flow velocity u is calculated from $\tau_m$ and the sensor spacing L.

$$u = L / \tau_m \qquad (2)$$

Since only the transit time is measured between two fixed locations, the flowmeter is largely unaffected by wide

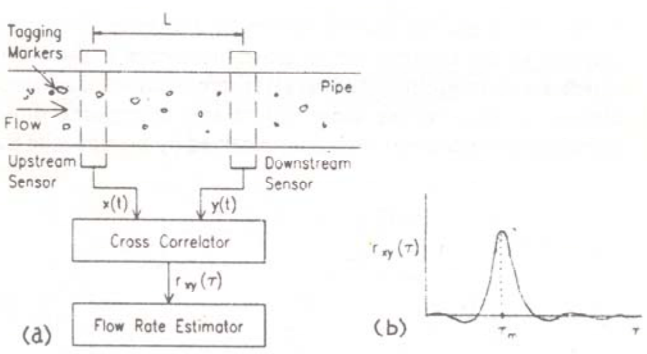


Fig. 1. Schematic of flow measurement by cross correlation technique. (a) block diagram of cross correlation flowmeter; (b) plot of a typical cross correlation function $r_{xy}(\tau)$ versus time delay $\tau$.

variations in the fluid properties and environmental factors. In addition, some aspects of transducer design are not very critical; for example, the transducers do not need to be linear; and the DC stability of the transducer is not important since the signals which are cross correlated are AC (usually within a bandwidth between 1 Hz and 1 kHz). However, phase delay does need careful consideration [3].

## 2. SENSING TURBULENCE BY PULSED ULTRASOUND

The most common method of sensing tagging markers in single phase flow using ultrasound is by detecting modulation of ultrasonic beam transmitted across the diameter of the pipe. In our investigation, preliminary experiments conducted on clean water flow through pipe showed no appreciable amplitude modulation, however small phase modulation was observed. Similar results have been reported by Beck and Plaskowski [3].

The major advantage of using pulsed ultrasound over continuous wave ultrasound is that it avoids standing waves which are inherent when continuous wave ultrasound is used. The standing wave pattern in the pipe alters with change in acoustic path length, mainly due to variations in fluid properties and instability of the oscillator exciting the transducers. This results in erroneous detection of phase of the received ultrasound unless a feedback control system is employed to correct undesired variations in the standing wave pattern [1]. In addition, the acoustic short circuit through the pipe wall tends to swamp the liquid-borne signal [5].

A steady turbulent flow can be regarded as a mean flow vector, with additional fluctuating velocities that average out to zero over sufficiently long period. The fluctuating velocities are mainly due to the irregular motions of the eddies. Thus sensing turbulent component normal to the flow direction can impart adequate information of the turbulence in the pipe.

The variation in time of flight of an ultrasonic pulse due to the velocity component of turbulence normal to the flow axis is extremely small compared with the total time of flight of the pulse across the pipe diameter and therefore difficult to measure reliably (e.g. the transit time of a pulse across a pipe of 90 mm diameter carrying water is about 60 μs and the variation in transit time due to a turbulent velocity component of 0.1 m/s is approximately 4 ns). Besides uncertainty in the instant of the arrival of the pulse adds to the errors.

A new technique for pulsed ultrasound has been developed to overcome these difficulties. The block diagram of the system used to sense turbulence is shown in Fig. 2. Two ultrasonic transducers, both of which act as transmitter and receiver, are mounted diametrically opposite on the pipe wall. They transmit ultrasonic pulses at the same instant and in opposite directions. The pulses, after interaction with the turbulent velocity component, are received by the opposite transducers which now act as the receivers.

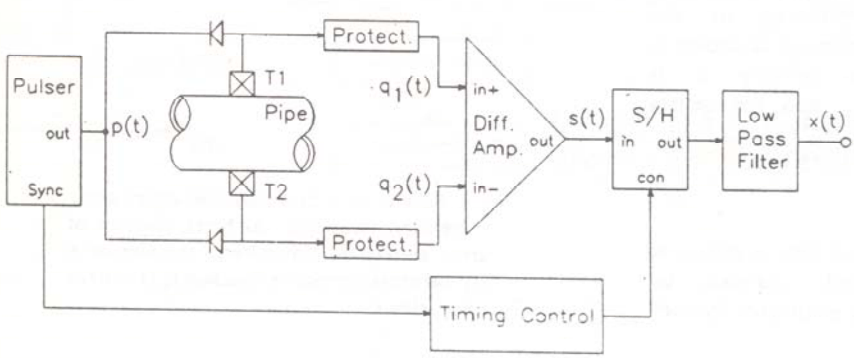


Fig. 2. Block diagram of the system used to sense turbulence in a pipe.

The turbulent velocity component alters the velocity of the pulses and the time of flight of the pulses is changed differently. The signals are fed to a differential amplifier and its output is sampled at the instant corresponding to a zero crossing instant of the received pulses at zero flow, in order to maximize the sensitivity to the turbulent velocity component. Since the turbulent velocity component alters the time of flight of the two pulses by almost the same magnitude but in opposite directions, the sampling instant remains unchanged and can be derived from the instant of pulse transmission with the help of a preset delay. An example of the waveforms is given in Fig. 3. The sampled magnitude is a function of the line integral of the normal turbulent velocity components encountered by the pulses. The principal criteria for the pulsed method are that the pulse repetition period should be longer than the transit time of the pulse across the pipe, and that this pulse repetition frequency should substantially exceed the upper cut-off frequency of the flow turbulence signal; in order to give an accurate reconstruction of the flow turbulence. The low pass filter smoothens the output of the sample-and-hold amplifier. Fig. 4 shows an example of reconstructed turbulence signal.

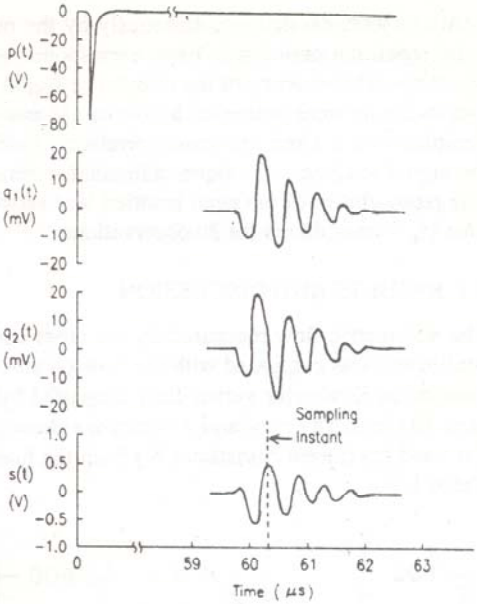

Fig. 3. Waveforms showing excitation pulse p(t), received pulses $q_1(t)$ and $q_2(t)$, and differential amplifier output s(t).

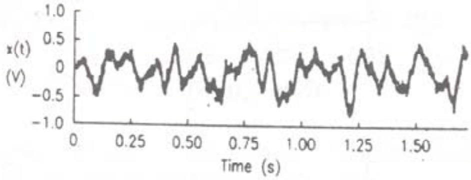

Fig. 4. Waveform showing an example of reconstructed turbulence signal.

## 3. SYSTEM DESCRIPTION

The block diagram of the experimental set-up for flow measurement is shown in Fig. 5. The transducers were clamped on a PVC pipe of outer diameter of 90 mm and wall thickness of 3.5 mm in a water circulation system. The transducers at both the

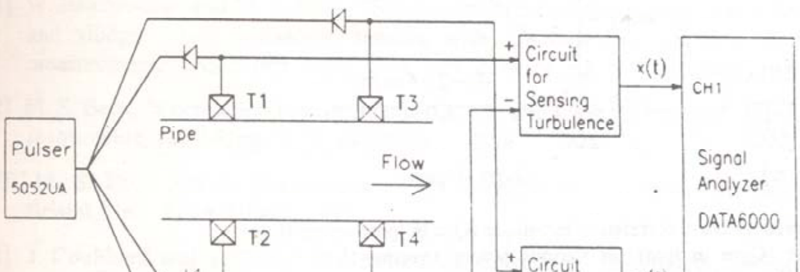

Fig. 5. Block diagram of the experimental set-up for flow measurement by cross correlation technique.

locations were excited simultaneously by the pulser of the ultrasonic analyzer Panametrics 5052UA. The pulse repetition period was 1 ms, corresponding to a frequency of 1 kHz which substantially exceeded the upper cut off frequency of the turbulence signal (about 100 Hz) [2]. The turbulence signals obtained at the two locations were processed by the signal analyzer DATA6000. The signals were sampled at a rate of 1 k Samples/s for 1 s and the cross correlation function was computed with the help of the built-in function in the signal analyzer. A unique, dominant, consistent peak was observed in the cross correlation function. The repeatability of the peak position was satisfactory, e.g. standard deviation was 2 ms and mean transit time ($\tau_m$) was 160 ms for 20 observations.

## 3.1 RESULTS AND DISCUSSION

The volumetric flow measured by the cross correlation flowmeter was calculated assuming uniform flow profile and was compared with the flow obtained by a venturimeter. The graphs of flow measured by cross correlation flowmeter versus flow measured by venturimeter for various sensor spacings, viz. 35 mm, 50 mm, 101 mm, 187 mm, and 254 mm are shown in Fig. 6(a)-(e) respectively. A table of standard deviation ($\sigma$) and maximum deviation ($\delta$) from the linear best fit line, for various sensor spacings ( L ) is given in Table 1.

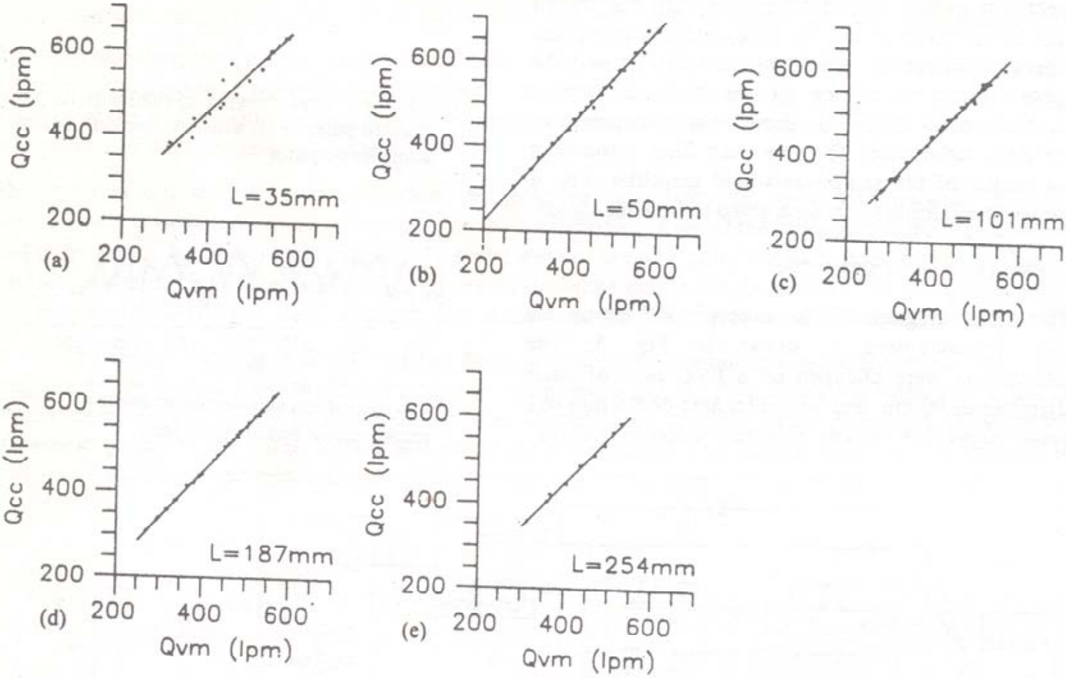


Fig. 6. Graphs of flow calculated by cross correlation technique (Qcc in lpm) versus flow measured by venturimeter (Qvm in lpm) for various sensor spacings (L): (a) 35 mm; (b) 50 mm; (c) 101 mm; (d) 187 mm; (e) 254 mm.

From these graphs it is observed that for small sensor spacing (35 mm) the deviation of the plotted points from the linear best fit line is large. From (2), it implies that for small transit time, the resolution of measured flow is poor. Smaller the sensor spacing, smaller is transit time ($\tau_m$). Hence the resolution is poor for sensor spacing of 35 mm (Fig. 6(a)). The deviation from the best fit line reduces progressively as the sensor spacing is increased from 35 mm to 187 mm. However further increase in the sensor spacing (Fig. 6(e)) results in more deviation from the best fit line. The effect of increase in the sensor spacing is the decrease in the cross covariance due to break-up of the turbulence pattern as it proceeds along the pipe. Therefore the peak in the cross correlation function becomes broad and less distinct, and may introduce considerable errors in estimating the position of the peak. Hence the flowmeter readings deviate more when the sensor spacing is increased from 187 mm (Fig. 6(d)) to 254 mm (Fig. 6(e)). In addition, higher the flow, smaller is $\tau_m$, hence poor resolution. This can be observed in the graph of deviation versus flow rate for 50 mm sensor spacing shown in Fig. 7.

Table 1. Standard deviation ($\sigma$) and maximum deviation ($\delta$) from best fit line for various sensor spacings (L).

| L (mm) | $\sigma$ (lpm) | $\delta$ (lpm) |
|---|---|---|
| 35 (Fig. 6(a)) | 22 | 62 |
| 50 (Fig. 6(b)) | 8 | 25 |
| 101 (Fig. 6(c)) | 6 | 16 |
| 187 (Fig. 6(d)) | 4 | 8 |
| 254 (Fig. 6(e)) | 6 | 10 |

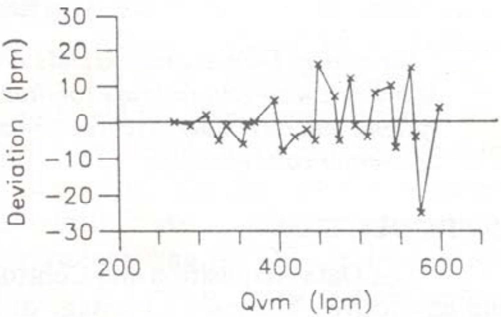


Fig. 7. Graph of deviation from best fit line versus flow for sensor spacing of 50 mm.

Efforts are in progress to find optimum sensor spacing, cross correlator parameters, and to improve accuracy of the system.

## ACKNOWLEDGMENT

The authors would like to thank Board of Research in Nuclear Sciences — the sponsor of the project on Ultrasonic Cross Correlation Flowmeter (25-5-92-G) at Indian Institute of Technology, Bombay.

## REFERENCES

[1] W. Balchandran and M. S. Beck, "Solids concentration measurement and flow measurement of slurries and sludges using ultrasonic sensors with random data analysis, Part 1: Solids-concentration measurement," *Trans. Inst. Meas. Con.*, vol. 2, No. 4, pp. 181-197, Dec. 1980.

[2] M. S. Beck, "Correlation in instruments: Cross correlation flowmeter," *Journal of Physics E : Scientific Instruments*, vol. 14, pp. 7-19, 1981.

[3] M. S. Beck and A. Plaskowski, *Cross Correlation Flowmeters - Their Design and Application.* Bristol, UK: Adam Hilger, 1987.

[4] J. Coulthard and Y. Yan, "Ultrasonic cross-correlation flowmeters," *Measurement+Control*, vol. 26, pp. 164-167, Aug. 1993.

[5] L. C. Lynnworth, *Ultrasonic Measurement for Process Control - Theory, Techniques, Applications.* San Diego, CA: Academic, 1989.