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Sensing Turbulence Transit Time by Pulsed Ultrasound for Single-Phase Fluid Flow Measurement

Harshal B. Nemade, T. Anjaneyulu, and Prem C. Pandey
Department of Electrical Engineering
Indian Institute of Technology, Bombay
Powai, Mumbai 400076 INDIA
Phone (+91-22) 578-2545 extn. 2455 Fax (+91-22) 579-3707 E-mail: pcpandey@ee.iitb.ernet.in

Abstract* — A new technique for sensing turbulence in single-phase fluid flow by pulsed ultrasound is developed. 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 transmitted simultaneously in the 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. A numerical simulation of the technique based on a theoretical model has been carried out. The technique has been implemented to measure volumetric flow noninvasively in a water circulation system with PVC pipes.

I. 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 [1]. 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 τ 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 transit time τ_m is determined as the delay corresponding to the peak in the cross correlation function as shown in Fig. 1(b). The flow velocity u is calculated from τ_m and the sensor spacing L as

$$u = \frac{L}{\tau_m} \qquad (2)$$

Since only the transit time is measured between two fixed locations, the flowmeter is largely unaffected by wide variations in the fluid properties and environmental factors. In addition, the sensors do not need to be linear, and since the cross correlated signals are AC (usually within a bandwidth between 1 Hz and 1 kHz) the DC stability of the sensors is not important. However phase delay does need careful consideration [1].

II. SENSING TURBULENCE BY PULSED ULTRASOUND

The most common method of sensing tagging markers in fluid flow using ultrasound is by detecting modulation of ultrasonic beam transmitted across the diameter of

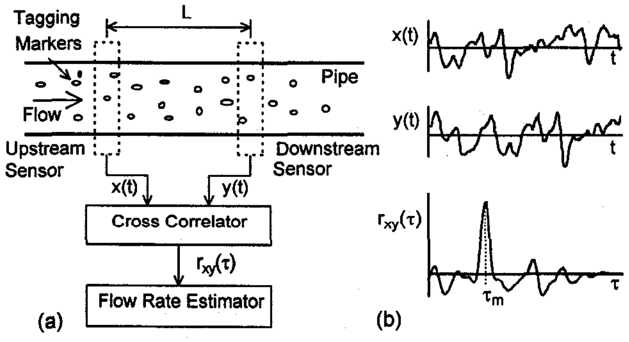

Fig. 1. Schematic of flow measurement by cross correlation technique. (a) Block diagram of cross correlation flowmeter; (b) signals $x(t)$ and $y(t)$ obtained at the two sensing locations, and their cross correlation function $r_{xy}(\tau)$.

the pipe. In our investigations, experiments conducted on clean water flow through a pipe showed no appreciable amplitude modulation, however small phase modulation was observed. Similar results have been reported by Beck and Plaskowski [1]. The major advantage of using pulsed ultrasound over continuous wave ultrasound is that it avoids standing waves that are inherent when continuous wave ultrasound is used. The standing wave pattern in the pipe alters with change in the acoustic path length, mainly due to variations in the fluid properties and instability of the oscillator exciting the transducers. This results in erroneous detection of the phase of the received ultrasound, unless a feedback control system is employed to correct the undesired variations in the standing wave pattern [2]. In addition, the acoustic short circuit through the pipe wall tends to swamp the fluid-borne signal [3].

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 because of irregular motions of the eddies. Thus the turbulent component normal to the flow axis can be sensed as the variation in time of flight of an ultrasonic pulse, transmitted along the pipe diameter. However the variation is extremely small compared with the 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 arrival of the pulse adds to the errors.

A new technique using 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 the opposite directions. The pulses, after traveling through fluid in the pipe, are received by the opposite transducers which now act as the receivers.

The turbulent velocity component, along the axis of placement of the transducers, 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 of the received pulses at zero flow, in order to maximize the sensitivity to the turbulent velocity component, because 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 can be derived from the instant of pulse transmission with the help of a preset delay. An example of the waveforms $p(t)$, $q_1(t)$, $q_2(t)$, and $s(t)$ in Fig. 2 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. A two-stage sample-and-hold amplifier has been used to achieve low dynamic sampling error and low droop rate. 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 the corresponding pulse repetition frequency should substantially exceed twice 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 a reconstructed turbulence signal.

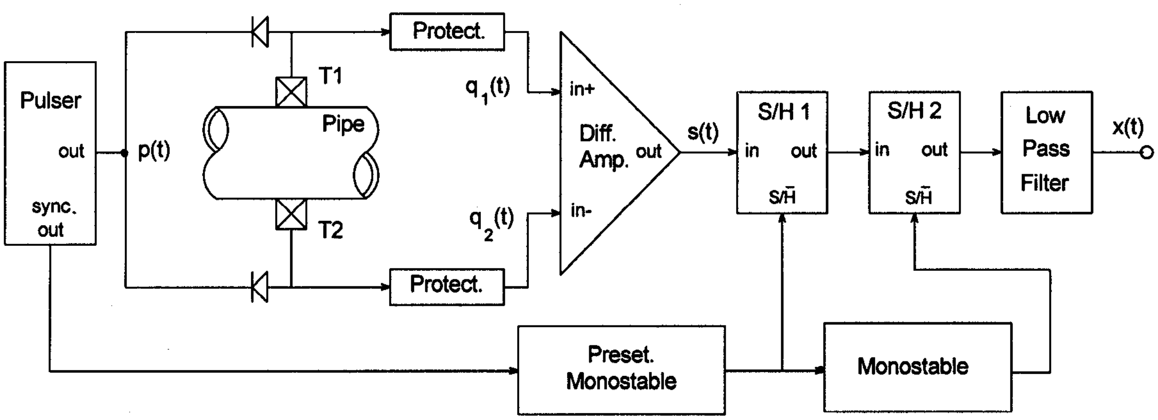

Fig. 2. Block diagram of the system used to sense turbulence in a pipe.

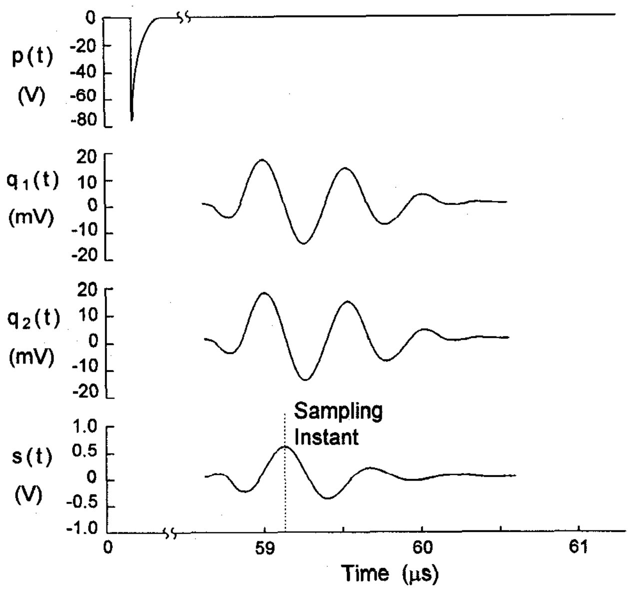

Fig. 3. Waveforms showing excitation pulse $p(t)$, received pulses $q_1(t)$ and $q_2(t)$, and differential amplifier output $s(t)$.

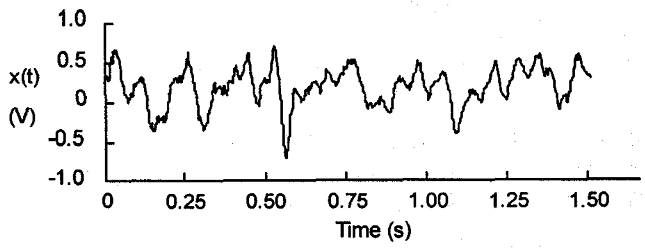

Fig. 4. Waveform showing an example of a reconstructed turbulence signal.

III. 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 locations were excited simultaneously by the pulser 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) [4]. The turbulence signals obtained at the two locations were processed by the signal analyzer Analogic 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 (τ_m) was 160 ms for 20 consecutive observations. The experimental results are given in Section V.

IV. NUMERICAL SIMULATION

Consider two ultrasonic transducers T1 and T2 separated by distance d and facing each other as shown in Fig. 2. The transducers transmit ultrasonic pulses simultaneously, and the pulses after propagation in the opposite directions are received. The difference in the two received signals is sampled at an appropriate instant. Let c be the velocity of sound in the fluid and v be the velocity component of the turbulence in the direction of pulse propagation. A model of the transmission and reception of ultrasonic pulses is developed with the following assumptions :

1. The impulse responses of a transducer as a transmitter $h(t)$ and as a receiver $h'(t)$ are related as

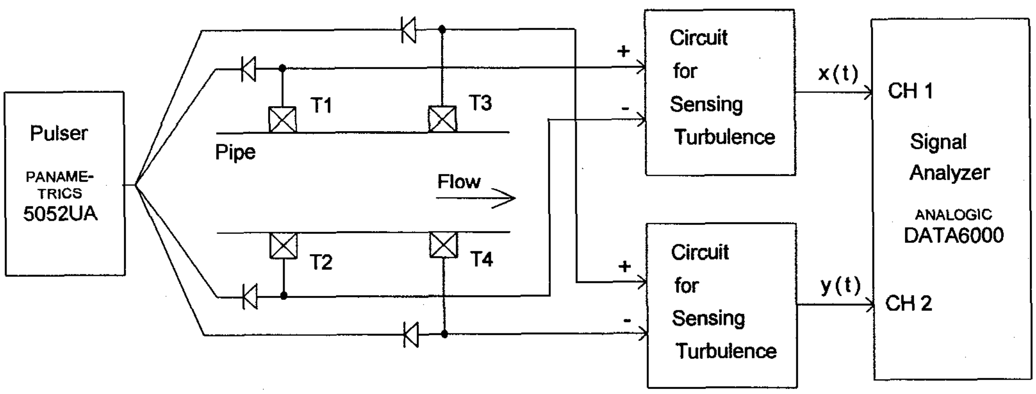

Fig. 5. Block diagram of the experimental set-up for flow measurement by cross correlation technique.

$$h(t) = -k\, h'(t) \quad (3)$$

where k is a constant and is the same for both the transducers.

2. The turbulent velocity components encountered by the ultrasonic pulse remain unchanged during the transit time of the pulse across the pipe.

The block diagram of the model is shown in Fig. 6. The pulser is modeled as an impulse generator. The transducers T1 and T2 as transmitters are modeled by the impulse responses $h_1(t)$ and $h_2(t)$ respectively. The ultrasonic pulses arrive at the receivers after the delays of t_2 and t_1 respectively. T1 and T2 as receivers are modeled by the impulse responses $h_1'(t)$ and $h_2'(t)$ respectively.

At zero flow, the outputs of the receivers are given by

$$q_1(t) = h_2(t) * \delta(t-t_0) * h_1'(t) \quad (4)$$

$$q_2(t) = h_1(t) * \delta(t-t_0) * h_2'(t) \quad (5)$$

where t_0 = transit time of the pulses between the transducers at zero flow and is given by

$$t_0 = \frac{d}{c} \quad (6)$$

From (4), (5), and the assumption 1 given above

$$q_1(t) = q_2(t) \quad (7)$$

Thus the received pulses are identical and arrive at the same instant at zero flow. In the presence of a turbulent velocity component v, the outputs of the receivers are

$$q_1(t) = h_2(t) * \delta(t-t_1) * h_1'(t) \quad (8)$$

$$q_2(t) = h_1(t) * \delta(t-t_2) * h_2'(t) \quad (9)$$

where

$$t_1 = \frac{d}{c-v} \quad (10)$$

$$t_2 = \frac{d}{c+v} \quad (11)$$

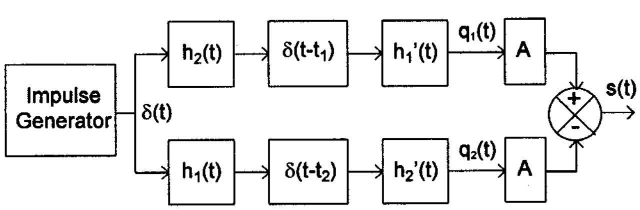

Fig. 6. Model of ultrasonic pulse transmission and reception.

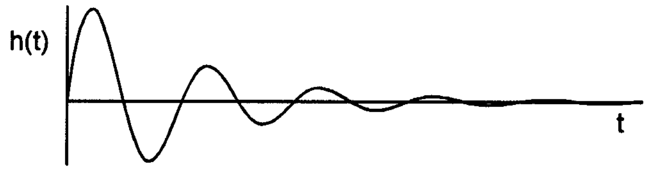

Fig. 7. Simulated impulse response $h(t)$ of the transducer.

In the numerical simulation, we have modeled an ultrasonic transducer as a second order system, with the impulse response

$$h(t) = \left(\frac{\omega_0}{\omega}\right) e^{-\zeta\omega_0 t} \sin \omega t \quad (12)$$

where ω_0 = undamped natural frequency of oscillation

ζ = damping ratio

$$\omega = \omega_0 \sqrt{1-\zeta^2}$$

and it is shown in Fig. 7 for $\zeta = 0.15$.

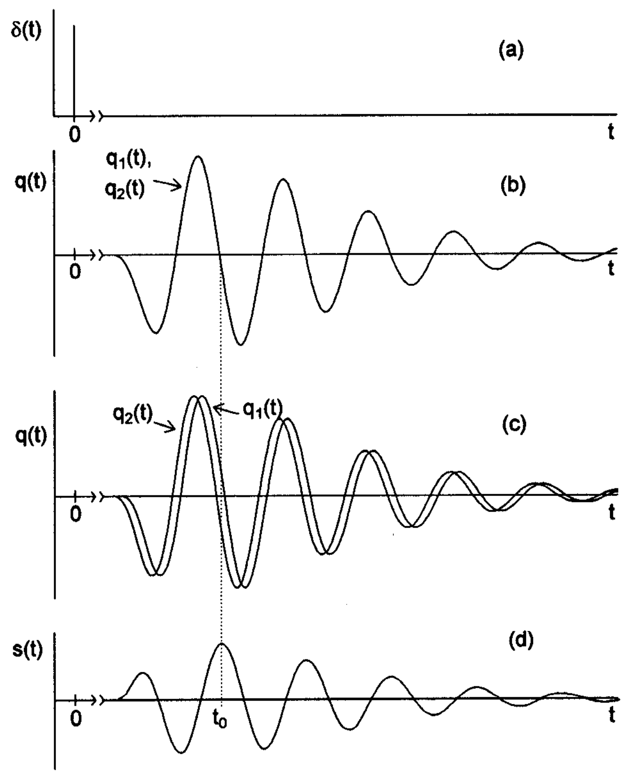

Fig. 8. Results of simulation of the model given in Fig. 6. (a) shows the excitation impulse $\delta(t)$. The Receiver outputs $q_1(t)$ and $q_2(t)$ as shown in (b) arrive at the same instant at zero flow. Receiver outputs and differential amplifier output $s(t)$ in the presence of a turbulent velocity component are shown in (c) and (d) respectively. t_0 indicates the sampling instant.

The turbulent velocity component $v(t)$ is simulated with the help of a random number generator. The received waveforms $q_1(t)$ and $q_2(t)$ are calculated for $\zeta = 0.15$ and are shown in Fig. 8. The function of differential amplifier is simulated by multiplying $q_1(t)$ and $q_2(t)$ by a constant A equal to the gain of the amplifier and subtracting $q_2(t)$ from $q_1(t)$ pointwise. The differential amplifier output $s(t)$ is sampled at $t = t_0$ as shown in Fig. 8(d), and the samples are stored in an array which is operated on by a low pass filter in order to simulate band limited nature of the turbulence signal and the filtering effect due to the transducer width. The signals $x(k)$ and $y(k)$ sensed at the two locations on the pipe are obtained by choosing two sets of contiguous samples from the array, displaced by certain number of samples corresponding to the transit time of the turbulence pattern between the two sensing locations. Examples of $x(k)$ and $y(k)$ for a displacement of 100 samples are shown in Fig. 9(a) and (b) respectively. The cross correlation function $r_{xy}(j)$ is calculated as

$$r_{xy}(j) = \sum_k x(k-j)\, y(k) \tag{13}$$

and is shown in Fig. 9(c). Dispersion in turbulence pattern as it moves along the pipe is simulated by adding random noise in the turbulence signal $y(k)$ obtained at the downstream sensor. Examples of the cross correlation function $r_{xy}(j)$ for various percentage of noise added in $y(k)$, viz. 100%, 200%, 300%, 400% are shown in Fig. 10 (a), (b), (c), (d) respectively. As seen from Fig. 10, the peak in the cross correlation function becomes less dominant with more dispersion in the turbulence pattern.

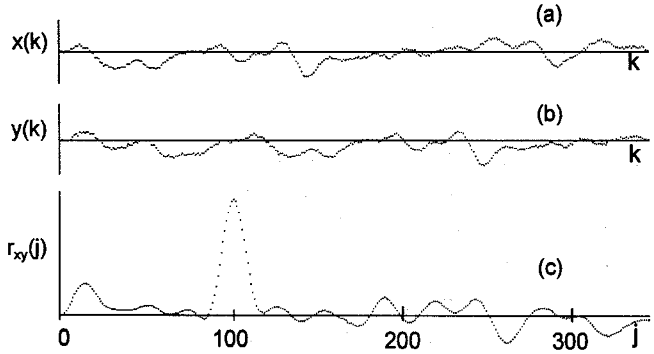

Fig. 9. Results of cross correlator simulation. (a) turbulence signal $x(k)$ obtained at upstream sensor; (b) Turbulence signal $y(k)$ obtained at downstream sensor; (c) cross correlator output $r_{xy}(j)$.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The volumetric flow measured by the cross correlation flow measurement system described in Section III 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. 11(a)-(e) respectively. A table of standard deviation (σ) and maximum deviation (δ) from the linear best fit line, for various sensor spacings (L) is given in Table I. From the graphs given in Fig. 11, 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 (τ_m), the resolution of measured flow is poor for a given sampling rate. The closer the sensing locations, the smaller is the transit time. Hence the resolution is poor for sensor spacing of 35 mm. 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. 11(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 the dispersion 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 to 254 mm. In addition, the higher the flow rate, the smaller is τ_m, hence poor resolution. This can be observed in Fig. 11(b) as the observations deviate more from the best fit line at higher flow rates.

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

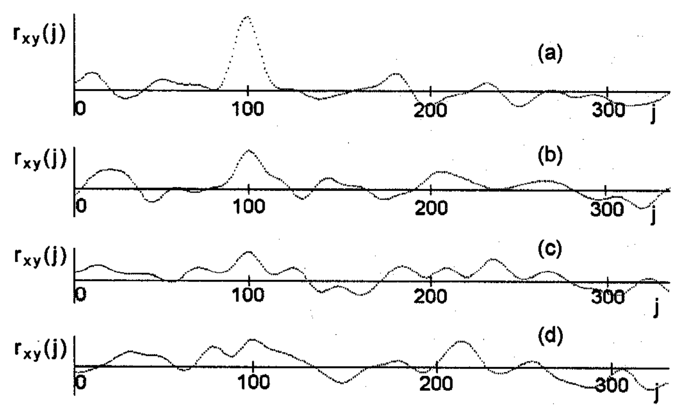

Fig. 10. Cross correlator output with random noise added in the turbulence signal obtained at the downstream sensor. Amount of noise added: (a) 100%; (b) 200%; (c) 300%; (d) 400%.

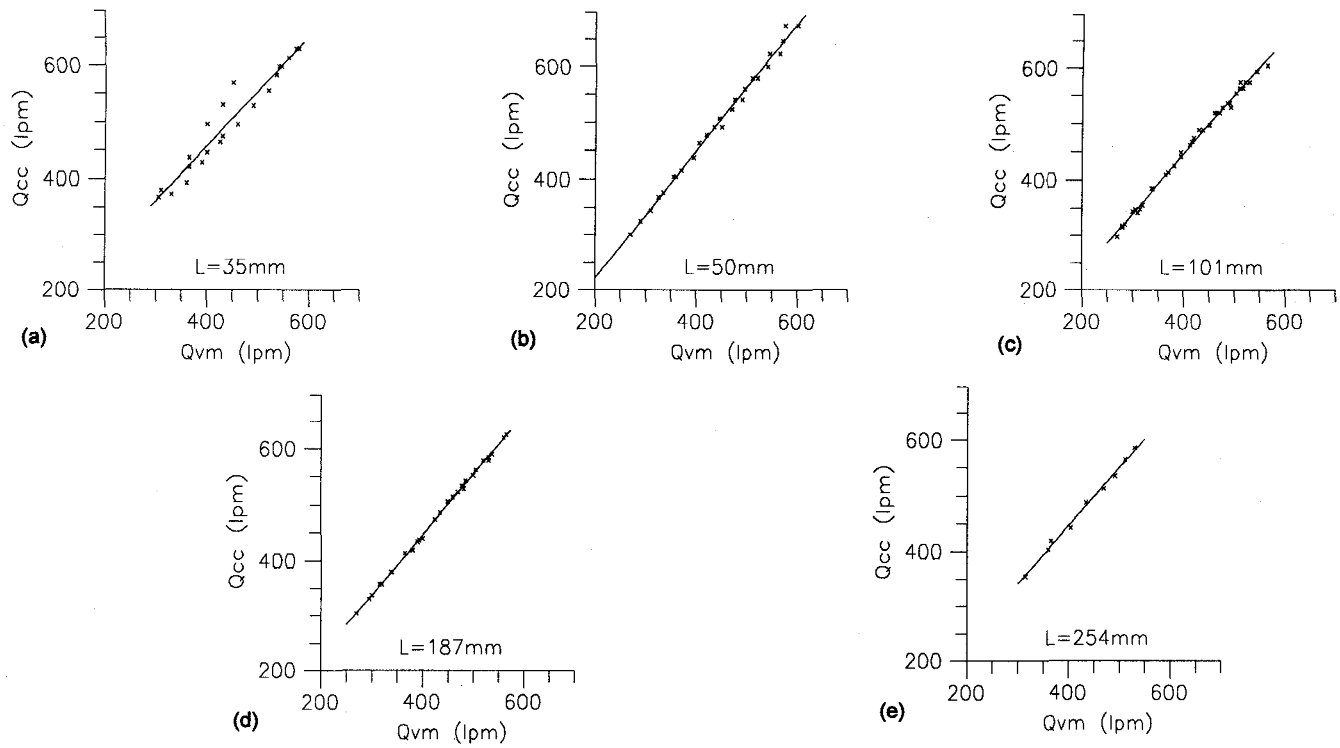

Fig. 11. Graphs of flow calculated by cross correlation technique (Qcc in lpm) versus flow measured by venturimeter (Qvm in lpm) for various sensor spacings (L): (a) 35 mm; (b) 50 mm; (c) 101 mm; (d) 187 mm; (e) 254 mm.

VI. CONCLUSIONS

A new technique has been developed to facilitate sensing turbulent velocity components normal to the flow axis in single-phase fluid flow by pulsed ultrasound. The turbulence signals sensed by using the technique are suitable for flow measurement by cross correlation. A numerical simulation of the technique based on a theoretical model has been carried out. An experimental set-up based on the technique has been employed to sense turbulence signals at two locations on a PVC pipe carrying water, and tested for flow measurement by cross correlation. Volumetric flow is calculated by assuming uniform flow profile and is compared with that obtained by a venturimeter, for various sensor spacings. A range of sensor spacing that would give linear relationship has been estimated. However, it requires further investigation to optimize the flowmeter parameters like sensor spacing, sampling rate, and sampling duration.

TABLE I

Standard deviation (σ) and maximum deviation (δ) from linear best fit line for various sensor spacings (L).

L (mm)	σ (lpm)	δ (lpm)
35 (Fig. 11(a))	22	62
50 (Fig. 11(b))	8	25
101 (Fig. 11(c))	6	16
187 (Fig. 11(d))	4	8
254 (Fig. 11(e))	6	10

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