An ultrasonic flowmeter based on the direct transit time technique.

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Abstract

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Ultrasonic flowmeters are suited to applications where the flowmeter should not obstruct the flow. Transit time flowmeters are useful in single-phase flow measurements. The direct transit time flowmeter involves the measurement of transit time differences in the transit times of ultrasound pulses in the upstream and downstream directions. This difference for water flow is in the range of tens to hundreds of nanoseconds. The vernier technique suited to short time-interval measurements suffers from the instability of quick-start oscillators.

In many applications the flow pattern changes slowly. Therefore, repeated observations of the transit time difference intervals remain approximately the same. Accumulation of counts over several intervals can be used to improve the resolution, provided that the clock period is not a sub-multiple of the time-interval. Therefore a clock waveform with a stable mean frequency, but with a certain randomness associated with the arrival of the clock pulses has been employed.

A direct transit time flowmeter based on a simultaneous transmission scheme, incorporating a pseudo-random binary sequence (PRBS) clock waveform for the measurement of the transit time differences has been developed. The upstream transit time is measured to provide acoustic velocity compensation.. Variable delays are introduced in the paths of the transmitted and received signals to reduce the errors due to the effect of delays in the non-flow parts of the flowmeter and the electronic measuring delays. FAST TTL ICs have been used to obtain better resolutions. High speed ICs have been used in the receiver circuits to reduce the electronic measuring delay. The flowmeter developed yields repeatable results and the relationship between the actual flow (measured using a venturi meter) and the measured flow is monotonic.

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List of Symbols

θ	angle between the flow velocity and the path of the ultrasonic beams
$\Delta\phi$	phase difference between upstream and downstream phases
d	transducer separation
v	mean flow velocity of the fluid
f_u	upstream 'sing-around' prf
f_d	downstream 'sing around' prf
Δf	difference in upstream and downstream prfs
T_u	upstream transit time
T_d	downstream transit time
ΔT	transit time difference

List of Abbreviations

PRBS	Pseudo-random binary sequence
FTTL	FAST™ transistor-transistor logic
prf	Pulse repetition frequency
ADC	Analog-to-digital converter
BRNS	Board of Research in Nuclear Sciences

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Chapter 1
Introduction

1.1 Overview

Over the years, different methods, for the measurement of the fluid flow have been developed. These flowmeters are based on mechanical, differential pressure, electromagnetic, and ultrasonic techniques [1]. Although mechanical and differential type flowmeters are economical and reliable, they obstruct the flow and have poor response to the fast changes in the flow velocity. In many fluid flow applications, it is required that the flow measurement should not obstruct the flow. Both electromagnetic and ultrasonic flowmeters satisfy this requirement. Electromagnetic flowmeters, although suited to a wide range of liquid flow applications, cannot be used where the flow involves liquids of poor conductivity. They are also expensive when large pipe sizes are involved.

Ultrasonic flowmeters measure the flow velocity by monitoring the interaction between the flowstream and the ultrasonic beams transmitted through it. They offer no mechanical obstruction to the flow and the measurements can be made non-intrusively. Thus they are of particular importance, when flows of chemically active or abrasive fluids are to be measured. They also offer fast response and wide dynamic range with virtually maintenance free operation.

Some of the widely used ultrasonic methods [2], [3] for the measurement of the flow velocity are:

a) Doppler frequency shift technique

b) cross correlation techniques

c) transit time techniques.

Doppler flowmeters employ the scatterers in the flow, such as solid particles or gas bubbles for the necessary frequency shift. This frequency shift is directly related to the flow velocity of the scatterers. As it is essential that the flow being measured have sonically reflective particles, flowmeters based on the Doppler frequency shift technique are not suitable for clear fluid flows [2], [4].

Cross correlation flowmeters are based on the measurement of the cross correlation of electrical signals derived from ultrasonic waves, modulated by disturbances in the flow. Cross correlation flowmeters for multi-phase flow applications heve been developed [5], [6]. Efforts are on for developing a single-phase cross-correlation flowmeter involving the detection of naturally occurring or deliberately introduced disturbances in the form of eddies, and the measurement of their transit times between two such detectors [7].

The transit time techniques involve the measurement of the time difference between the arrival of ultrasonic beams transmitted in the upstream and the downstream directions in the fluid. They are suited to single-phase flow applications [2]. The three methods which may be employed to measure the transit times are:

a) phase measurement technique

b) 'sing-around' technique

c) direct transit time technique.

The phase measurement technique determines the phase shift as a consequence of the flow [2], [8]. The transmitted ultrasound is in the form of continuous waves or sinusoidal bursts. This technique suffers from the problem of phase ambiguity for phase differences greater than 360 degrees, which restricts its applications. Moreover, any acoustic coupling between the transmitting and receiving transducers through the pipe walls causes undue phase changes resulting in errors. In the 'sing-around' method, a pulse of ultrasound is transmitted through the flowing fluid. The received pulse is then used to retrigger the transmitter resulting in a pulse repetition frequency (prf). The difference in the prfs for the downstream and upstream transmissions is directly proportional to the flow velocity. Errors are introduced in the 'sing-around' technique due to delays in the non-flow liquid parts of the flowmeter [9]. The direct transit time method involves the actual measurement of the time difference between the upstream and downstream transit times. Since the transit time differences are usually of the order of tens of nanoseconds, it is required that the flowmeter includes a measurement scheme that provides the necessary accuracy and resolution. The mean transit time through the flow is measured to make the flow velocity measurements independent of the speed of sound in the fluid.

1.2 Scope of the Project

As a part of BRNS sponsored project for developing ultrasonic flowmeters, a flowmeter based on dual path 'sing-around' technique, was earlier developed by Satish Kumar at IIT Bombay in 1996 [9]. It was found that errors were introduced in the 'sing-around' frequencies because of delays in the non-flow liquid parts of the flowmeter.The objective of the present dissertation was to design, fabricate and test a direct transit time ultrasonic flowmeter based on the simultaneous or four transducer scheme, in order to overcome the drawbacks of the 'sing-around' flowmeter developed.

The direct transit time flowmeter involves the measurement of transit time differences, which are of the order of tens of nanoseconds. The vernier technique, which can be used for short time-interval measurements in the sub-nanosecond range, requires quick-start oscillators. As the frequency determining components in the quick-start oscillators are resistors and capacitors, these oscillators suffer from instability in their frequency.

In this project, a technique using accumulation of counts over several time-intervals has been implemented, and tested for the measurement of short time-intervals. This technique has been applied for the measurement of the difference between the upstream and downstream transit times and a flowmeter based on it has been developed. Testing of this flowmeter using a water circulation system has been carried out.

1.3 Outline of the Report

A description of the flowmeters based on the transit time technique is given in Chapter 2. The drawbacks of some of the short time-interval measurement techniques, for the measurement of transit time difference are also mentioned. Chapter 3 provides the details of the implemented direct transit time flowmeter based on the simultaneous transmission scheme. It includes the details of the transit time difference measurement scheme, the measurement electronics and, the transmitter and receiver circuits. The experimental set-up and the test results of the flowmeter are discussed in Chapter 4. Finally, the summary of the work done and some suggestions for future improvements are mentioned in Chapter 5.

Chapter 2
Transit time flowmeters

Transit time flowmeters [2], [3] measure the difference between the transit times of an ultrasonic beam transmitted in the upstream and downstream directions of the flow as shown in Fig. 2.1. The transit time techniques are classified into :

a) phase measurement technique

b) 'sing-around' technique

c) direct transit time technique.

The different transit time techniques are compared, with special emphasis on the direct transit time techniques. Some of the techniques that can be used for the measurement of the transit time difference are mentioned and their drawbacks are listed.

2.1 Phase measurement technique

This technique involves the measurement of the phase difference between the acoustic waves traveling in the upstream and downstream directions. The transmitted signal can be in the form of continuous waves or sinusoidal bursts.

If the transmitted signal is given by,

$$V = V_m \sin\omega t$$

then the change in the phase angle of the received signal as compared to the transmitted signal will be,

$$\phi_1 = \omega.d\,/\,(c + v.\cos\theta)$$

$$\phi_2 = \omega.d\,/\,(c - v.\cos\theta)$$

for the downstream and upstream cases respectively. Where,

d = the transducer separation

c = the acoustic velocity in the fluid

v = the average flow velocity.

The difference in the phase changes for the two cases is then given by,

$$\Delta\phi \approx 2.\omega.d.\cos\theta \;/\; c^{2} \tag{2.1}$$

since $c^{2} >> v^{2}.\cos^{2}\theta$.

The above expression indicates that the measurement is dependent on the sound velocity c in the flowing fluid. In the dual frequency method described by *Noble* [8], signals with slightly different frequencies are propagated in opposite directions between a single pair of transducers. The phase comparison is performed at the difference frequency generated by mixing the transmit and receive signals present on both the transducers and, the system provides measurement of both the liquid velocity and the speed of sound in the fluid, which is required for compensation.

The method suffers from the problem of phase ambiguity, for $\Delta\phi > 2\Pi$, since the phase difference is no longer unique. This restricts the pipe sizes and the flow velocities over which this technique can be employed [2]. Also, any acoustic coupling between the transmitting and receiving transducers through the pipe walls and housing causes the addition of the wave thus received with the wave traveled through the water. This causes undue phase change, causing an error in the reading.

2.2 'Sing-around' technique

In the 'sing-around' method [2], [4] ultrasound pulses are transmitted through the fluid at an angle to the flow axis as shown in Fig. 2.2. The received pulse is used to retrigger the transmitter, resulting in a periodic pulse train. The pulse repetition frequency (prf) in the case of upstream direction is given by,

$$f_{u} = (c - v.\cos\theta) \;/\; d \tag{2.2}$$

In the downstream direction the prf is given by,

$$f_d = (c + v.\cos\theta) / d \tag{2.3}$$

The difference in the 'sing-around' frequencies Δf is given by,

$$\Delta f = f_d - f_u = 2.v.\cos\theta / d \tag{2.4}$$

which gives a measurement independent of the changes in the acoustic velocity c in the fluid.

A 'sing-around' flowmeter based on single-transmission path with automatic recording has been described by *Greenspan & Tschiegg* [10]. In this system, pulse repetition frequency is measured for either upstream or downstream directions only, and flow velocities are calculated using either Eqn. 2.2 or Eqn. 2.3. Hence the measurements are affected by changes in the acoustic velocity.

In dual path 'sing-around' flowmeters [11], [12] with simultaneous transmissions in both upstream and downstream directions, the flow velocities are calculated using Eqn. 2.4, and hence the measurements are independent of the sound speed c.

However, this technique suffers from the errors introduced in the 'sing-around' frequencies due to the delays in the non-flow part of the flowmeter [9]. To evaluate the effect of additional delay introduced in the sonic path and electronic circuits, a non-flow dependent sonic path element x and an electronic measuring delay τ are introduced in the expression for the transit times. Here $d = (D / \sin\theta)$, where D is the diameter of the pipe. It is assumed that the delays are the same in both directions.

The transit times in the downstream and downstream directions with the additional delays become,

$$T_{de} = \{(d / \sin\theta) / (c + v.\cos\theta)\} + x / c + \tau \tag{2.5}$$

$$T_{ue} = \{(d / \sin\theta) / (c - v.\cos\theta)\} + x / c + \tau \tag{2.6}$$

The difference between the 'sing-around' frequencies, Δf_e [3] is then,

$$\Delta f_e = [1 + (2.A.c.\sin\theta) / D + \{(A.c.\sin\theta)(1 - (v.\cos\theta) / c) / D\}^2]^{-1}$$

where $A = x / c + \tau$. In the perfect case where $x = 0$ and $\tau = 0$,

$$\Delta f = v.\sin(2\theta) / D \qquad (2.7)$$

The relative error may be defined as,

$$e = (\Delta f - \Delta f_e) / \Delta f$$

$$e = -\{2.A.c.\sin\theta) / D - (A.c.\sin\theta)(1 - (v.\cos\theta) / c)\}^2 / D^2$$

As v is small compared to c, $(1 - (v.\cos\theta) / c) \rightarrow 1$. Hence the error is given by,

$$e \approx 1 - \{1 + (A.c.\sin\theta) / D\}^2$$

or, $$e \approx -\{2.A.c.D.\sin\theta + (A.c.\sin\theta)^2\} / D^2 \qquad (2.8)$$

The above expression indicates that

a) error is composed of both geometric and time dependent quantities.

b) error is dependent on the sonic velocity and hence is temperature and pressure sensitive.

2.3 Direct Transit Time Technique

This method is based either on a sequential (multiplexed transducers for transmission and reception) scheme or a simultaneous measurement (or four-transducer arrangement) scheme [2].

Fig. 2.3 shows the schematic of the sequential technique. The sequential technique consists of alternating the roles of the two transducers using one as the transmitter and the other as the receiver by means of a multiplexer. The system sequentially measures the upstream and downstream transit times. It has the advantage of providing measurement down to zero flow [2], since it involves a single set of electronics for measurements.

Fig 2.4 describes the direct transit time flowmeter with simultaneous measurement. With X1 as the transmitter and X2 as the receiver the upstream transit time T_u is obtained and is given as,

$$T_u = d \,/\, (c - v.\cos\theta) \qquad (2.9)$$

The downstream transit time T_d is obtained using X3 as the transmitter and X4 as the receiver and is given as,

$$T_d = d \,/\, (c + v.\cos\theta) \qquad (2.10)$$

The difference ΔT in the two transit times is then,

$$\begin{aligned} \Delta T = T_u - T_d &= 2.v.d.\cos\theta \,/\, (c^2 - v^2.\cos^2\theta) \\ &\approx 2.v.d.\cos\theta \,/\, c^2 \qquad (2.11) \end{aligned}$$

since $c^2 >> v^2.\cos^2\theta$

A correction has to be employed to make the measurement independent of the acoustic velocity c in the fluid. Without compensation the flowmeter would have a temperature coefficient of -0.4%/°C for measurements of flow velocities of water [2]. The product of the transit times can be used to provide the required correction [2], [13]. The product of T_u and T_d is given by,

$$\begin{aligned} T_u.T_d &= d^2 \,/\, (c^2 - v^2.\cos^2\theta) \\ &\approx d^2 \,/\, c^2 \qquad (2.12) \end{aligned}$$

From Eqns. 2.10 and 2.11,

$$\Delta T \,/\, (T_{u}.T_{d}) \approx 2.v.\cos\theta \,/\, d$$

Therefore,

$$v \approx d.\Delta T \,/\, (2.\cos\theta.T_{u}.T_{d}) \qquad (2.13)$$

The above expression is independent of the acoustic velocity.

The effect of delays in the non-flow part of the flowmeter is now evaluated. From Eqn. 2.5 and Eqn. 2.6, the transit time difference ΔT in the presence of equal delays in the two transmission directions becomes,

$$\Delta T_{e} = T_{ue} - T_{de} = \{(d \,/\, (c - v.\cos\theta)) + x \,/\, c + \tau\}$$
$$- \{(d \,/\, (c + v.\cos\theta)) + x \,/\, c + \tau\} \qquad (2.14)$$

where,

x is a non-flow dependent sonic path element

τ is the electronic measuring delay.

$$\Delta T_{e} \approx 2.v.d.\cos\theta \,/\, c^{2} = \Delta T \qquad (2.15)$$

When the acoustic velocity correction is employed in the form of the product of the transit times, additional terms corresponding to the delays are introduced. From Eqn. 2.14, the product of the transit times becomes,

$$T_{ue}.T_{de} \approx \{d^{2} + 2.(x \,/\, c + \tau).d.c + (x + \tau.c)^{2}\} \,/\, c^{2} \qquad (2.16)$$

From Eqn. 2.15 and Eqn. 2.16,

$$\Delta T_e / T_{ue} \cdot T_{de} \approx 2.v.d.\cos\theta / \{d^2 + 2.A.d.c + (A.c)^2\} \quad (2.17)$$

where,

$A = x / c + \tau$

The relative error is given as,

$$\varepsilon = \{(\Delta T / T_u.T_d) - (\Delta T_e / T_{ue}.T_{de})\} / (\Delta T / T_u.T_d)$$

$$\varepsilon \approx 1 - d^2 / \{d^2 + 2.A.d.c + (A.c)^2)\}$$

$$= \{2.A.d.c + (A.c)^2\} / \{d^2 + 2.A.d.c + (A.c)^2\} \quad (2.18)$$

Recalling that $d = (D / \sin\theta)$, Eqn. 2.18 can be expressed as,

$$\varepsilon \approx \{2.A.c.D.\sin\theta + (A.c.\sin\theta)^2\} / \{D^2 + 2.A.c.D.\sin\theta + (A.c.\sin\theta)^2\} \quad (2.19)$$

Comparing the terms in Eqn. 2.8 with those in Eqn. 2.19, it can be noted that the error resulting in the direct transit time method (due to delay in the non-flow liquid part of the flowmeter and electronic measuring delay), is less severe as compared to the error in the 'sing-around' technique for all the possible values of x and τ, particularly for small pipe diameters. It is to be noted that the error is contributed by the velocity correction and can be avoided, if we measure the fluid temperature and directly apply the correction.

2.4 Development of Direct Transit Time Flowmeters

Different direct transit time flowmeter schemes have been developed over the years. Some of them are described below.

In the year 1979, *Appel et al.* [13] proposed a microprocessor.based simultaneous direct transit time flowmeter scheme with two transducers. A train of oscillations of frequency of about 5 MHz is sent simultaneously on two transducers. At the end of transmission, the electronic circuits are switched into reception. The delays of the two received trains relative to the transmitted train are then determined. The system uses a mix of digital and analog circuits, for the measurement of the transit time difference. A major part of the transit time difference measurement is done using digital technique. The residue which corresponds to a fraction of the clock period is measured using constant current integrators (analog method). Periodic calibration signals are used to provide compensation for the drifts of the zero and of the gain of the analog integrators.

The major limitation of dual path flowmeters is that the measurements are related only to the mean flow velocity along the path of the transducers. The multi-path flowmeter overcomes this limitation by sampling the flow along many chords of the pipe cross-section.

In the year 1983, *Nolan & O'Hair* [14] reported a four-path direct transit time flowmeter for gases. The system has a multiplexer unit to select the connections of the ultrasonic drive/detection unit to each pair of probes in turn. The transit times are measured by a timer, triggered by pulses marking the beginning and end of each transit time, and their difference is taken. A microprocessor computes the mean gas velocities usually averaging over a 12 second interval during which 200 measurements are made. the mean flow velocity is calculated by adding the weighted measurements an the four chords together. Due to much higher velocity of sound in liquids, the differences in the transit times are typically in the nanosecond range, and hence cannot be accurately measured by taking the difference of two transit time measurements.

The principle methods available for the measurement of time-intervals in the nanosecond and sub-nanosecond range [15] are :

a) vernier technique

b) pulse overlap technique

c) methods based on the start-stop principle.

The principle of the vernier technique has been described in Appendix A. Based on the vernier method, *Chande & Sharma* [16] have described a scheme for determining the transit time difference. The transit times are measured separately and their difference is then determined.

The vernier technique has the following drawbacks that make its implementation difficult.

i) The technique requires stable oscillators which need to be started and stopped quickly. But stable clock sources like the quartz oscillators cannot be started quickly without adversely affecting the frequency stability. Quick-start oscillators on the other hand, have poor frequency stability.

ii) Good resolution can be obtained if the two clock sources used, differ in clock frequency by a very small quantity. Operation of two such clock sources in close proximity requires careful shielding , since the oscillators tend to lock into constant relative phase with identical periods [15].

The pulse overlap technique and the methods based on the start-stop principle are analog methods. So they suffer from poor long term stability. Therefore an alternative scheme is needed for the measurement and. the technique used in this project is discussed in the next chapter.

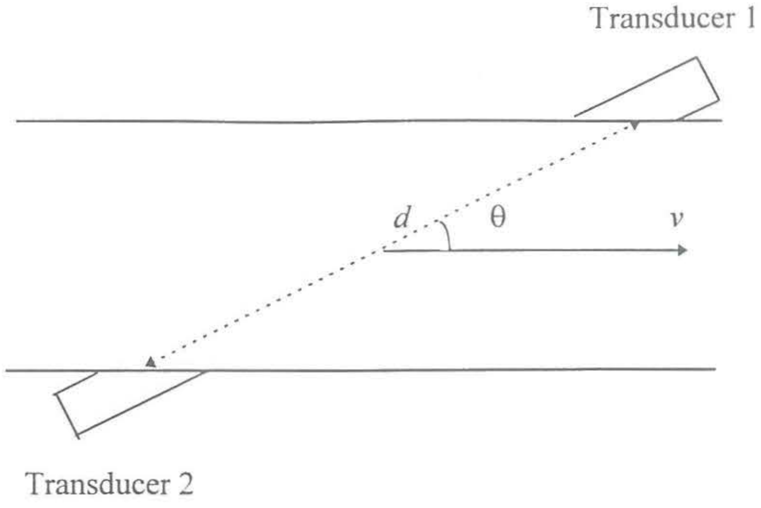


Fig. 2.1 Transducer arrangement in a transit time flowmeter

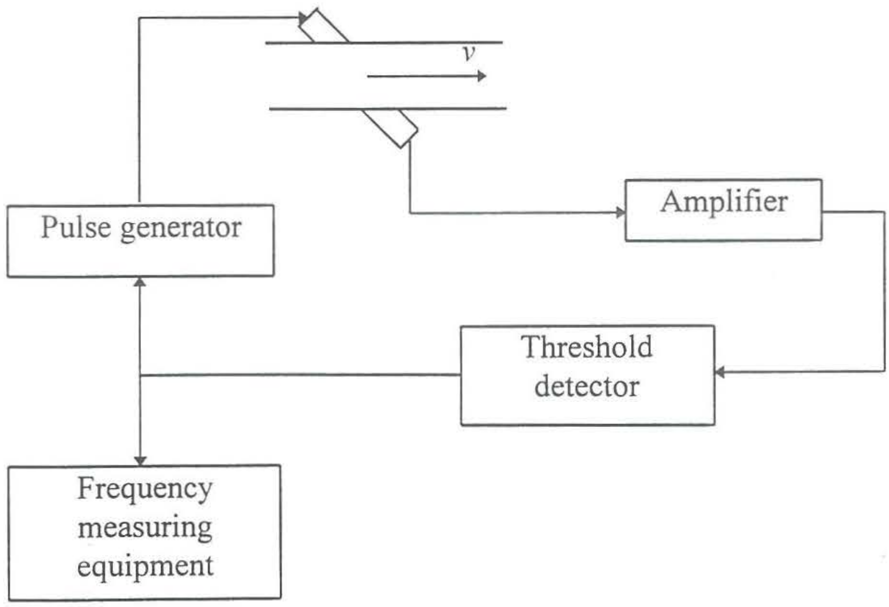


Fig. 2.2 Block diagram showing 'sing-around' principle

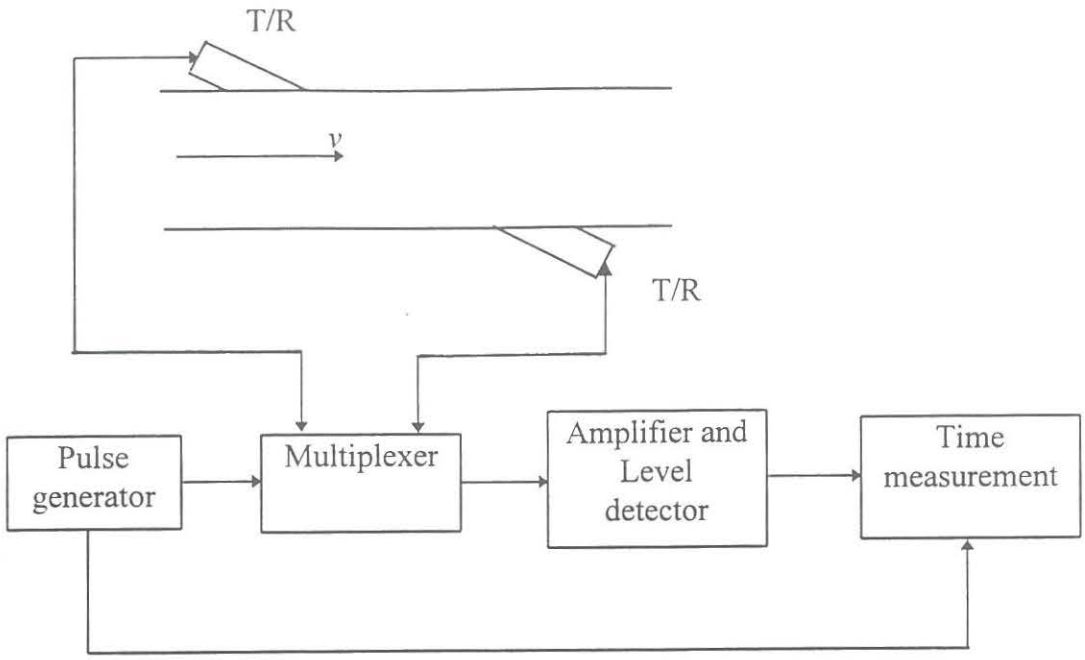


Fig. 2.3 Sequential direct transit time flowmeter scheme

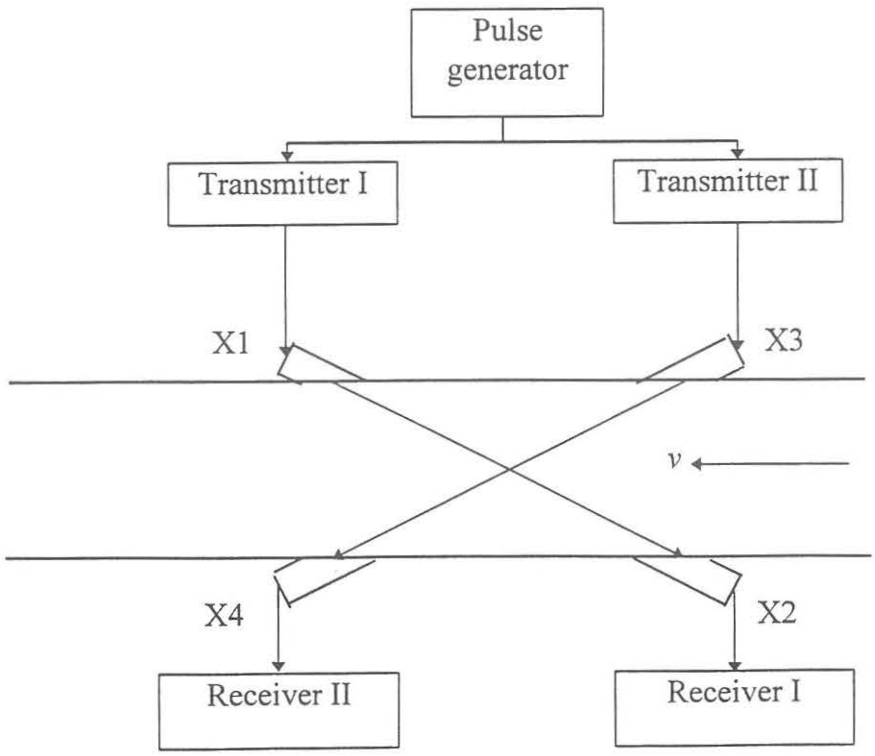


Fig. 2.4 Simultaneous direct transit time flowmeter scheme

Chapter 3
System Description

The direct transit time flowmeters are based on two measurement schemes namely; the sequential and the simultaneous schemes. The sequential scheme offers the advantage of minimal electronics, but if the transmissions in either directions do not sample the same fluid, there will be subsequent errors in the measurement data. Thus simultaneous transmission is the better situation from an accuracy point of view [3].

Our flowmeter system is based on the simultaneous scheme, or the four-transducer arrangement of direct transit time measurement. It involves the measurement of the transit time differences as well as the upstream transit times, to provide acoustic velocity compensation. The essential features of a direct transit time flowmeter with a four-transducer arrangement is shown in Fig. 3.1. The upstream transit time is obtained with X1 as the transmitter and X2 as the receiver. Similarly, the downstream transit time is measured with X3 as the transmitter and X4 as the receiver The time-intervals are controlled by high-speed comparators which change state at preset levels of the received signals.

The expression for the flow velocity as determined by the direct transit time method is given by,

$$v \approx d.\Delta T \,/\, (2.\cos\theta.T_u.T_d)$$

The product of $T_u.T_d$ can be approximated by either T_u^2 or T_d^2. Such an approximation provides adequate velocity of sound compensation, although a nonlinear factor in the flowmeter output is introduced [2].

The circuits operating in the two transmitter and the receiver channels are not strictly identical. This results in the introduction of a differential delay in the separate channels. Also, an unknown delay equal to the time during which the amplified pulse spends below the noise level, is introduced [10]. This delay depends on the attenuation characteristics of the liquid.

Taking this into account, provision for the introduction of a variable delay in the transmitter and the receiver channels is made.

3.1 Transit Time Difference Measurement

The direct transit time difference flowmeter involves the measurement of very short time-intervals, normally in the range of tens of nanoseconds. We can measure the short interval Δt of the difference in the two transit times, by accumulating the clock pulses over time Δt,

$$N = f_o.\Delta t.$$

where N = number of pulses accumulated

f_o = frequency of the clock pulses.

We can use a very stable f_o but the resolution in the measurement of Δt is limited to $1 / f_o$. With commercially available counters, the maximum clock frequency that can be used is 90 MHz. This gives a best resolution of 11 ns which is insufficient for the transit time difference measurement, in the case of liquid flow measurement

The transit time difference measurement technique used here [17], takes advantage of the fact that the flow pattern does not change rapidly. This means that repeated measurements can be made, with the transit time difference intervals remaining approximately the same. Thus accumulating of the counts over a number of such repeated observations is used for obtaining the required resolution. If the clock time period is not a submultiple of the time interval being measured, the errors in the count for each interval will be random and therefore resolution will improve with the number of intervals. Therefore we need a clock with a very stable mean frequency but with a certain randomness associated with the arrival of the clock pulses. This clock can be obtained from a pseudo-random binary sequence (PRBS).

A PRBS can be obtained as a maximal length sequence from a sequence generator [18]. A sequence generator consists of N cascaded flip-flops with a clock waveform simultaneously applied to all the flip-flops. The input to the first flip-flop is a function of the outputs of the flip-flops, i.e. $D_1 = f\,(Q_1\ Q_2\ Q_3,....Q_n)$. In a maximal length sequence, the sequence repeats after 2^{N-1} successive bits. Maximal length sequences have a certain degree of randomness associated with them.

We have not come across literature regarding the use of this technique for the actual measurement of time-intervals, but basically the same principle has been employed for phase measurement as well as for obtaining improved resolutions in the A/D converter. *Bell & Leedham* [19] describe a digital phase measurement system that samples the time-interval corresponding to the phase difference between two signals at random instants with respect to the input waveforms. (This is true if the sampling frequency is not a multiple or a sub-multiple of the input frequencies). For a sufficiently large number of samples/observation the number of pulses counted conform to a Gaussian distribution. Increasing the number of samples/observation reduces the probability of the error being not more than a certain value. In a mixed-signal processor, based on the sigma-delta conversion process, described by *Davis et al.* [20], a resolution of 16 bits is achieved using averaging and filtering. The Dynalog Micro SITE Data Logger [21] employs a carefully tailored random modulation of the reference voltage to the ADC. This dither in the ADC reference combined with averaging leads to better resolutions (13-bit resolution from an 8-bit ADC).

3.2 Block Description

The block diagram of the system is given in Fig. 3.2. The hardware includes a measurement unit, two receiver channels, two transmitter channels, and a power supply. The transmitters exciting the transducers, are periodically triggered at a fixed frequency during the measurement period. The received ultrasound signal, after amplification and signal conditioning is used to trigger the comparators in the receiver circuits. The triggering of the comparators results in the generation of time-intervals corresponding to the upstream and downstream transit times. The measurement of the transit time difference and the upstream transit time is performed by the measurement unit. The measurement unit can be interfaced to a PC or a microcontroller.

3.3 Transmitter and Receivers

3.3.1 Transducers

Immersion type, straight contact piezo-electric transducers, having a resonant frequency of 5 MHz are employed in the flowmeter. The specifications of the transducers are mentioned in Appendix B.

Fig. 3.3 gives the schematic of the type of transducer used [22]. It consists mainly of the oscillator disc, a protective layer and the damping block. electrical matching elements are built into the housing. The thickness of the crystal corresponds to the required frequency and both its surfaces are metallized to act as electrodes. The damping block absorbs that part of the energy radiated backwards and the oscillator is thereby strongly damped in order to suppress the reverberations of the pulse. The protective layer as well as protecting the crystal is also used to match the acoustic impedance for optimum coupling.

3.3.2 Transmitter

Fig. 3.4 shows the block diagram of the transmitter circuit which includes a pulse train generator, a variable delay circuit (monoshots), a trigger circuit, and a transmitter. The pulse train generator determines the rate at which the transducers are to be excited. Fig. 3.5 gives the diagram of the pulse train generator and the delay circuit. An IC555 in the astable configuration, generates the pulse train with a repetition frequency of 1.5 kHz.

Since there are two separate transmitter electronics involved, differential delays in the two channels lead to an incorrect measurement of the transit time difference. Therefore variable delays, in the form of monoshots are introduced in the transmitter channels to compensate for any differential delay.

The circuit diagram for the trigger circuit along with the transmitter is shown in Fig. 3.6. The trigger circuit provides the electrical pulses required to drive the MOSFET switch of the transmitter circuit. A common collector stage switches in response to the pulses from the monoshot to give pulses with a peak amplitude of +12 V.

The transmitter provides the excitation for the transducers, which emit a short duration pulse of ultrasonic energy. This is done by applying a transient electrical pulse to transducer. The transmitter consists of a capacitor, connected to the output of a MOSFET switch. When the MOSFET is in the off state, the capacitor is charged to the supply voltage. The application of an appropriate trigger pulse turns on the MOSFET switch, resulting in a negative spike voltage across the transducer. This excites the transducer, and an acoustic pulse is transmitted into the water via a coupling layer.

The amplitude and the shape of the pulse determine the nature of the transmitted ultrasound. The width of the pulse and hence the energy transferred to the transducer can be varied by varying the capacitor value. The damping of the transducer can be trimmed with the resistance R7. The optimum pulse width (for flow applications) as suggested by *Greenspan & Tschiegg* [10], is 100 to 200 ns. This is because pulse widths in excess of 500 ns tend to excite transverse modes of the transducer, which send sound pulses through the solid parts of the flowmeter. The actual pulse width employed for transmission is 200 ns.

3.3.3 Receiver

The transmitted ultrasonic pulses are attenuated as they travel through the flowing fluid. The receiver circuits perform the necessary amplification of the signals, received by the transducers and subsequently detect the instant of arrival of the acoustic pulse at the receiver. Fig. 3.8 describes the receiver circuit, which comprises of an amplifier circuit, a comparator, a variable delay circuit and, an S-R flip-flop for generating the transit times.

Several methods of detecting the exact arrival of the acoustic pulse have been suggested [4], [23] to overcome the effect of amplitude fluctuations of the received signal, on the performance of the flowmeter. Implementation of these methods involves complicated electronics. Instead the approach employed by Satish Kumar [9] has been followed. This involves amplifying the received waveform to such an extent that the amplifier saturates. This prevents small amplitude fluctuations from affecting the level of output. The amplification is carried out in two stages, with a diode clipping circuit in between the two stages. The gain of the pre-amplifier is adjusted so that the level of noise and echoes, even after amplification is less than the cut-in voltage of the diode. This prevents the false triggering of the comparator.

The amplifier section is shown in Fig. 3.9. It consists of a preamplifier followed by a second amplifier with a diode clipping circuit connected in between them. The gain of the preamplifier is set at such a value that the noise and the echoes in the received signal are not passed through the diode clipping circuit. The second stage amplifies the signal to the saturation level. The frequency response of the amplifier circuit is shown in Fig. 3.11. It has a bandwidth of 45 MHz.

The amplifier section is built using NE592, which is a differential input, differential output, wide band video amplifier [24]. The gain of the amplifier can be varied with a variable resistance between pins 4 and 11.

The comparator circuit is shown in Fig. 3.12. The comparator determines the instant of the arrival of the ultrasonic pulse by switching its state, when a prescribed threshold is exceeded by the amplified signal. The switching threshold, which is well above the noise level, can be trimmed with the variable resistance. NE521, a high speed, dual comparator is used.

The variable delay circuits are employed to reduce the differential delay in the two receiver channels. They also reduce the error in the measurement of transit time difference resulting due to the effect of unequal path lengths of the transmitted ultrasonic beams.

The S-R flip-flop is set when the transmitter is triggered and reset when the comparator output goes high, which indicates the arrival of the transmitted ultrasound pulse. Thus, the transit times in the upstream and downstream directions are obtained.

3.4 Measurement Unit

The block schematic of the system for transit time measurements is shown in Fig. 3.14. The unit consists of a PRBS clock generator and counters for the measurement of transit time difference and the upstream transit time. It also includes an accumulating counter, a circuit for generating the transit time difference intervals, and a calibration circuit. The transit time intervals are generated from the time-intervals corresponding to the upstream and downstream transit times. The counts are then accumulated over a fixed number of intervals, for both the transit time difference and the upstream transit time. The clock waveform is a PRBS. The accumulating counter counts the number of intervals in the measurement period. The calibration circuit can be used to test the performance of the measurement unit. The counts are latched at the end of a measurement period and then the system is reset. The features incorporated in the system are :

a) A measurement cycle is initiated only when a reset pulse is applied to the unit.

b) The measurement cycle continues till 2048 pulses corresponding to the transit time-intervals, have been counted.

c) The transmitters are disabled as soon as the measurement cycle is completed. This means that the latched outputs remain until a fresh cycle is started.

d) A calibration cycle can be carried out to determine the performance of the system

The features of the components of the unit are discussed below.

3.4.1 PRBS generator

The PRBS waveform for measuring the transit time difference, is generated using a 4-bit shift register (74F194), as shown in Fig. 3.15 .The length of the PRBS sequence is 15 bits. The clock to the shift register is obtained from a stable. 80.0 MHz crystal oscillator. The average frequency of the PRBS so generated is 24 MHz. This PRBS is then delayed (delay corresponding to that of two FTTL gates) and then inverted. (The delay to be introduced was empirically chosen to provide the most stable waveform for the final PRBS). The XOR of the original sequence and the delayed one is performed to give a PRBS with an average frequency of 48 MHz (frequency doubling). This is used as the clock waveform for the measurement of the transit time difference.

As mentioned earlier, we also have to measure the transit time (the upstream transit time is measured), which is of the order of 100 microseconds. The PRBS clock for its measurement is derived from the 24 MHz PRBS waveform by dividing it by 160.

The PRBS can fail to start-up if all the flip-flops in the shift register hold a logic 0 when the unit is powered. This is avoided by loading 1010 to the parallel inputs D_0-D_3 of the flip-flops, when a reset pulse appears at the beginning of a cycle.

3.4.2 Counters

Two separate counter units are used for the measurement of the transit time difference and the upstream transit time.

a) Counter for transit time difference measurement

This counter comprises of 4 binary counters, cascaded in ripple fashion, as shown in Fig. 3.16. The input to the first counter (74F163) is the gated PRBS (48 MHz). The gating interval is the transit time difference. The count is accumulated over 2048 time-intervals. The 8 least significant bits (LSBs) in the counter output are ignored (not latched) in the measurement process.

b) Counter unit for upstream transit time measurement

Fig. 3.17 shows the block diagram of this counter unit. It is similar to the previously described counter unit , except that a FTTL counter is not used. Here the 8 LSBs of the counter output are not latched.

Both the counter outputs are latched using latches with tri-state outputs.

3.4.3 Accumulating counter

A 14-stage CMOS counter (CD4020) counts the number of transit time-intervals occurring during the measurement period, as shown in Fig. 3.18. The clock input to the counter is obtained from a divide by two flip-flop to ensure proper operation. The Q_{11} output of the counter triggers a monoshot. The monoshot output resets the CMOS counter and provides a latch enable signal to latch the outputs of the counter units. After a time delay, all the other counters and the flip-flops are reset. Simultaneously a flip-flop (FF4) is set to indicate the completion of a cycle.

3.4.4 Generation of transit time difference intervals

Fig. 3.19 describes the generation of the transit time difference pulse from the upstream and downstream transit times, which are obtained from the receiver circuits. The XOR of the outputs of the toggle flip-flops gives a pulse width corresponding to the transit time difference. This implementation prevents any differential delay in the transmitter circuits, from affecting the transit time difference interval.

3.4.5 Calibration circuit

The calibration circuit, as shown in Fig. 3.20, repeatedly generates two pulses with widths, that differ by a fixed time-interval of 50 ns. These are similar to the transit time pulses, and are considered as such during the calibration cycle. A monoshot (IC555 in the monostable configuration) is triggered in response to a 'CALIBRATE' pulse, and the entire calibration cycle is completed before the monoshot output goes low.

3.5 Power Supply

The power supply unit feeds the required dc voltages to the circuits. It comprises of step-down transformers, bridge rectifiers, capacitor filters and the corresponding on-board regulators for each of the dc supplies. A dc supply of +160 V, as shown in Fig. 3.7, is provided for the transmitters for the generation of the high voltage transmitter pulses. Separate ±6 V have been used for the receiver amplifiers, as shown in Fig. 3.10. A +12 V dc supply is provided for the trigger circuits. A ±5 V supply is used for the comparator circuits. This supply also feeds the oscillator, the variable delay, and the S-R flip-flop circuits. The comparator and trigger circuit supplies are shown in Fig. 3.13. The measurement unit needs a +5 V supply. This is shown in Fig. 3.21.

3.6 Digital Interface

The measurement unit can be interfaced to a PC or a microcontroller, to automate the operation of the entire system. Since the latches have a tri-state output, their outputs have been tied together, and these can be applied to the PC bus or a microcontroller port. A measurement cycle can be initiated in response to a key being pressed. The output of the flip-flop (FF4), which is set at the end of the measurement cycle, can be used to interrupt the PC. Output enable signals are then sent to the latches, and the latched data is read. The flow velocity and flow rate are then displayed after the necessary computations have been performed on the data, that has been read.

Printed circuit boards for the system were designed using "Circuit Maker' software. The two trigger circuits and the two transmitter circuits were included in a single PCB. Separate PCBs have been used for the two receiver amplifiers to reduce the noise coupling between them. The oscillator and variable delay circuits for the transmitters, along with the comparators, and S-R flip-flops have been placed on one PCB. A separate PCB has been designed for the measurement unit. Multi point ground system has been used in boards with digital circuits to reduce the ground inductance. Short tracks have been wherever possible, especially for the analog circuits. Capacitors with short lead lengths, have been placed close to the supply leads of the ICs to provide power supply decoupling.

3.7 Sources of Error in the Measurement

The flow velocity measurement system suffers from inaccuracies as a result of the following assumptions [3]:

(i) that there is a uniform flat velocity profile across the pipe diameter. This is true only in conditions of fully developed turbulent flow at very high Reynold's number.

(ii) that the front face of the transducer is located precisely an the pipe diameter, and is a point source. This can be only approximated because any practical transducer has finite size, and some medium must invariably be interposed between the active transducer crystal and the fluid medium. Also the transducers may be withdrawn outwards from the pipe diameter leaving a pocket of non-flowing fluid.

(iii) that the angles of the transducer axis in the upstream and the downstream directions with the flow axis are the same.

(iv) that there is no directional shift in the transmitted ultrasonic beam as it travels through the flowing fluid.

3.7.1 Effect of velocity profile

The transit time flowmeter measures the mean flow velocity along the path of the transmitted ultrasonic beam. This makes the flowmeter subject to velocity profile errors in the presence of velocity profile skewing. Velocity profile skewing is imparted to the fluid due to an asymmetrical obstruction or curve in the pipeline. *Y. A.Al-Khazraji et al.* [25] assessed the effect of upstream fittings such as valves, bends, etc. on the output of ultrasonic flowmeters, by creating a distorted profile using an eccentric orifice. The percentage change in the output was found to be 5-15%. Even in along straight pipe the velocity profile varies with the Reynold's number. An error of approximately 30% can occur, when moving from the turbulent regime to the laminar regime with a change in sensitivity of approximately 3.5%, as the Reynold's number changes from 10^{7} to 10^{4} [2].

3.7.2 Effect of unequal angle of inclination of transducers to the flow velocity axis

Let θ_1 and θ_2 be the angles of inclination of the transducers to the flow axis. Then the error introduced in the measurement is given by,

$$\Delta T / (T_{u} \cdot T_{d}) - \Delta T_{e} / (T_{ue} \cdot T_{de}) = (2.v.\cos\theta) / d - v(\cos\theta_1 + \cos\theta_2) / d$$
$$= \{2.v.\cos\theta(1 - \cos(\Delta\theta))\} / d$$

where $\Delta\theta = (\theta_1 - \theta_2) / 2$, and $\theta = (\theta_1 + \theta_2) / 2$.

The relative error e is then,

$$e = 1 - \cos(\Delta\theta)$$

The error e is constant and depends solely on the error in the angles. The error in the angle of inclination is therefore a systematic error and can be reduced with calibration.

Although a beam of ultrasound can be considered to be confined to the projection of the face of the transducer, in reality there is always some spreading. This spread is a function of the ratio λ / δ [27], [22], [28], where λ is the wavelength of the ultrasonic wave, and δ is the distance across the face of the transducer (i.e. diameter for circular plates). In an ordinary quartz plate the energy is located in a cone, whose half angle of spread B is given by,

$$\sin B = 1.22\, \lambda / \delta$$

For a circular plate transducer with a diameter of 1 inch, emitting ultrasound at a frequency of 5 MHz, most of the energy in the ultrasonic beam is confined within a cone with an half angle of 3.5 degrees [27]. Therefore a slight misalignment of the transducers for transmission and reception, does not result in a severe loss of signal strength at the receiving transducer.

3.7.3 Effect of transducer frequency

The choice of the ultrasound frequency is the result of a compromise between the required measurement accuracy, size of the transducer used to generate the ultrasound, and the frequency dependence of absorption of sound in the particular fluid.

It may be shown [26] that for a disc of diameter δ vibrating at a frequency, for which the wavelength in the medium into which it is transmitting is λ, that the main sound energy is transmitted from the disc in all directions within a cone of angle α where, $0 < \alpha < (\lambda / \delta)$, and very little is transmitted in other directions. Hence if sound is to be directed in a narrow beam from a transducer with a vibrating area of diameter δ, it is necessary that $\lambda << \delta$. If c is the velocity of sound in the medium, $\lambda = (c / f)$ so then the condition for beaming becomes $f >.> (c / \delta)$ and the angle of divergence of the beam, $\alpha = c / (f.\delta)$. The beaming requirements thus demand high frequencies. Frequencies that are too low result in (i) spreading of the sound in the fluid and therefore attenuation of the received signals, (ii) spreading of the sound in the tube wall and therefore unwanted coupling of the transducers via the wall. The attenuation of sound, in clean fluids increases with the square of the frequency [2]. So high frequencies result in more attenuation of the sound signals. The sound pressure of a plane wave, which decreases only as a result of attenuation can for the purpose of calculation be written in the form of an exponential function [22],

$$p = p_o . e^{-\beta l}$$

p_o and p are the sound pressures at the beginning and end, respectively of a section of length l and with the attenuation coefficient β. The frequency dependence of β [22] is given as,

$$\beta = 0.22 . f^2 \text{ dB / m}$$

with f expressed in MHz. For a 5 MHz transducer β has a value of 5.5 dB / m.

The best frequency in a particular application is therefore one which is not too high as to result in a great attenuation and at the same time is not too low to prevent reasonable beaming. In common pipes containing water, frequencies in the range of 3-5 MHz are the best [2].

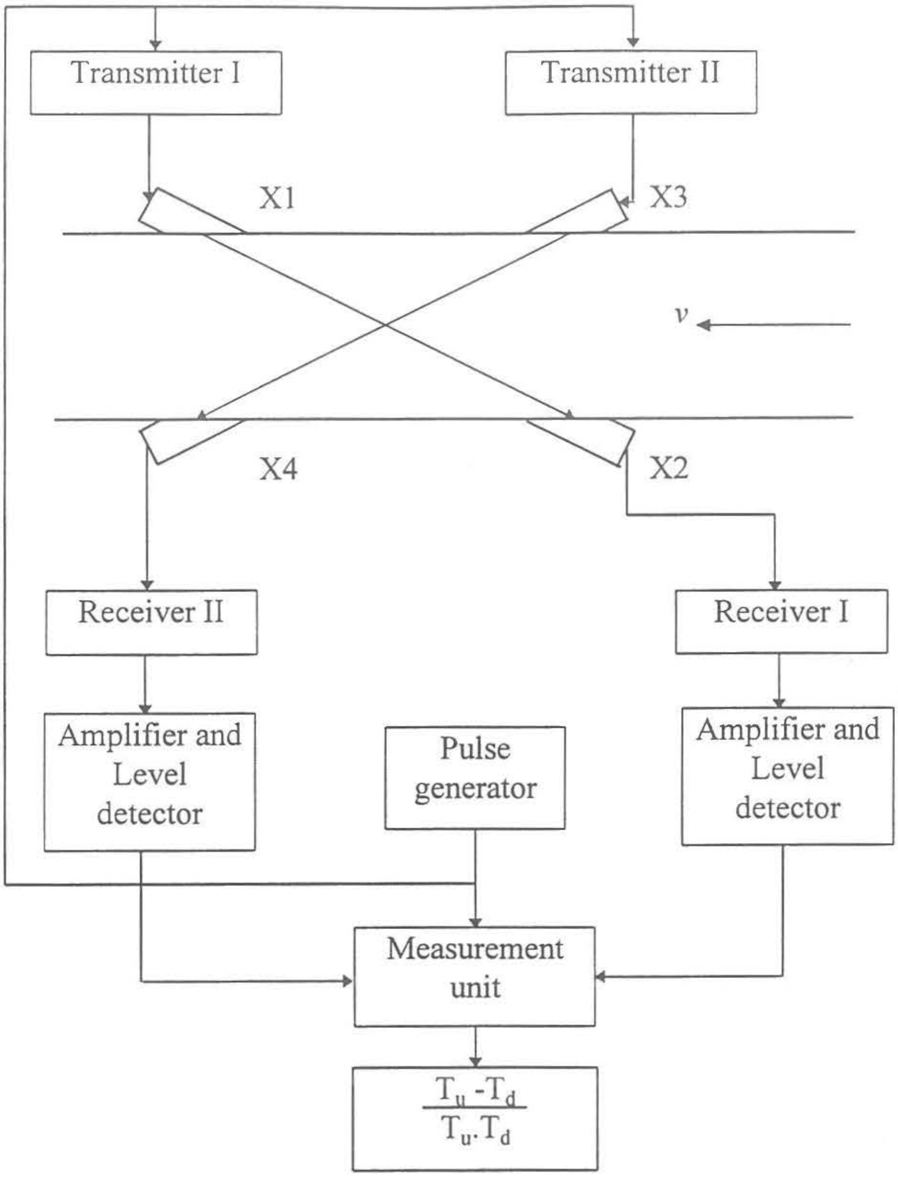


Fig. 3.1 Simultaneous transit time flowmeter scheme

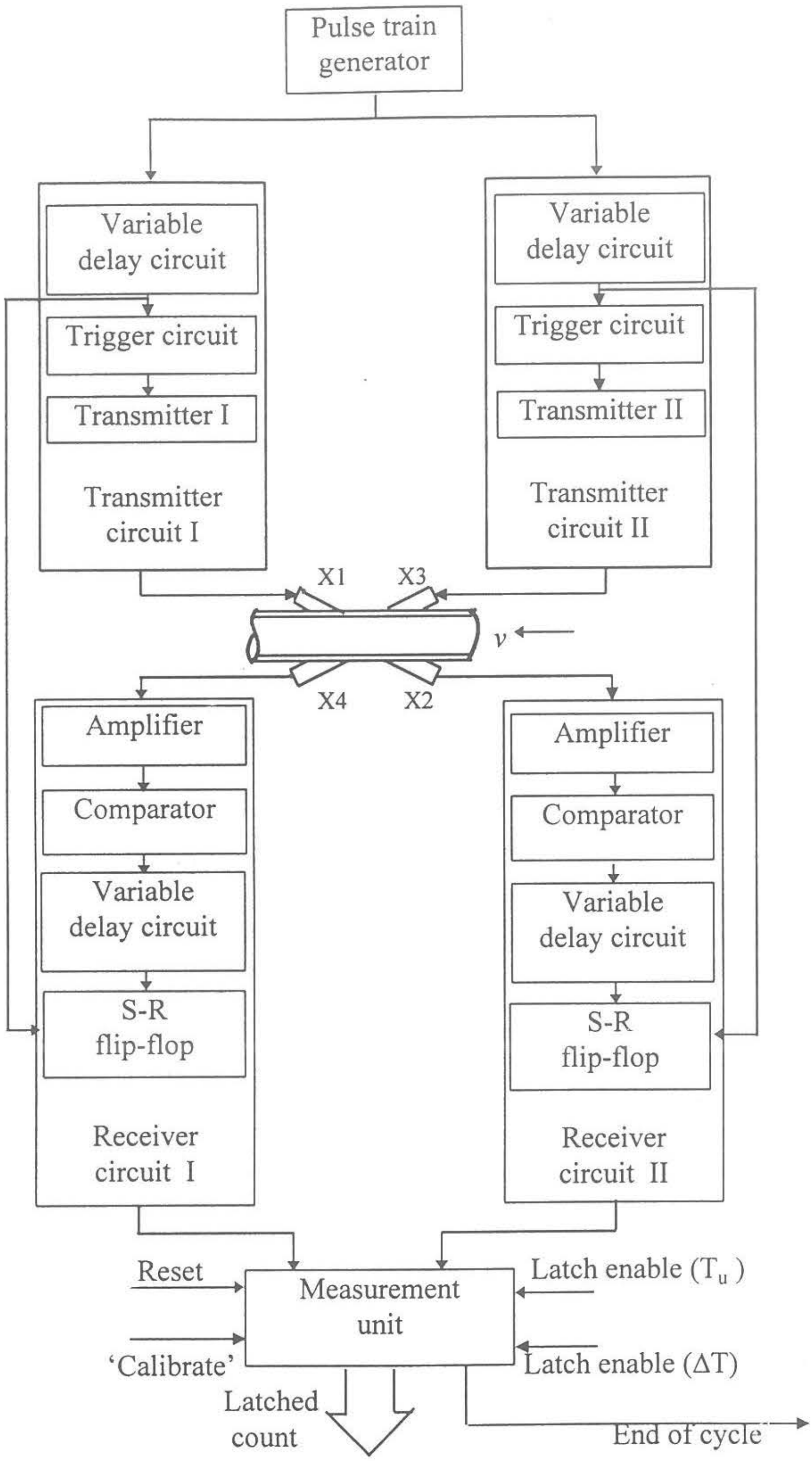


Fig. 3.2 Block diagram of the flowmeter system .

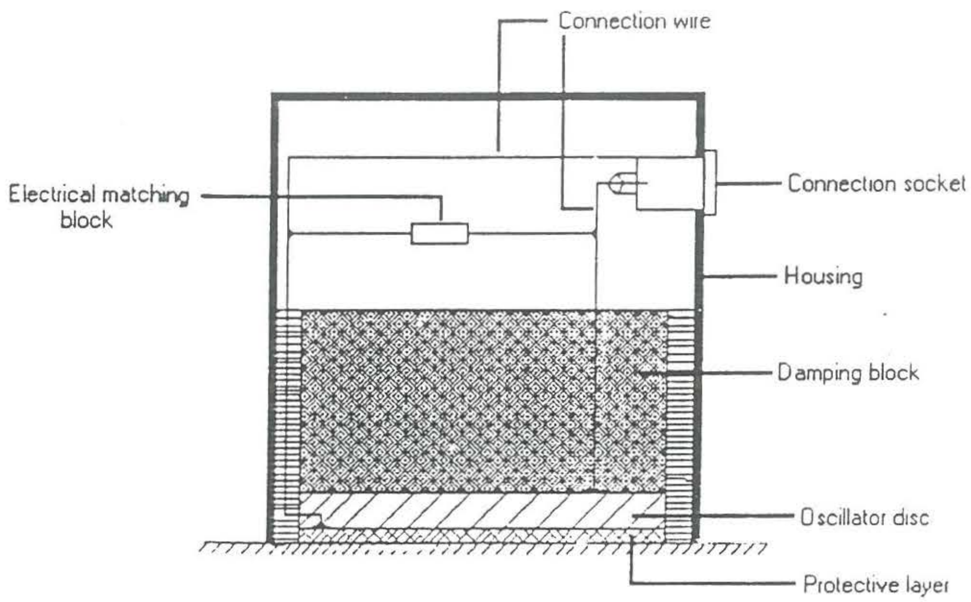


Fig. 3.3. Schematic of an ultrasound transducer

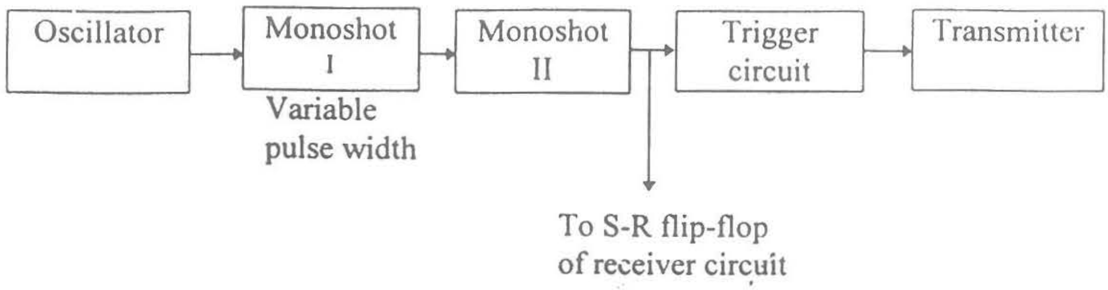


Fig. 3.4. Block diagram of the transmitter circuit

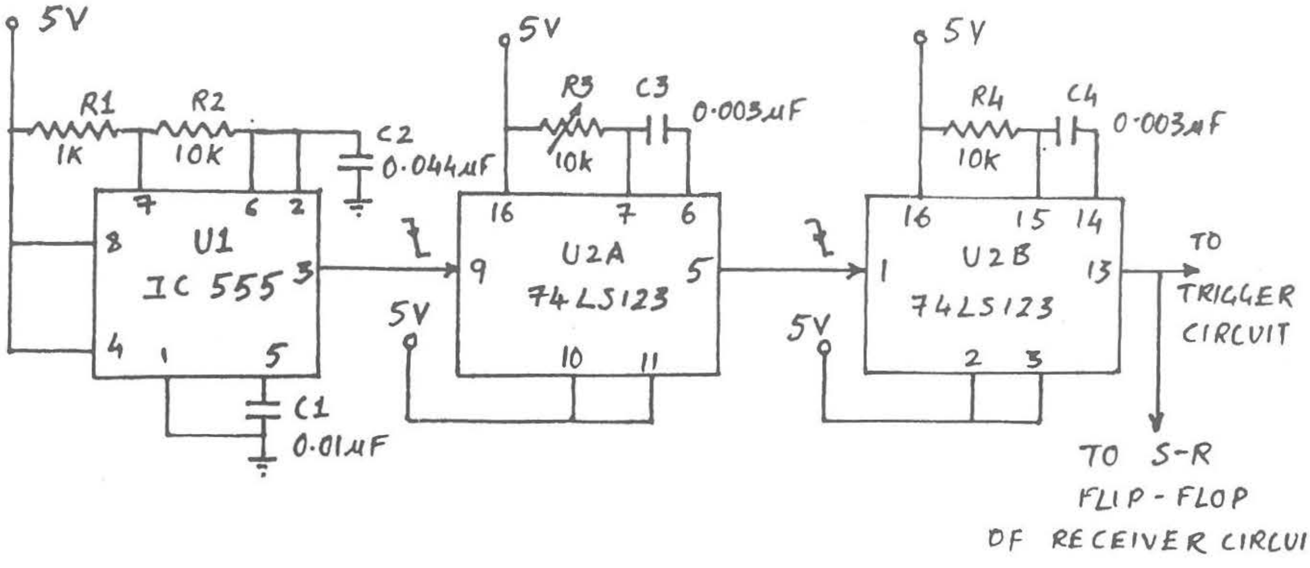


Fig. 3.5. Pulse train generator and delay circuits

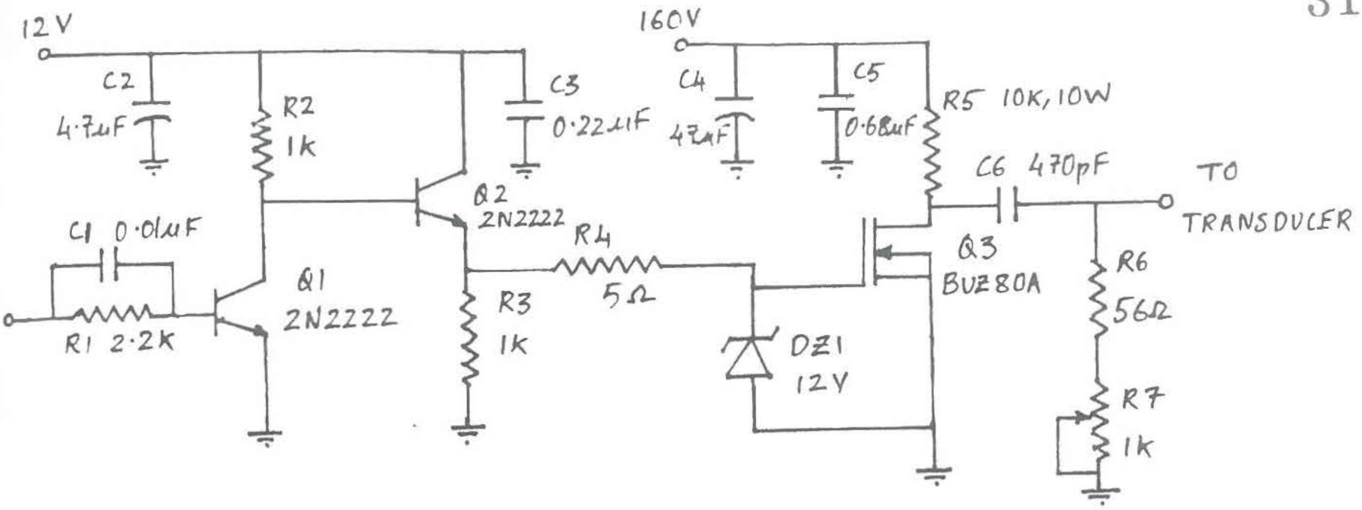


Fig. 3.6. Trigger and transmitter circuits

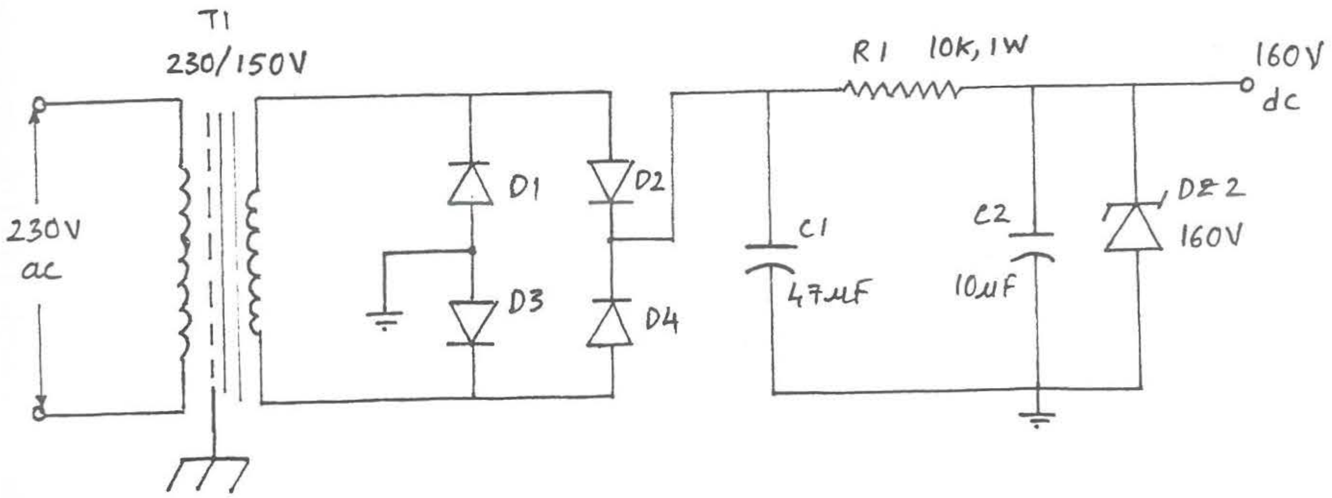


Fig. 3.7. Power supply for the transmitter

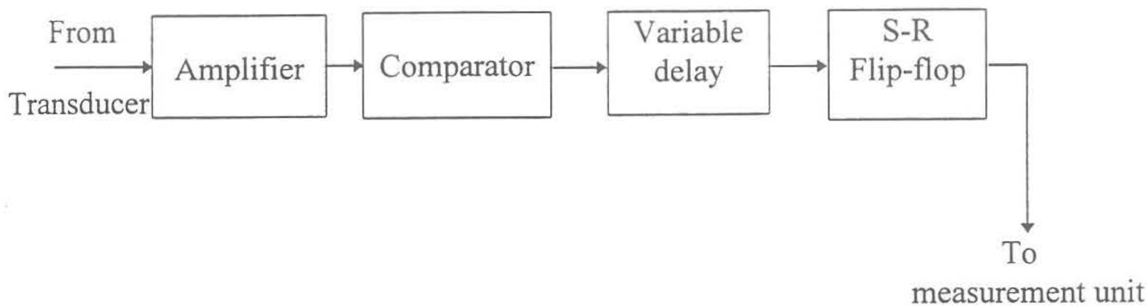


Fig. 3.8 Block schematic of receiver circuit

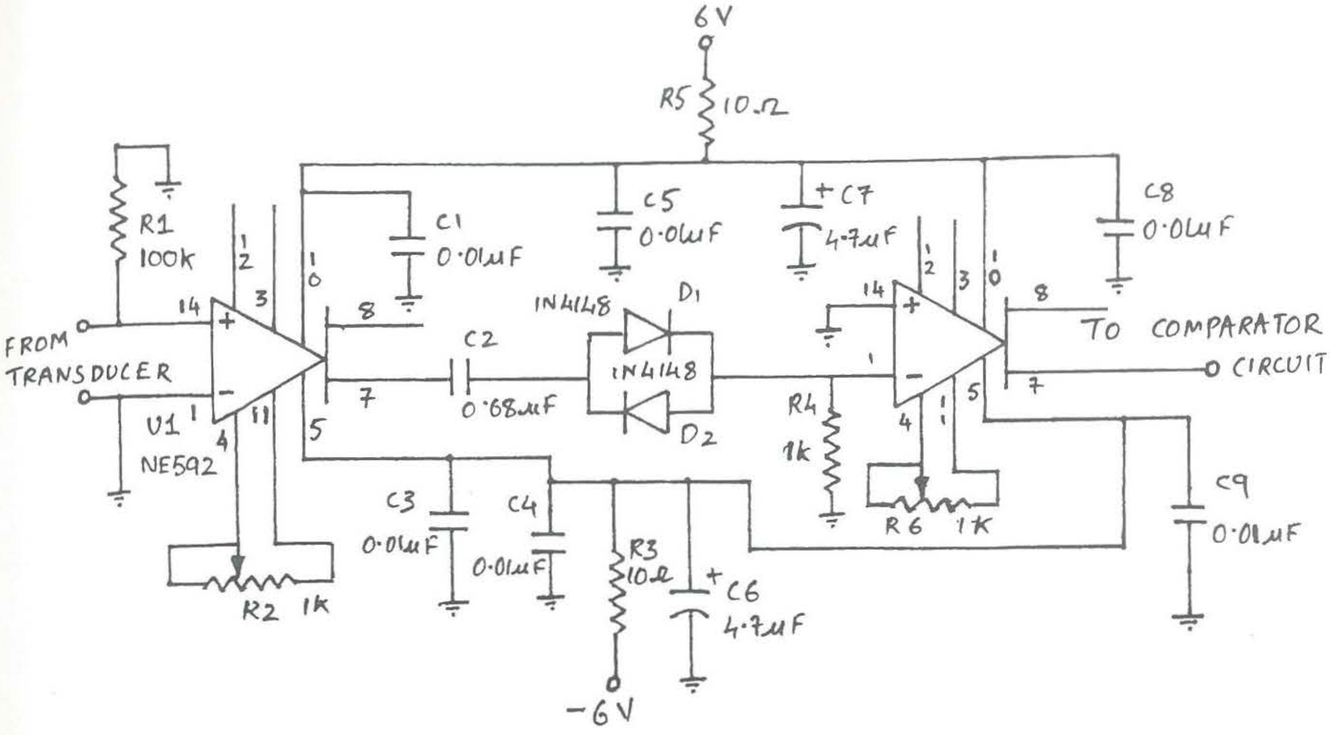


Fig. 3.9. Amplifier circuit

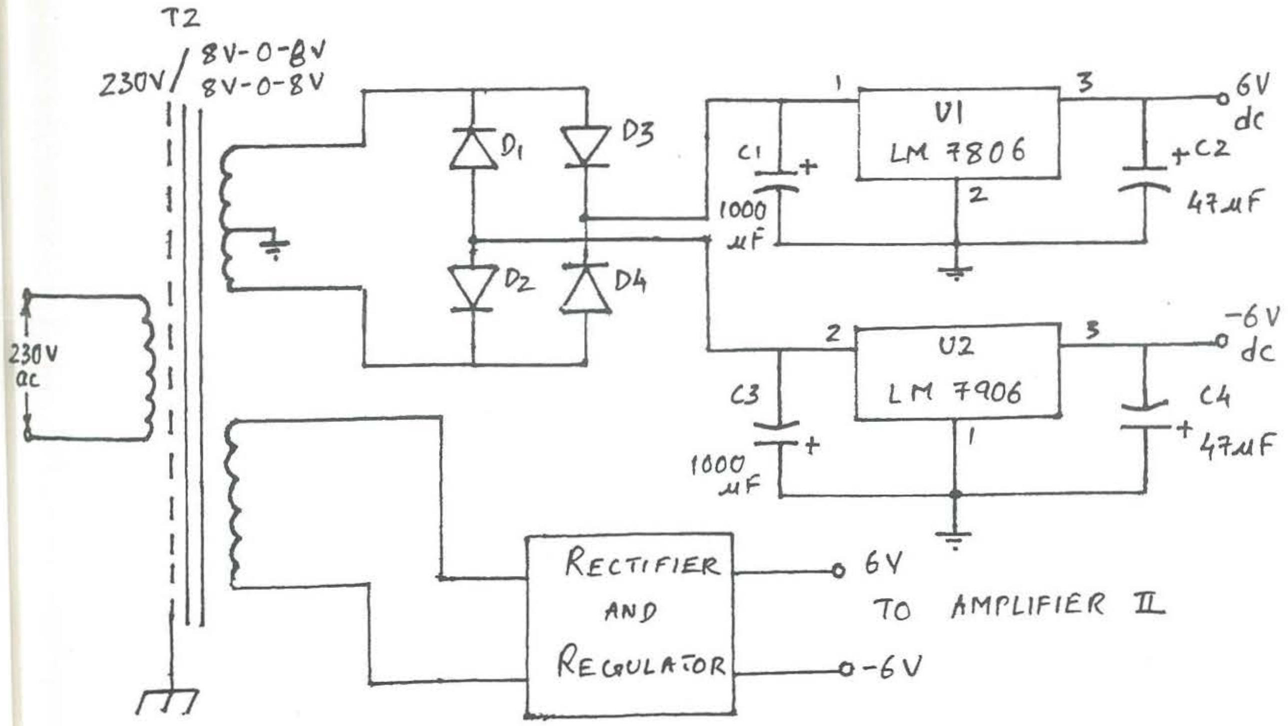


Fig. 3.10. Power supply for the amplifier circuit

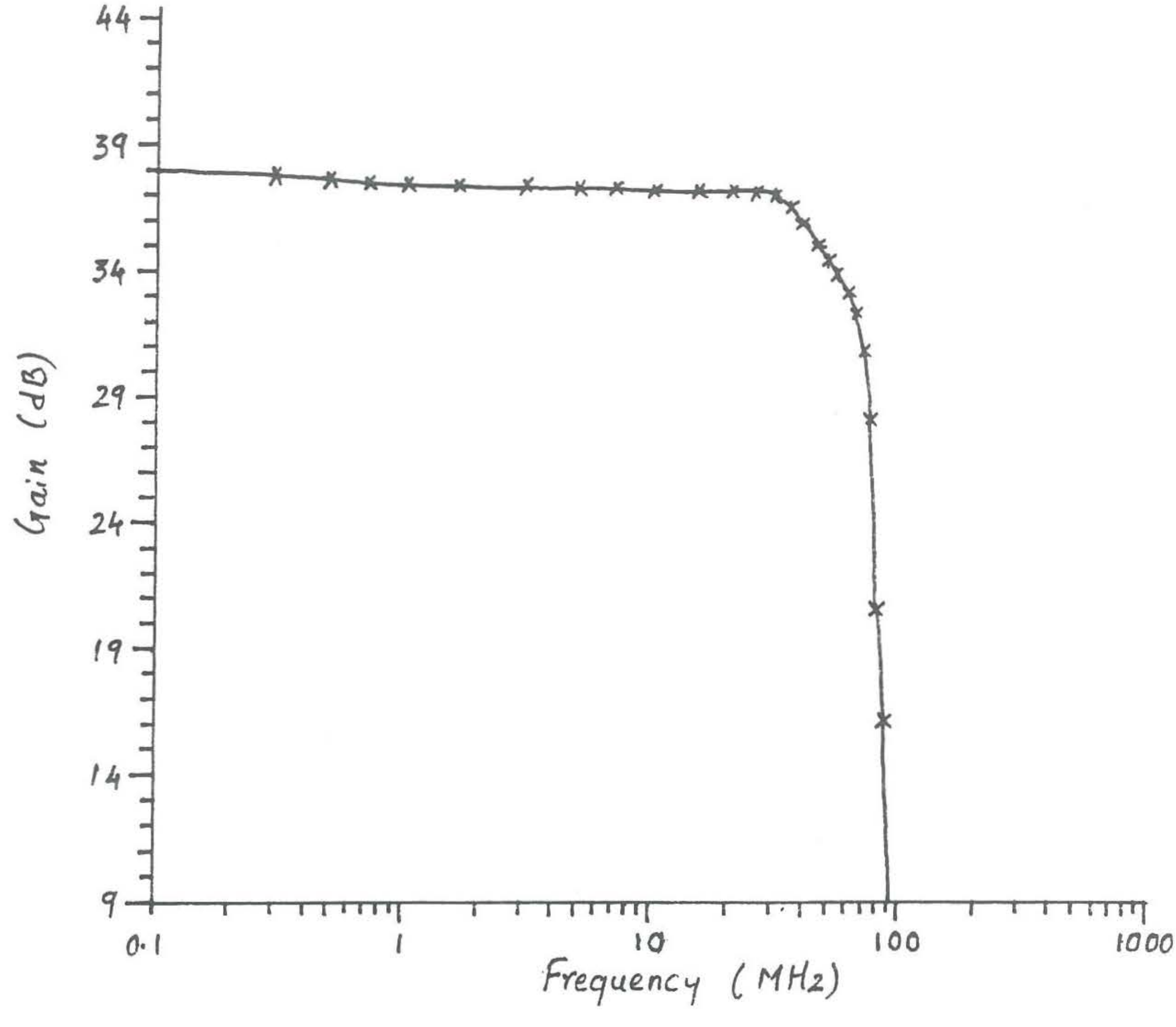


Fig. 3·11. Frequency response characteristic of receiver amplifier.

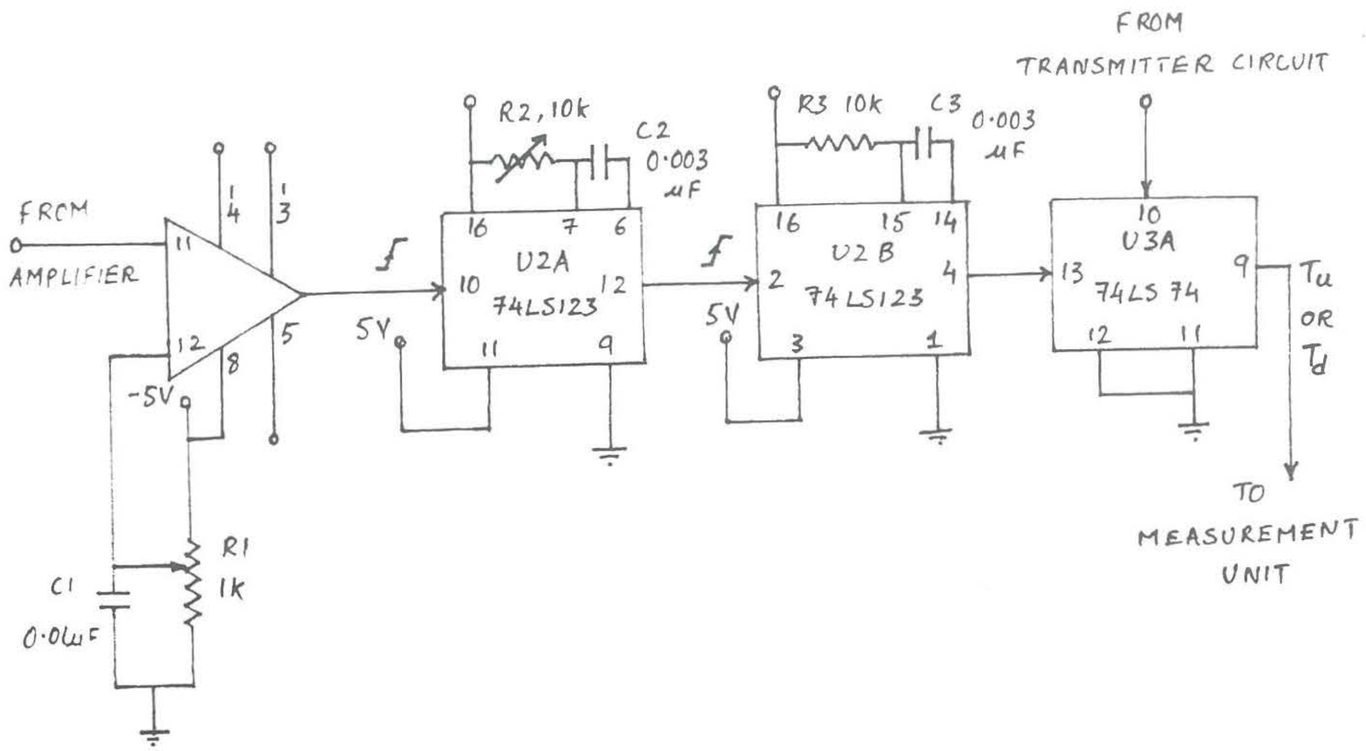


Fig. 3.12. Comparator circuit

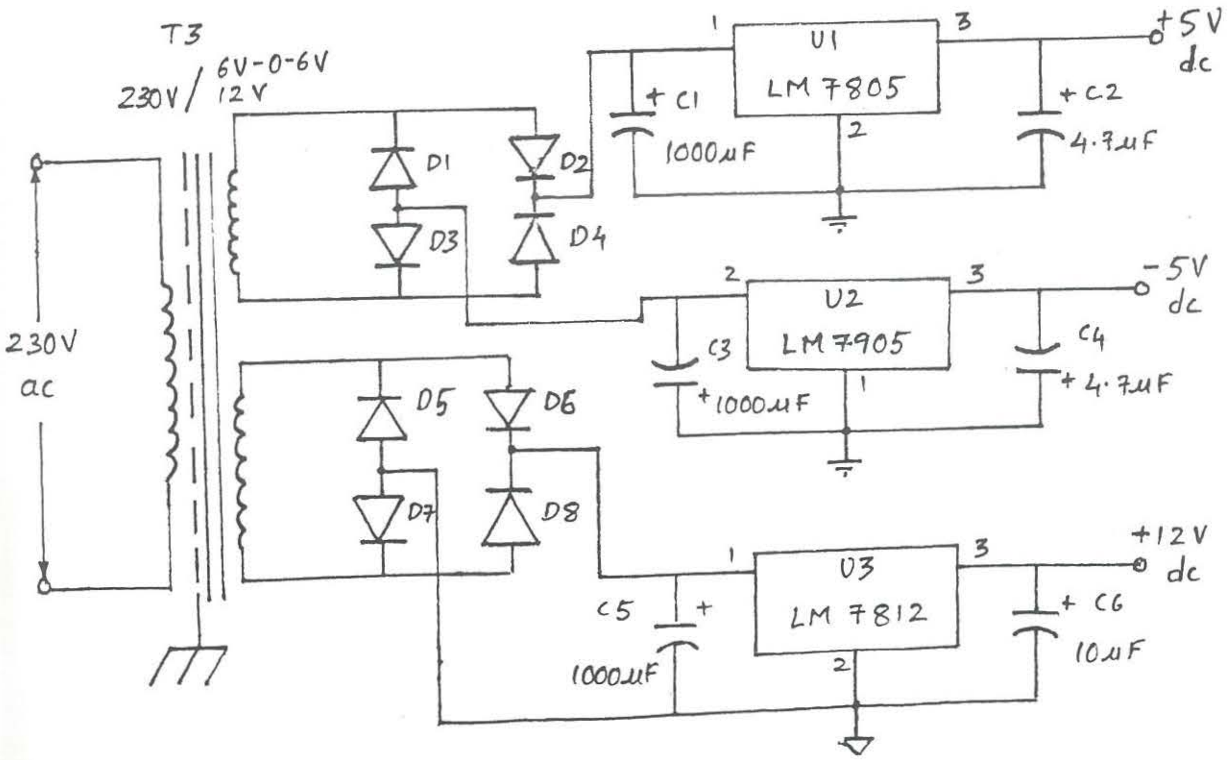


Fig. 3.13. Power supply for the comparator circuit

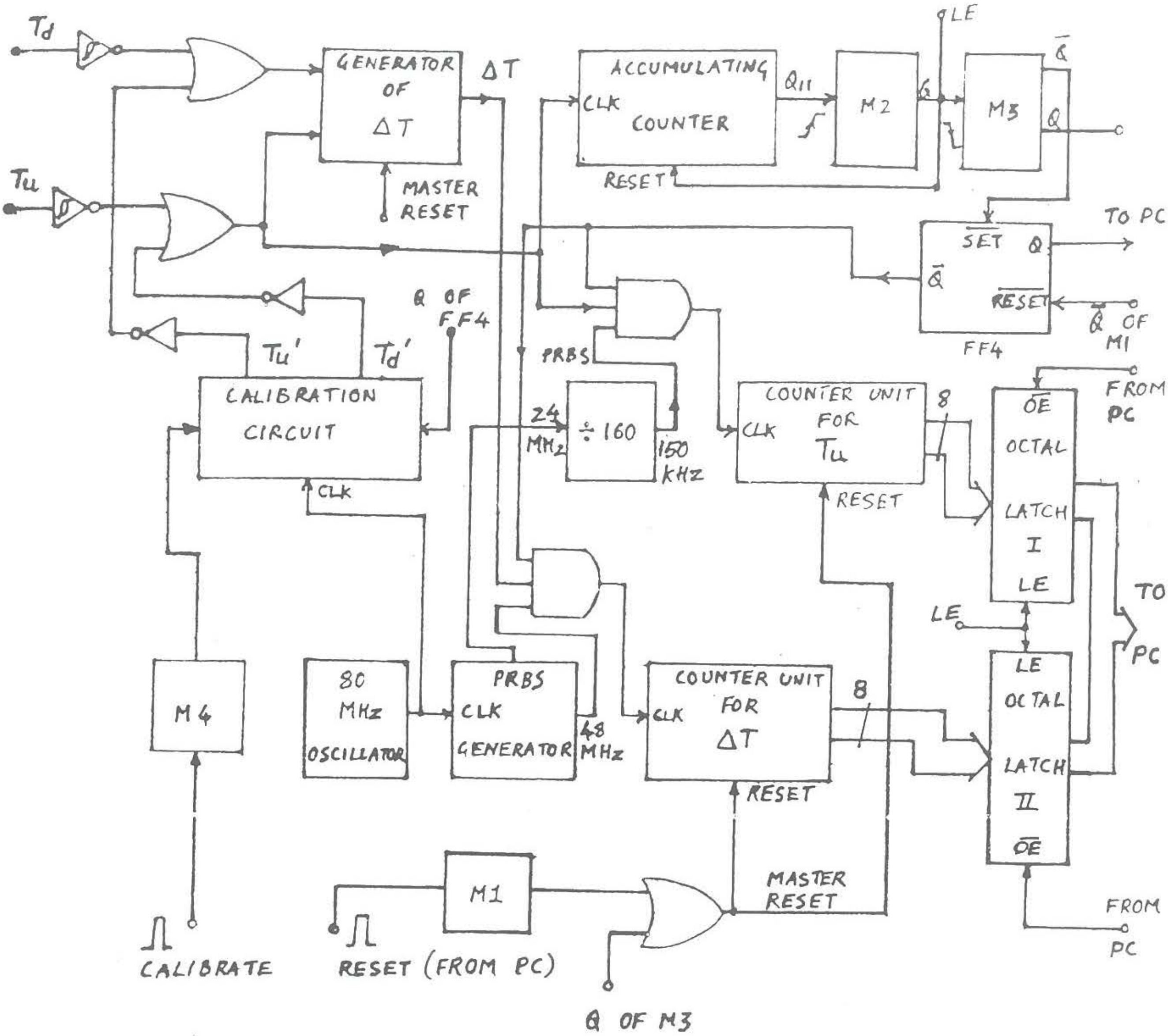


Fig. 3.14. Block diagram of the measurement unit

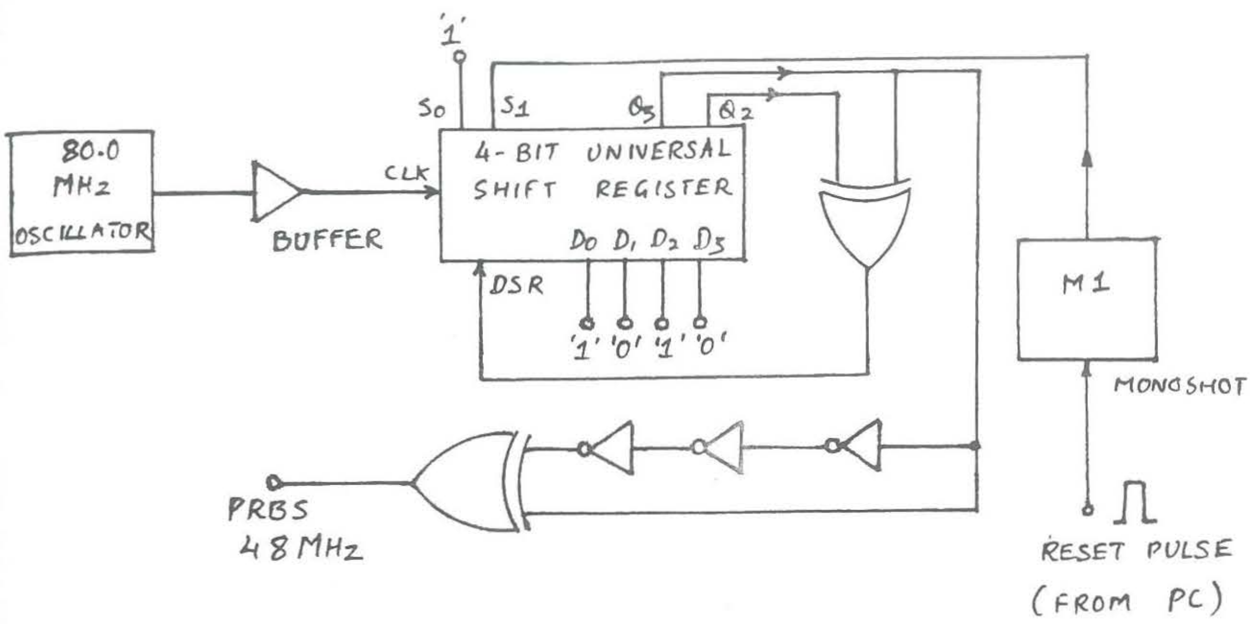


Fig. 3.15. PRBS generation

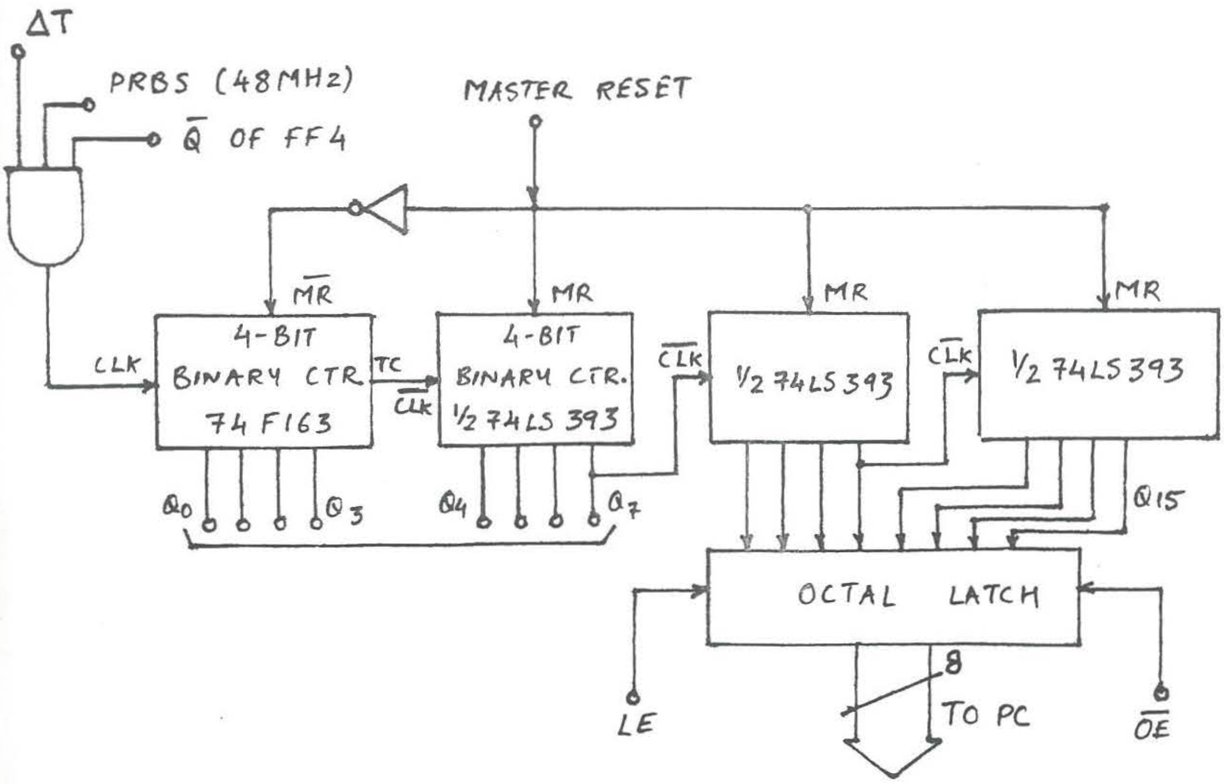


Fig. 3.16. Counter for transit time difference measurement

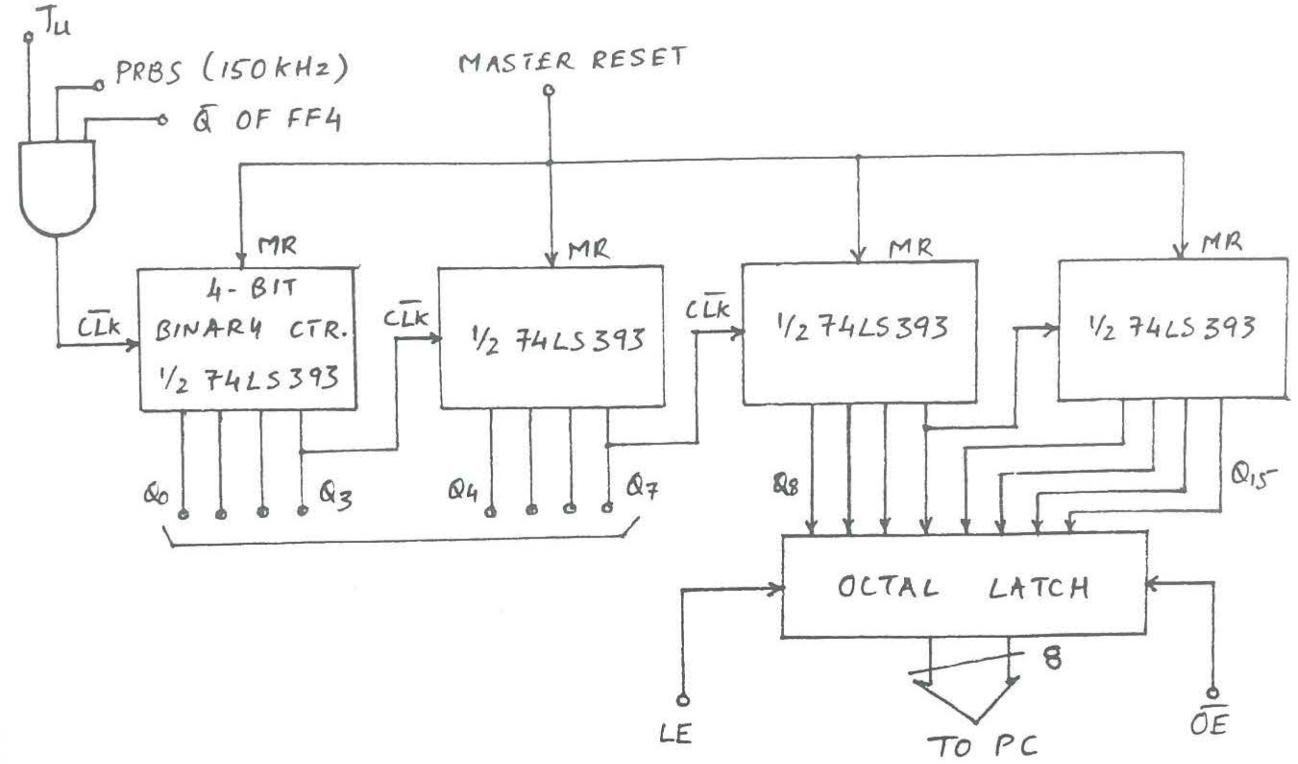


Fig. 3.17. Counter for upstream transit time measurement

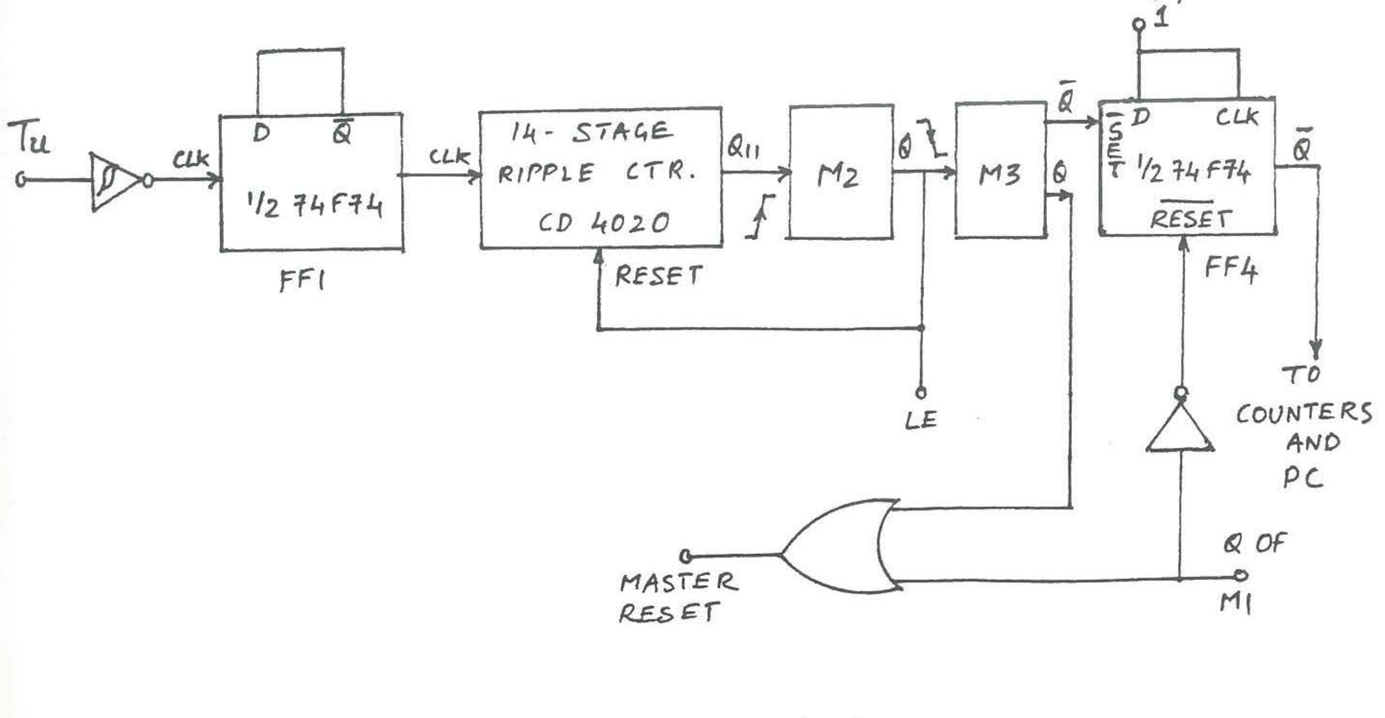


Fig. 3.18. Accumulating counter circuit

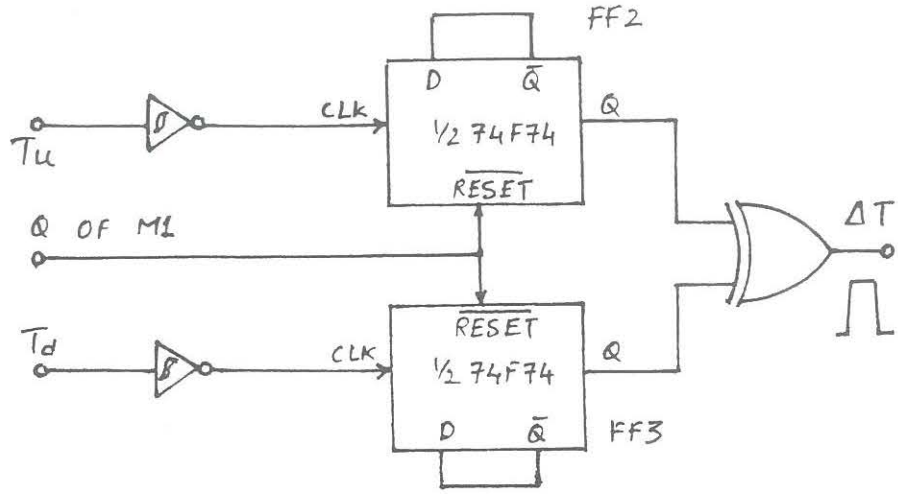


Fig. 3.19. Generation of transit time difference intervals

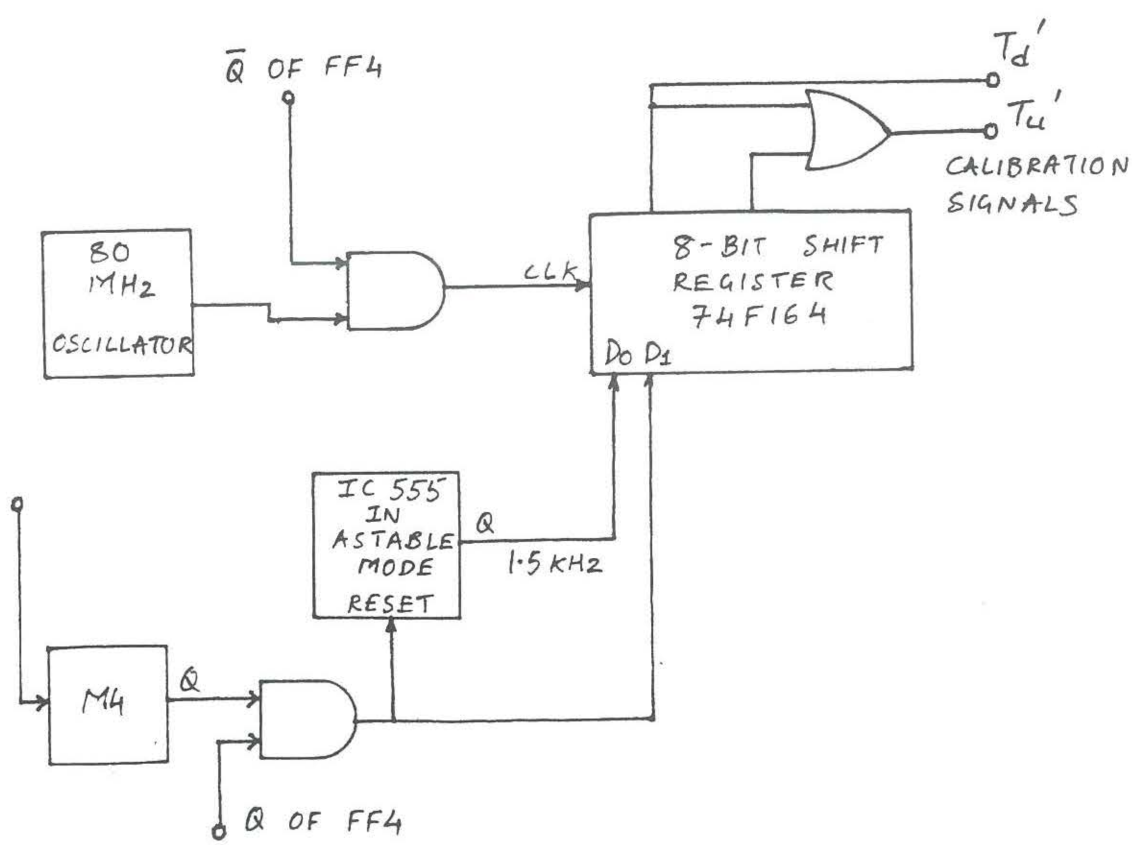


Fig. 3.20. Calibration circuit

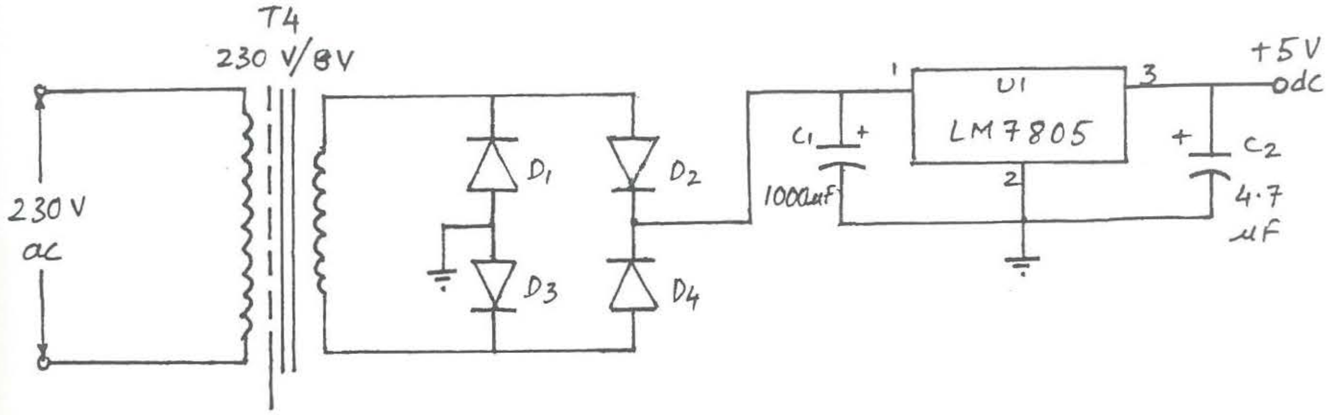


Fig. 3.21. Power supply for the measurement unit

Chapter 4
Experimental Set-up and Results

The experimental set-up for the flowmeter consists of the water circulation system, transducer assembly, electronics, and calibration system. In this chapter the water circulation system, transducer assembly, calibration system and test results of the electronic circuits are discussed. The overall performance of the flowmeter as an instrument is presented later.

4.1 Experimental Set-up

4.1.1 Water circulation system

The experiment set-up for the water circulation system is shown in Appendix C. It consists of a tank, a pump set, and a set of pipes of different diameters, the outlet of which goes back into the tank. The pump delivers a maximum flow rate of 600 lpm. There is a bypass line across the test pipe where the ultrasonic transducers are connected. By adjusting the flow through the bypass line, with the help of valves, the flow through the test pipe can be controlled. A venturi meter has been installed in the test pipe for measuring the actual flowrate.

4.1 2 Calibration system

A calibration system using a venturi meter is employed for calibrating the ultrasonic flowmeter. A U-tube manometer indicates the differential pressure across the venturi tube in mm of Hg. The flow rate corresponding to each differential height can be found out from the calibration curve of the venturi meter. The calibration curve of the venturi meter supplied by the manufacturer is given in Appendix D.

4.1.3 Transducer assembly

The transducers are installed in a set up, as designed by Satish Kumar [9]. Fig. 4.1 illustrates the transducer assembly. The immersion type piezoelectric transducers were held in pipe plugs which can be screwed in threaded yokes fitted to the pipe at an angle of 30 degrees. The distance between the transducers can be precisely adjusted by screwing the plugs. The yokes are stuck to the pipe with epoxy putty and the inner surface of the yokes was roughened so as to minimize sound conduction through the pipe wall. The length of the yoke was kept minimum to reduce the non-flowing liquid part.

4.1.4 Electronic circuits

Initially, the technique, using accumulation of counts over several time-intervals was implemented and tested for the measurement of short time-intervals (30 to 200 ns). PRBSs with different lengths (15, 63, 255 bits) were used as a clock waveform. The graphs of the relationships between the actual intervals and the corresponding counts, for the different PRBSs are shown in Fig. 4.2. It was found that the PRBS clock of length 15 bits (generated using four flip-flops) gave the best results in terms of accuracy. It was also observed that the counts obtained were more stable when the number of repeatedly available intervals were increased. Based on the above implementation the measurement unit was developed. Pulse trains, simulating the upstream and downstream transit times were used to test the working of the measurement unit. The interval between the instants of the falling edges of the two pulse trains corresponded to the transit time difference. The plot of the values of the measured intervals against the actual intervals is shown in Fig. 4.3. The readings of the measured intervals and the actual intervals are tabulated in Table E.1 of Appendix E. The time-intervals are measured on a 100 MHz CRO, with a best resolution of 20 ns/cm. The graph showing the values of the measured 'upstream transit time' at various values of the actual 'upstream transit time' is shown in Fig. 4.4. Table E.2 gives the readings for the 'upstream transit time' measurement. In both measurements, there is a linear relationship between the measured and actual values and the readings are repeatable.

4.2 Test Results

The working of the entire system including the transmitters and receivers was then tested, with the transducer assembly completely dipped in a tank filled with water (zero flow conditions). A circuit was set up to repeatedly provide reset pulses to the measurement unit so that the measurements were made continuously. The counts obtained at the end of each measurement period were displayed using LEDs. Because of alignment problems, in our transducer assembly, it was difficult to obtain equal path lengths in the two transmission directions. Therefore one of the ultrasound beams was received earlier than the other. By varying one of the delays in the receiver circuit it was possible to increase or decrease the transit time intervals as seen by the measurement unit. The variable delays in the receiver circuits were then adjusted, so that at zero flow the obtained upstream transit time interval was slightly longer than the downstream transit time interval. Fig. 4.5 shows the transit time intervals obtained from the receivers, before and after the introduction of the delay.

The transducer assembly was then introduced in the flow path. It was intended that the transit time difference as seen by the measurement unit should be made as short as possible (if not exactly zero) at zero flow, so as to have readings with minimum offset. However it was found that reducing the transit time difference interval at zero flow conditions, to a value less than 200 ns, resulted in instability of the counts obtained for low flow rates (less than 100 lpm). One explanation for the instability, might be the leakage of air into the flowstream. This leads to a severe attenuation of the ultrasound resulting in loss of triggering of the comparators. As the flow rate being measured was varied, it was observed that the counts obtained were not stable. The reason behind this was investigated. It was found that the trigger points on the received signals were not stable with changing flow. These trigger points were located on the first positive-going cycle of the received signals. This was remedied by locating the trigger points at the first negative-going cycle, since it has a stronger peak than the first positive peak. The trigger points for the earlier and later implementations are shown in Fig. 4.6. Another reason for the instability of the count, was the retriggering of the monoshots used for introducing a variable delay in receivers. The comparators were triggered again when the successive negative-going peaks of the received signals were of sufficient amplitude. The monoshots were then retriggered, resulting in pulse-stretching of the monoshot outputs. The monoshots were made non-rettriggerable by connecting the output to one of the inhibit pins.

The flow velocity and flow rate calculations were performed using the following data, pipe diameter = 63 mm.

d = 17.5 cm.

θ = 30 degrees.

We have set the value of ΔT at zero flow = 320 ns. The actual flow rate was determined from the calibration chart of the venturi meter. The upstream and downstream transit times at different flow rates are shown in Fig. 4.7. It can be seen that the upstream transit time increases with the flow rate, while the downstream transit time decreases as the flow rate is increased.

The readings of the actual flow rate and the measured transit time difference and the measured upstream transit time are tabulated in Table 4.1. A plot showing the mean and standard deviation of the measured transit time difference intervals at actual flow rates is shown in Fig. 4.8. The mean and standard deviation of the measured transit time differences have been tabulated in Table 4.2. Fig. 4.8 also shows the plot of the measured flow rates (calculated from the transit time difference intervals) at the actual flow rates. We see that the mean values of the transit time difference measured, change monotonically with the flow rate and the standard deviations are within 2% of the mean value.

It must be noted that the value of the upstream transit time interval measured is more than the actual value because of the deliberate introduction of delay in the receiver. This does not result in a significant error in the calculation of the flow velocity (flow rate) provided that only a minimum delay is introduced in the path of the received signal which traverses a longer path.

It was observed that the flow in the water circulation system was of a pulsating nature. This could have contributed to the distributivity of the counts obtained.

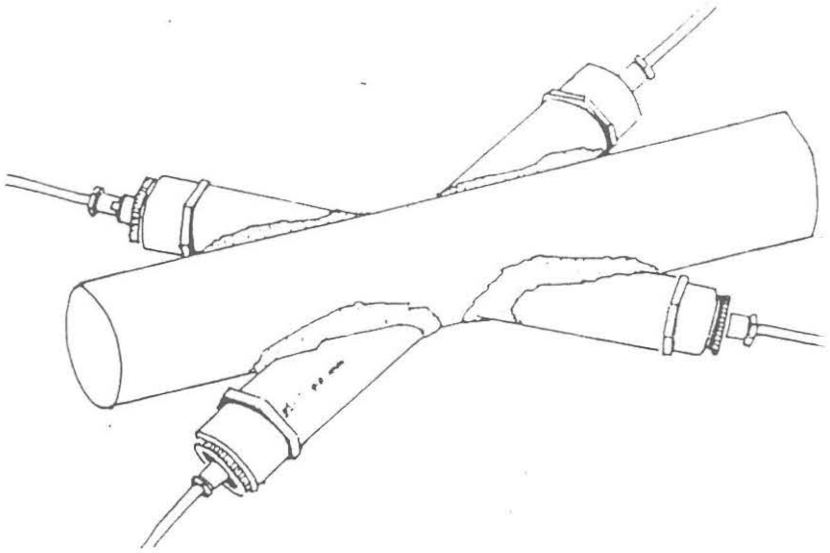


Fig. 4.1. Transducer assembly

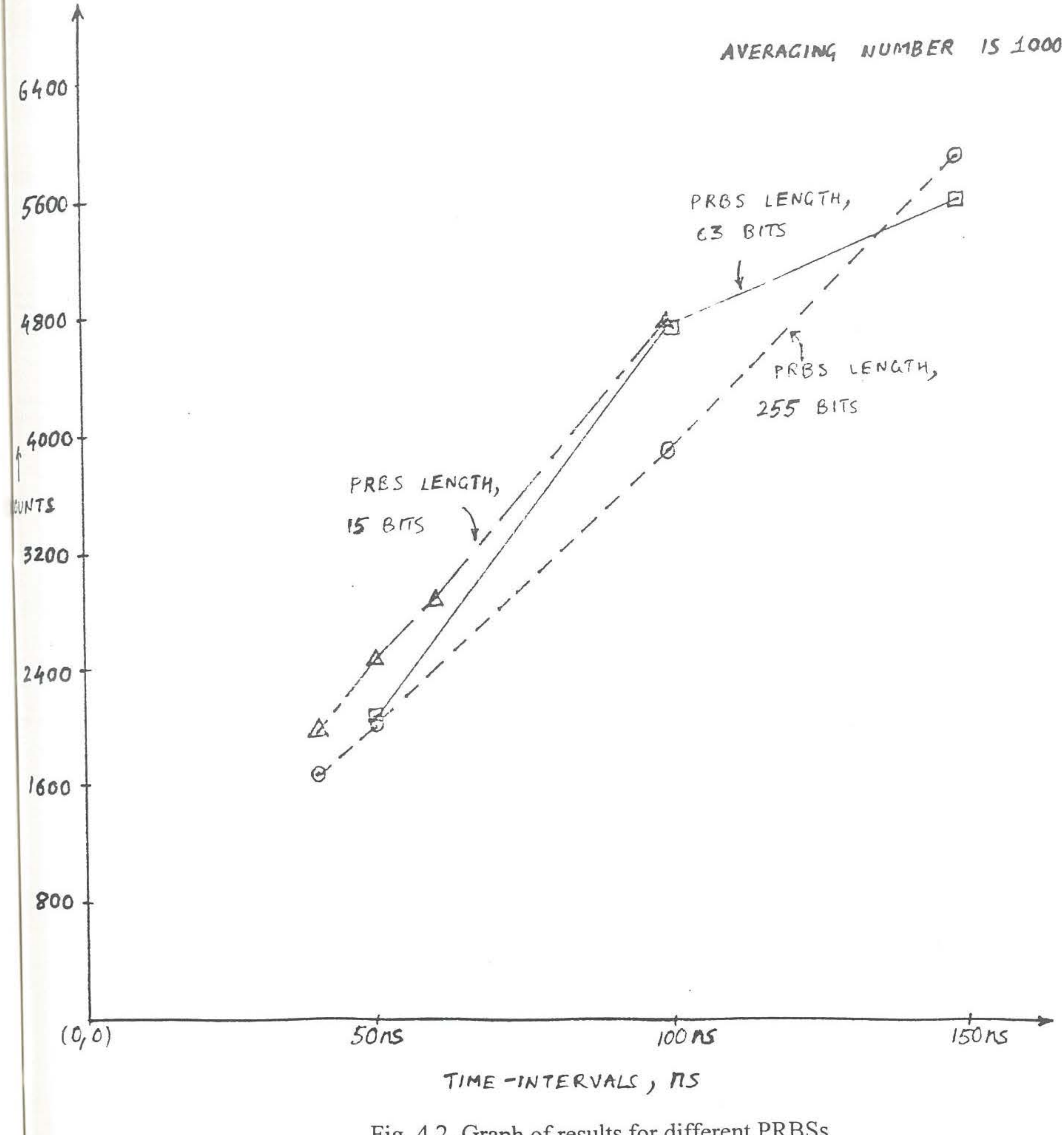


Fig. 4.2. Graph of results for different PRBSs

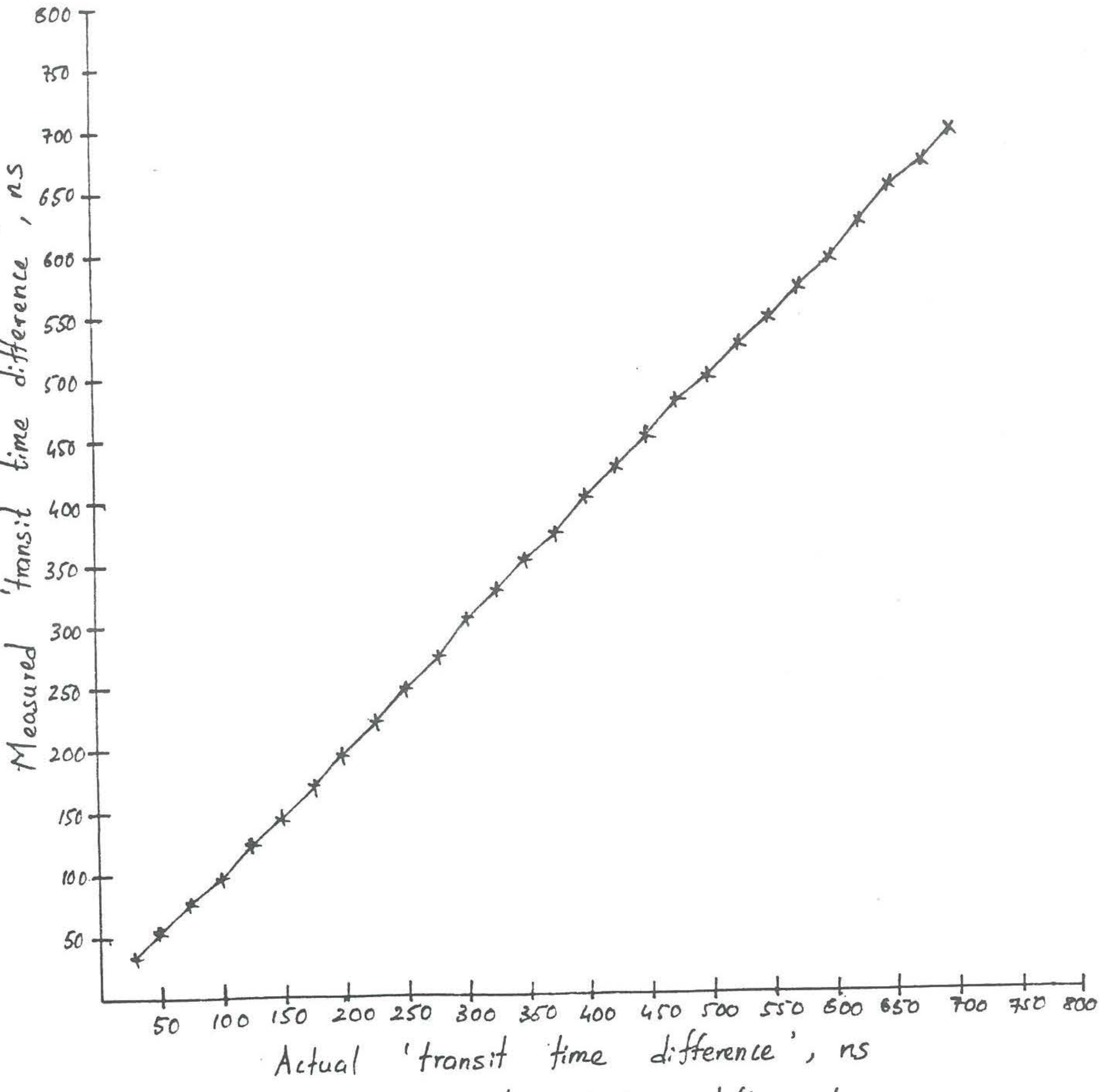


Fig. 4.3. Measured 'transit time difference' vs Actual 'transit time difference'

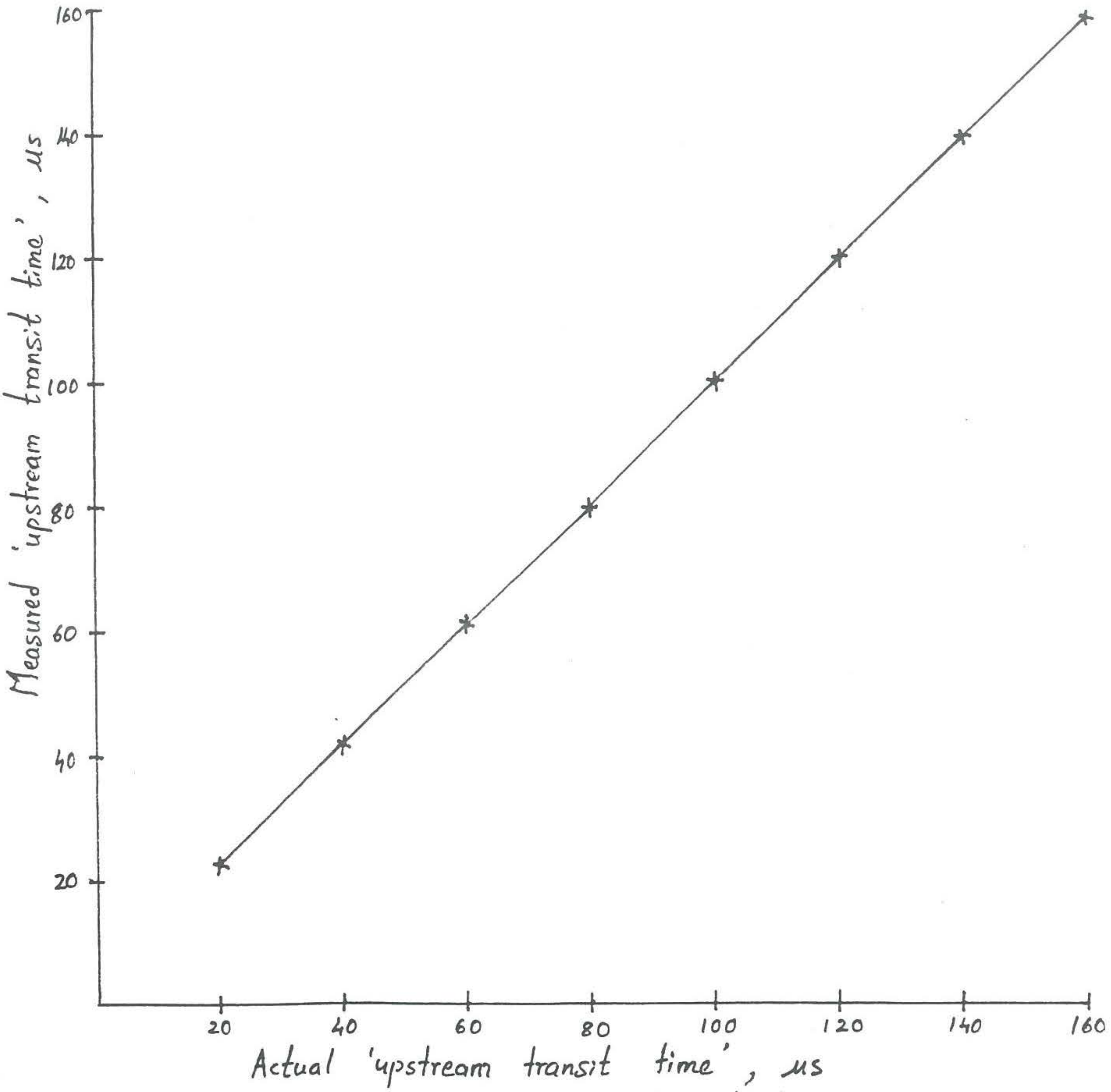


Fig. 4.4. Measured 'upstream transit time' vs Actual 'upstream transit time'.

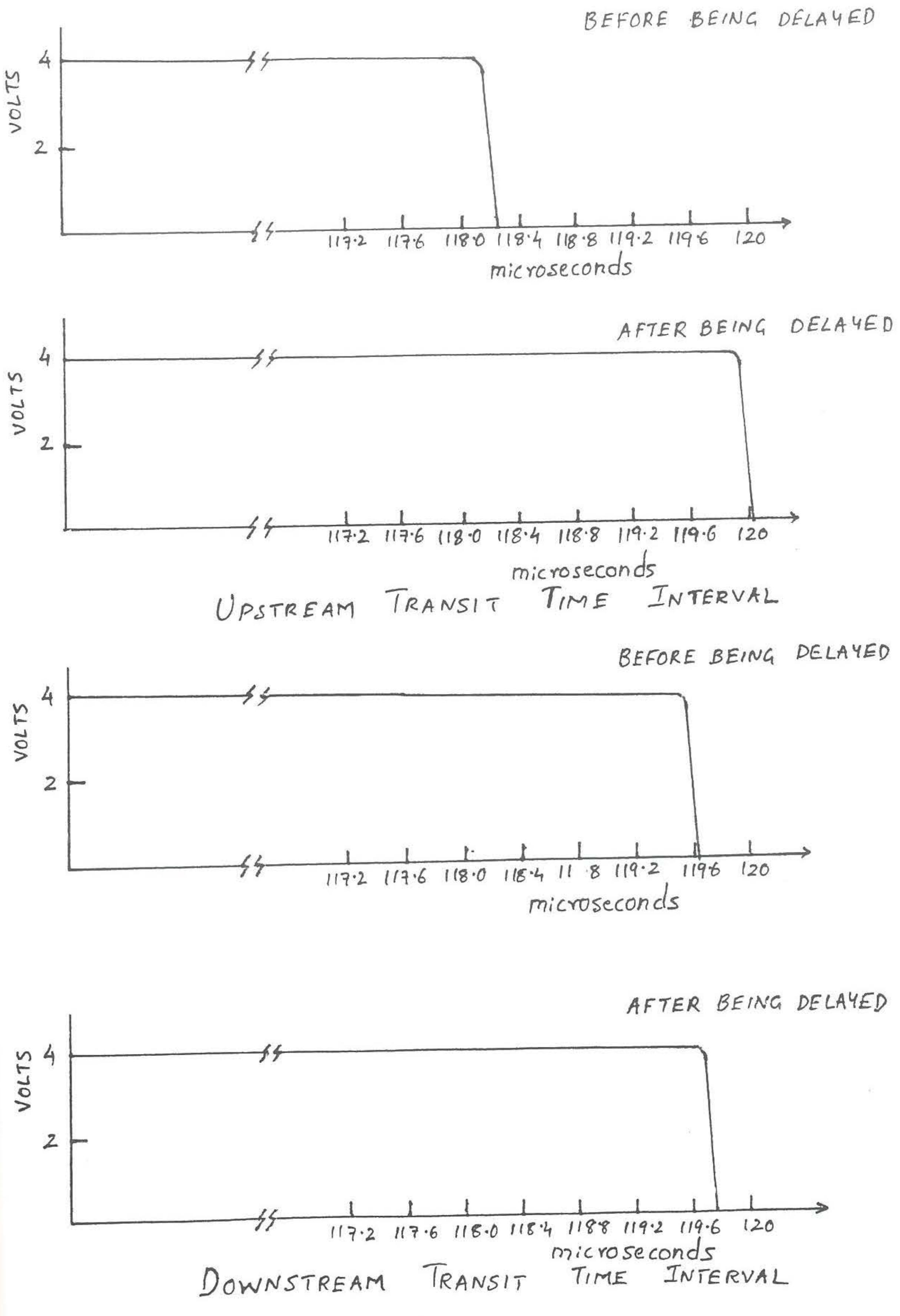
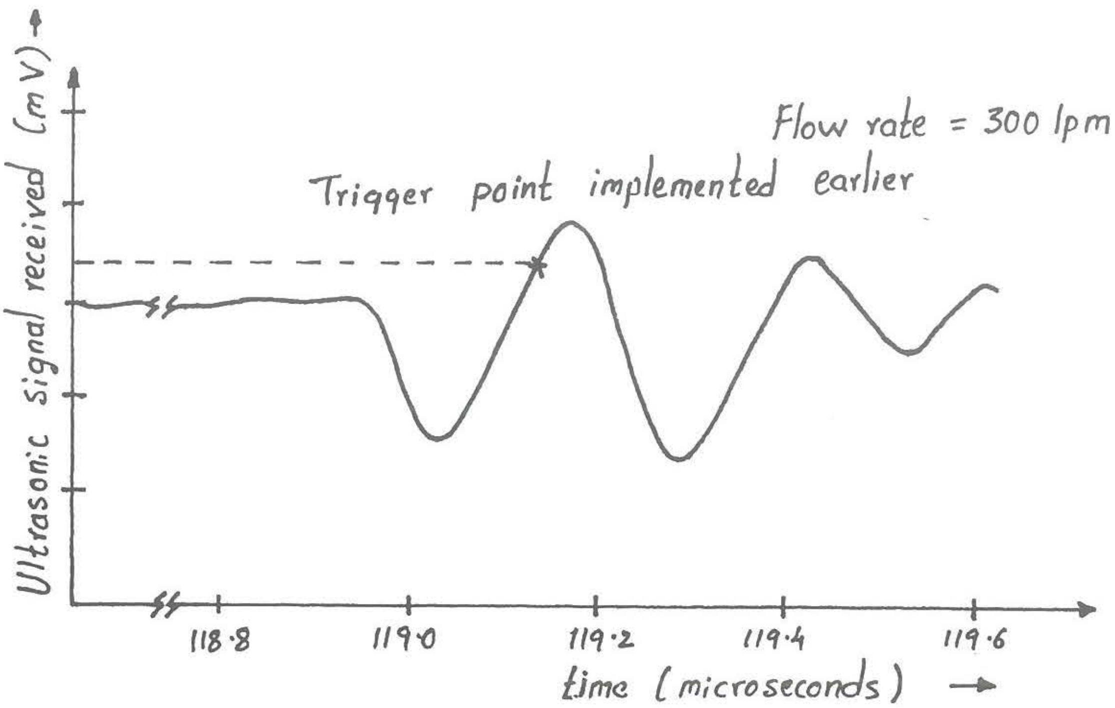


Fig. 4.5. Transit time intervals before and after introduction of delay



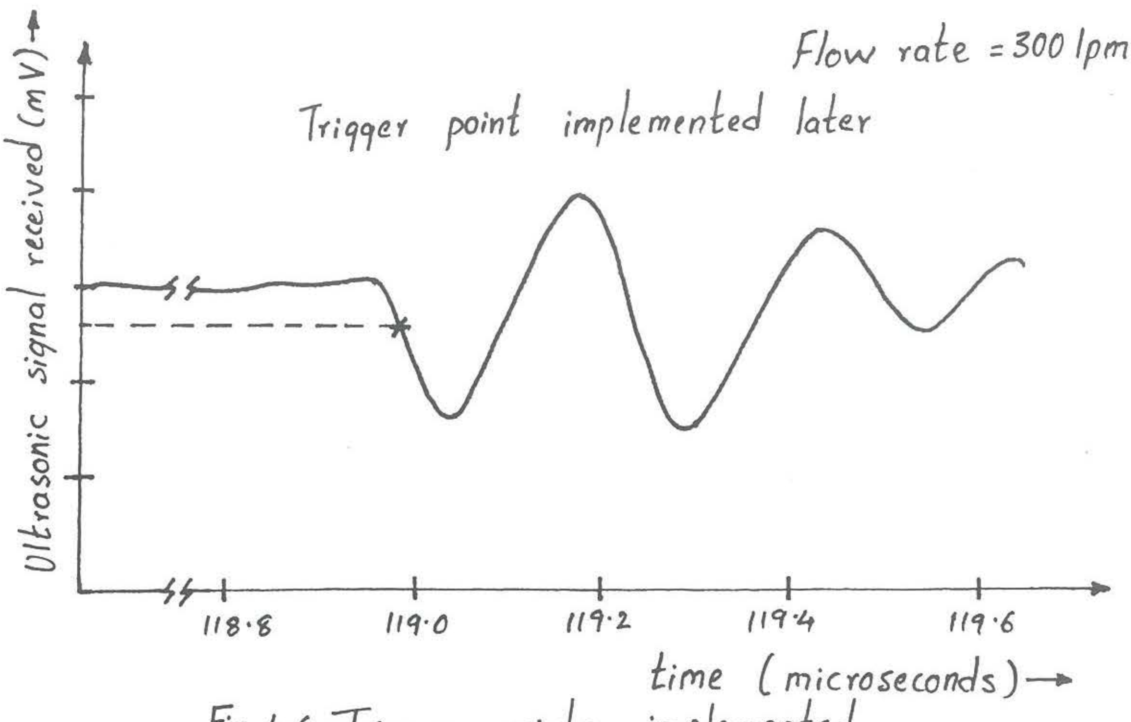


Fig. 4·6 Trigger points implemented

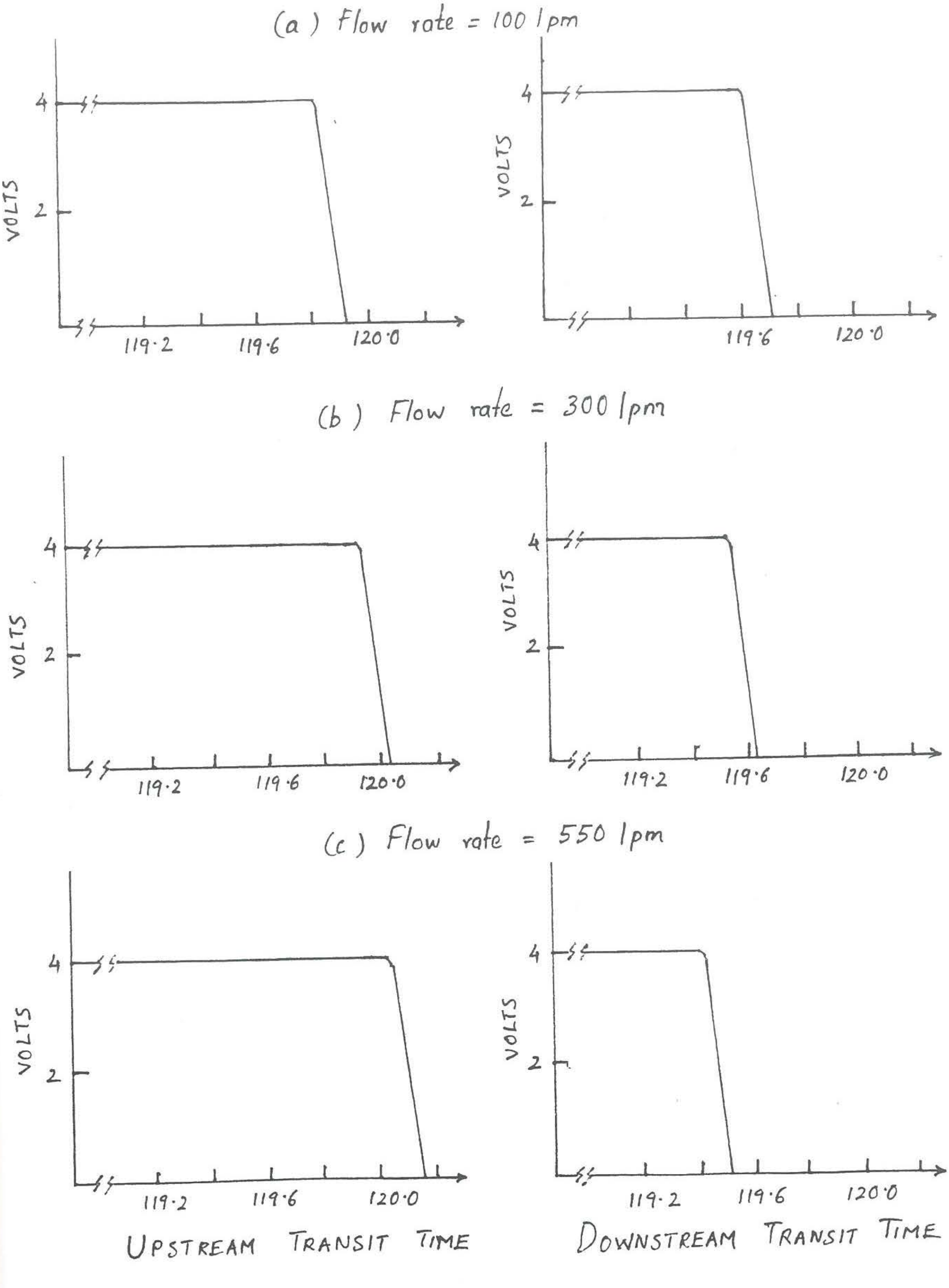


Fig. 4.7. Variation of the transit times with flow rate

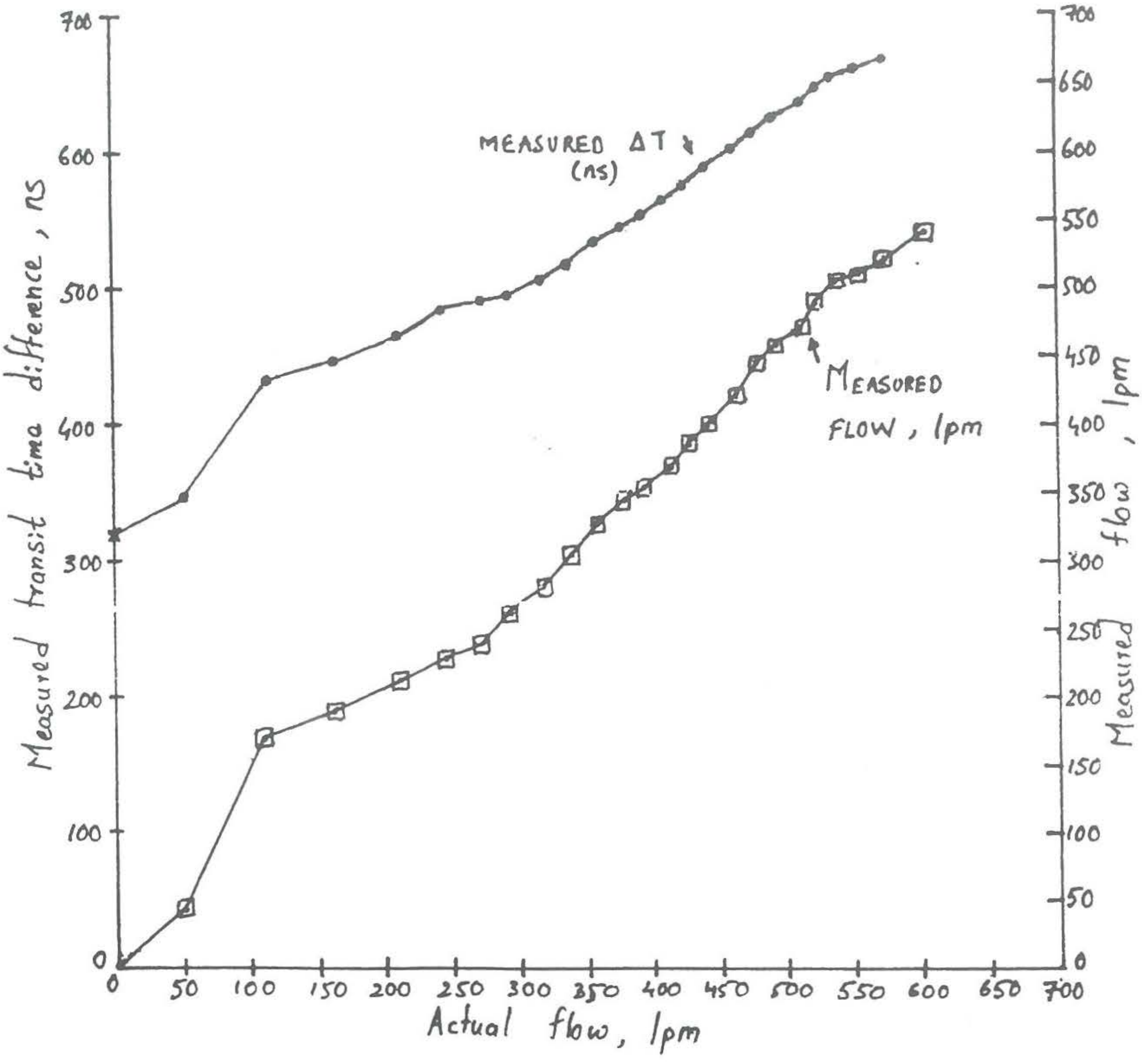


Fig. 4.8. Measured transit time difference and Measured flow rate vs Actual flow rate.

Table 4.1. Actual flow rate vs Measured flow rate

Actual flow rate (lpm)	Measured transit time difference (ns) and standard deviation as percentage of mean (N=10)	Measured upstream transit time (μs)	Measured flow rate (lpm)
0	320.0 (0.00)	119.2	0.0
50	345.9 (1.38)	119.2	39.3
105	433.1 (1.80)	119.2	171.0
160	444.7 (0.62)	120.0	188.9
210	462.1 (0.70)	120.0	215.2
245	473.8 (0.45)	120.0	232.6
270	479.6 (0.42)	120.0	240.8
290	494.1 (0.40)	120.0	263.2
315	508.2 (0.42)	120.0	282.0
335	523.2 (0.38)	120.0	305.3
355	537.7 (0.26)	120.0	327.3
375	549.4 (0.56)	120.0	344.1
390	555.2 (0.28)	120.0	355.7
410	563.9 (0.27)	120.8	367.9
425	578.4 (0.34)	120.8	389.6
440	587.1 (0.33)	120.8	400.2
460	601.7 (0.20)	120.8	423.8
475	616.2 (0.31)	120.8	449.5
490	624.9 (0.45)	120.8	458.0
510	636.6 (0.30)	120.8	472.7
520	648.2 (0.30)	120.8	492.4
535	654.0 (0.37)	120.8	501.6
550	659.8 (0.37)	121.6	509.1
570	668.5 (0.29)	121.6	523.8
600	677.3 (0.29)	121.6	537.0

Chapter 5

Summary and Conclusions

In this project, a technique using accumulation of counts over several time-inetervals has been implemented, and tested for the measurement of short time-intervals. The technique has been applied for the measurement of the difference between the upstream and downstream transit times and a flowmeter based on it has been developed.

FTTL ICs have been used to obtain better resolutions. Variable delays have been introduced in the paths of the transmitted and received signals, to reduce the errors due to the effect of delays in the non-flow liquid parts of the flowmeter and the electronic measuring delays. The amplifiers have a bandwidth of 45 MHz. This wide bandwidth prevents the distortion of the received signals when highly damped transducers of 5 MHz are used.

The actual readings given by the system are far from accurate. This could be due to the effect of non-uniform velocity profile created by obstructions in the pipe, such as valves, bends etc., or lack of perfect turbulence in the pipe. Also, as prior calibration of the venturi meter was not performed, the readings of flow rates obtained from its calibration chart could be erroneous. However, the flowmeter developed gives repeatable results and the relationship between the measured flow rate and the actual flow rate is monotonic. The distribution in the counts obtained could be because of the pulsating nature of the flow in the circulation system. The fluctuations in the flow, can be reduced by having graded pipe sections at the inlet and outlet of the flow. Or, a closed tank could be introduced in the flow path to absorb the fluctuations.

The sound pressure varies inversely with the distance from the source, according to the sound pressure-distance law. This sets an upper limit on the pipe size (for the transducers, amplifier circuit, and the threshold detection used), as 45.4 cms (Appendix F). The space requirements for the mounting of the transducers in the yokes decide the lower limit on the pipe size. For the particular transducers employed, the minimum pipe size is 4 cms. The flowmeter could be tested for different pipe sizes to understand the practical difficulties involved. Also, an assembly for applying the transducers on the outside of the pipe wall could be fabricated to facilitate measurements, without interrupting the existing flow pipe.

The system can be improved by interfacing it to PC or a microcontroller. The necessary calculations could then be automatically performed and the flow values could be immediately displayed. A look-up table approach could be used to obtain better results, in the presence of non-linearities. Also, on-line calibration of the measurement unit could be done if required.

The principal drawback of the developed system is that the delays in the receiver circuits are varied manually, and would vary from system to system depending on the geometry of the transducer assembly. This means that the flowmeter has to be carefully recalibrated whenever there is a change in the relative position of the transducers. Also, frequent calibration of the system may be required due to drifts in the values of resistors and capacitors with age. One solution is to introduce accurately known, stable delays under program control, so that appropriate corrections for the measured transit time difference can be made automatically. A better solution would be to employ a single pair of transducers both serving as transmitters as well as receivers. This scheme does not suffer from the problem of unequal path lengths for the upstream and downstream directions, and therefore no delays are needed to be introduced in the receivers.

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Appendix A

Vernier technique

The vernier technique can measure short time-intervals in the sub-nanosecond range [15]. It employs two clocks of slightly different frequencies f_m (main clock) and f_v (vernier clock) such that the time period T_m, corresponding to the frequency f_m, is slightly larger than the time period T_v, corresponding to the frequency f_v.

The principle is explained for the measurement of time-intervals τ smaller than T_m, with the help of the Fig. A.1. The block diagram of a measurement system using the vernier technique is shown in Fig. A.2. At the rising edge of the time-interval pulse the main clock (oscillator) is started. The vernier clock is started at the falling edge of the time-interval pulse. Since T_v is slightly smaller than T_m, the number of accumulated periods in the stop channel (vernier clock channel) gradually catch up with those in the start channel (main clock channel). The clocks are stopped, when there is a phase coincidence in the two channels. The number of elapsed periods n of the main clock are counted. Then,

$$n.T_m = \tau + n.T_v$$

$$\tau = n(T_m - T_v) = n.\Delta T = \Delta f / f_m.f_v$$

where,

$$\Delta T = T_m - T_v.$$

$$\Delta f = f_v - f_m.$$

Accuracy and resolution of the measurement is high, provided that, f_m, f_v are stable and Δf can be made sufficiently small (1% or less).

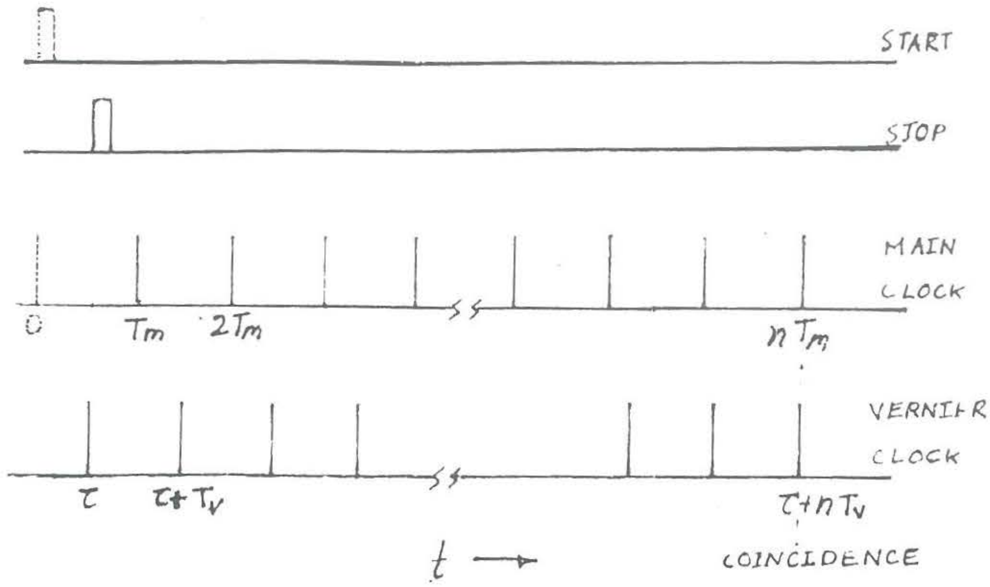


Fig. A.1. Principle of vernier technique

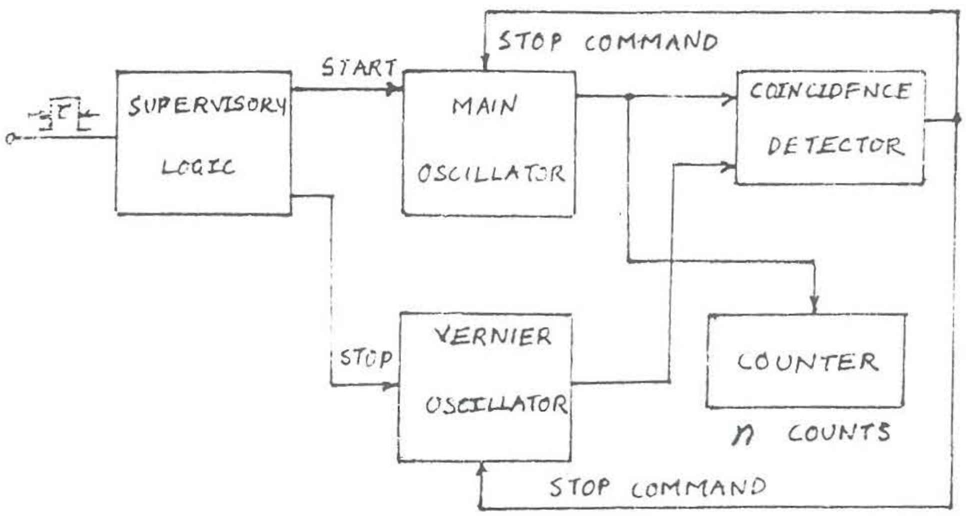


Fig. A.2. Block schematic for vernier technique

Appendix B

Specifications of the system

B.1 Transmitter

Output - Negative spike voltage

Amplitude - 50 to 180 V

Pulse width - !00 to 2000 ns

Input - +12 V pulse of 3 μs minimum width

Damping - 50 to 1050 Ω

B.2 Amplifier

Bandwidth - 0 to 45 MHz

Gain - 0 to 45 dB, variable

B.3 Transducer

Frequency - 5 MHz

Frequency Tolerance - ±10%

Bandwidth - 65 - 100%

Rise time cycles - 1

Decay time cycles - -Instant

B.4 Calibration system

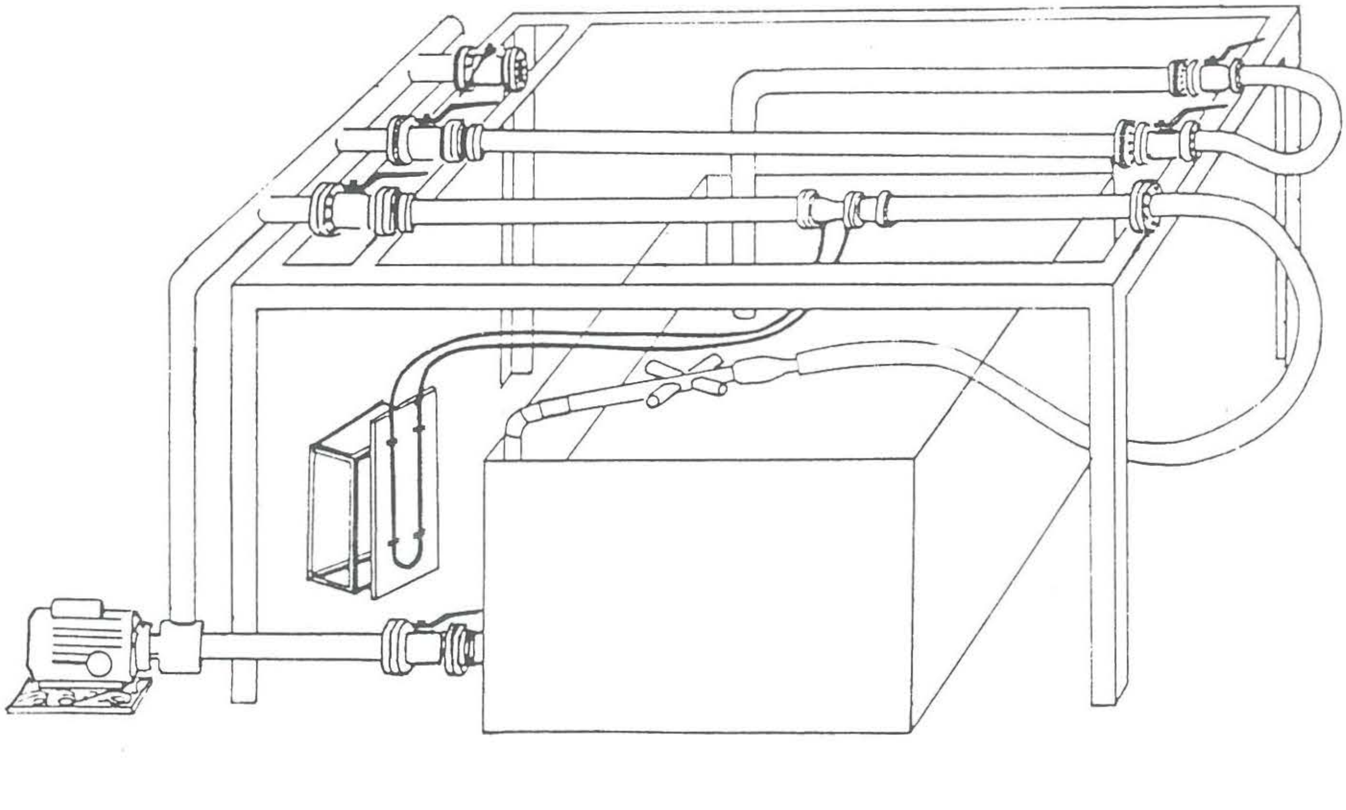
ment used - venturi meter

- 0 to 1500 lpm

acy - 3%

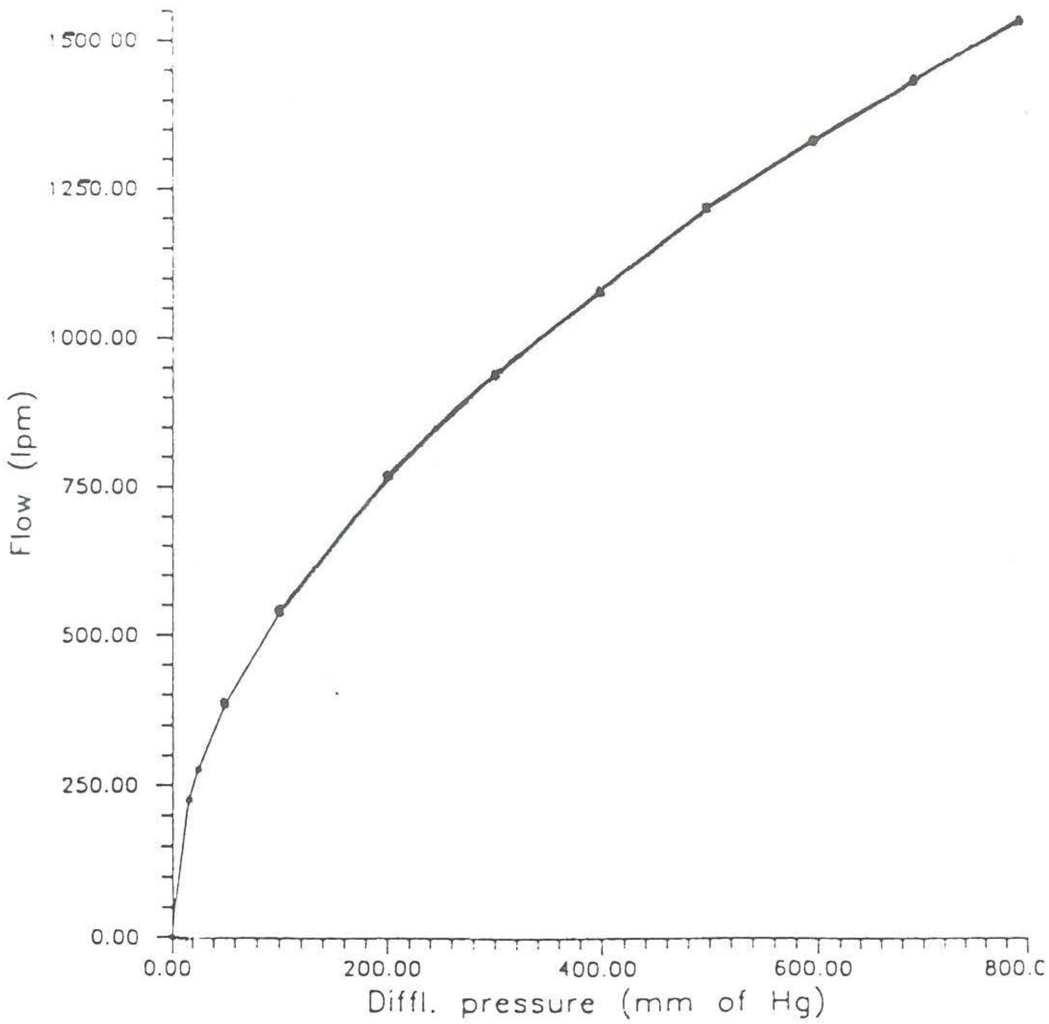
Appendix C

Water Circulation System



Appendix D

Calibration Curve of the Venturi meter



Appendix E

Tables of test data

Table E.1. Actual 'transit time difference' vs Measured 'transit time difference'

Actual 'transit time difference' (ns)	Measured 'transit time difference' (ns)
35	37
50	52
75	75
100	97
125	122
150	145
175	170
200	194
225	222
250	248
275	274
300	301
325	327
350	352
375	374
400	402
425	426
450	450
475	480
500	499
525	525
550	549
575	571
600	594
625	625
650	654
675	672
700	698

Table E.2. Actual 'upstream transit time' vs Measured 'upstream transit time'

Actual 'upstream transit time' (μs)	Measured 'upstream transit time' (μs)
20	22.5
40	42.4
60	61.4
80	80.4
100	100.3
120	120.2
140	139.3
160	158.0
170	169.4
180	180.0

Appendix F

Limitations on Pipe Size

The sound pressure varies inversely with the distance from the source, according to the sound pressure-distance law. This sets an upper limit on the pipe size (for the transducers, amplifier circuit, and the threshold detection used).

For the pipe size used (d = 17.5 cms), it was found that the strength of the received signal (first negative-going peak) at the input to the amplifier was 18 mV. Since the maximum gain of the amplifier is 38 dB, the input signal to the amplifier must have a minimum peak amplitude (for the first negative-going peak) of 6 mV. This is because the signal has to be amplified till the amplifier saturates ($V_{sat} = \pm 4.4$ V). The effect of the attenuation coefficient β = 5.5 dB / m, is small (less than 2.3 dB attenuation in the sound pressure for d = 46 cms) and can be neglected. Hence, according to the sound pressure-distance law, the maximum transducer separation d_{max} is given as,

$$d_{max} = (18 \text{ mV} / 6 \text{ mV}) \times 17.5 \text{ cms} = 52.5 \text{ cms}$$

For θ = 30 degrees, d_{max} corresponds to a maximum pipe diameter of 45.4 cms (with no non-flow liquid part in the yokes).

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