ULTRASONIC FLOW MEASUREMENT

A dissertation
submitted in partial fulfillment of the requirements
for the degree of
Master of Technology

By
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Dissertation Approval Sheet

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Abstract

Sathish Kumar C: Ultrasonic Flow Measurement, *M.Tech. Project Dissertation*, Department of Electrical Engineering, Indian Institute of Technology, Bombay, Jan. 1996.

In applications where the flowmeter should not obstruct the flow, ultrasonic flowmeters are best suited. An ultrasonic flowmeter for single phase liquid flow, based on dual path sing-around technique has been developed by B.P.Parmar as an M.Tech project at IIT Bombay, in 1995. A detailed testing of this system has been done in the laboratory. It was observed that at high flows, the sing-around loop of the system becomes unstable and gives erratic readings. Recording and analysis of the received ultrasonic signal, at various flow rates, has been done and it revealed that the instability is due to the change in relative amplitude levels of the peaks of the signal. As a particular level of the received signal was used for detection, this causes false triggering. A system, with an improved technique for the detection of the received signal, has been developed. In this system, the received signal, amplified to saturation level by two stages of amplification, with a diode clipping circuit in between to filter out any noise and echo signals, is used for detection. Thus small changes in amplitude levels do not cause errors in the detection of the signal. Further modifications have been incorporated in the new system in order to improve the performance. The flowmeter developed, has an accuracy of 5% and is suitable for measurement of liquid flow in the range 0-600 lpm.

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Chapter 1

Introduction

1.1 Overview

Different techniques have been developed over the years for measuring fluid flow. These flowmeters are based on mechanical, differential pressure, electromagnetic and ultrasonic techniques [1]. Different types of mechanical flowmeters are rotameters, positive displacement meters, turbine meters, and miniature Pelton wheel meters. Differential pressure flowmeters include venturi tubes, orifice plates, and nozzles. Mechanical and differential pressure type flowmeters are economical and their measuring techniques are simple, but they provide obstruction to the flow and have poor response to the fast changes in velocity of fluid. In many fluid flow applications, it is required that the flow measurement should not obstruct the flow. Two possible solutions to this are electromagnetic and ultrasonic flowmeters. Electromagnetic flowmeters, although suitable for a wide range of liquids, are unable to measure non-conductive liquids or those with a very low conductivity.

There are three main types of ultrasonic flowmeters: doppler shift, cross correlation, and transit time flowmeters [2]. Doppler flowmeters employ scatterers in the flow to provide the necessary frequency shift of the ultrasonic beam and as such are suited to measurements in liquids in which there are solid particles or gas bubbles to provide the interfaces to scatter the ultrasonic beam. Cross correlation technique is based upon cross-correlation of electrical signals derived from ultrasonic waves which have been modulated by the flow . Cross correlation method has limited accuracy for single phase flow [3]. Transit time flowmeters measure the time difference between ultrasonic beams transmitted upstream and downstream in the liquid, and as such are designed for use with homogeneous fluids.

There are three methods which may be employed to measure the transit times, viz. direct transit time techniques, phase measurement techniques, and sing-around techniques. In these methods, acoustic pulses are transmitted in the fluid at an angle to the flow axis. Direct transit time and phase measurement flowmeters, measure the transit times and phases of ultrasonic signal when it is passed through the fluid. In the sing-around method, the received pulse is used to trigger the transmitter, resulting in a pulse repetition frequency and this frequency gives a measure of the flow. In the dual path sing-around method, pulses are transmitted in both upward and downward directions. In that case, the frequency difference between upstream and downstream transmissions is directly proportional to the flow rate.

1.2 Scope of the Project

As a part of B.R.N.S. sponsored project for developing ultrasonic flowmeters, an ultrasonic flowmeter based on dual path sing-around technique, was earlier developed by B.P.Parmar at IIT Bombay in 1995 [4]. It includes transmitter, amplifier, pulse shaping circuit, a phase coincidence circuit to measure the difference of upward and downward pulse repetition frequencies, and a calibrating system. Hereafter, in this report, the flowmeter developed by B.P.Parmar will be referred to as SAF-1. The basic objective of the present dissertation project was to carry out a thorough testing of SAF-1 and develop a new system, which will have overcome the drawbacks existing in SAF-1.

In SAF-1, ultrasonic pulses are transmitted in upstream and downstream directions. The pulse received at the receiving transducer, after amplification and shaping, is used to trigger the transmitter and this sequence is repeated resulting in a pulse repetition frequency. The difference of pulse repetition frequencies in upstream and downstream directions is found out using a phase coincidence circuit and it is used for the calculation of flow rate.

A detailed testing of SAF-1 was done in the laboratory during the first stage of the project. During testing of SAF-1 it was observed that as the flow increases, the sing around loop becomes unstable and the flowmeter gives erroneous readings. The reason for this was analyzed and it was found that as the flow increases, the waveshape of the received ultrasonic signal changes which causes errors in the detection of exact arrival of ultrasonic signal at the receiving transducer. As the transmitter is triggered on detecting the signal, this causes false triggering of the transmitter. Apart from this, the change in amplitude of the received ultrasonic signal with flow, also causes a shift in triggering point. These undesired shifts in triggering point contribute errors. Moreover, the delay introduced in electronic circuits and non-flowing liquid part of the acoustic path, affects the accuracy of the system.

A new flowmeter based on sing-around principle, with an objective to overcome the problems faced in SAF-1, has been developed. In this report, this flowmeter will be referred to as SAF-2. An improved technique for detecting the arrival of received signal, which would be effective even in the presence of change in waveshape, has been used in SAF-2. To reduce errors due to delay occurring in electronic circuit, high speed ICs have been used in the circuit. A new set up for installing the transducers, such that the non-flowing liquid part of the system is minimized, was developed.

The transmitter and amplifier circuits of SAF-1 were not ideally suited for the application. An amplifier and transmitter, with vastly improved performance, have been designed and developed, for SAF-2.

Any obstructions in the liquid might cause a temporary loss of sing around, and would result a jitter in the pulse repetition frequency. To eliminate the effect of this jitter, a low pass filter is incorporated at the output of the phase coincidence circuit.

1.3 Outline of the Dissertation

Different types of flowmeters developed over the years have been explained in Chapter 2. They are transit time, doppler shift, and cross correlation flowmeters. Chapter 3 provides the details of SAF-1, a discussion on the its test results, and scope of improvement of its performance. The details of modifications incorporated in SAF-2 to overcome the drawbacks of SAF-1 are presented in Chapter 4. Chapter 5 deals with the experimental set-up and the test results of SAF-2. Finally, the summary of work done, along with some suggestions for further improvements, are discussed in Chapter 6.

Chapter 2

Ultrasonic Flowmeters

Ultrasonic flowmeters measure the velocity of a flowing medium by monitoring the interaction between the flowstream and ultrasonic waves transmitted through it. As the ultrasonic transducers can be mounted outside the pipe, it causes no mechanical obstruction to the flow. Since the measurements can be made completely non-intrusively, ultrasonic flowmeters are of particular importance, when flow of chemically active or abrasive liquids is to be measured. As the price tends to vary little with pipe size in contrast with most other meters, from the point of view of cost also, it is attractive. Apart from this, it offers fast response, wide dynamic range, inherent bidirectionality, and better accuracy.

Ultrasonic flowmeters can be classified into three, (a) Doppler frequency shift type, (b) Cross correlation type, and (c) Transit time type. Different classes of ultrasonic flowmeters, with special emphasis to transit time flowmeters, are discussed in this chapter.

2.1 Doppler Frequency Shift Flowmeter

These flowmeters employ scatterers within the fluid such as air bubbles or solid particles to produce frequency shift in the transmitted ultrasonic wave [2], [5]. This frequency shift gives a measure of the fluid velocity. Fig. 2.1 describes the principle of doppler frequency shift flowmeter.

The doppler frequency shift,

$$\Delta f = 2\, f_t \; sin\,(\phi) \;\; \frac{v}{c} \tag{2.1}$$

where f_t is the transmitted frequency, ϕ is the angle of entry of the ultrasonic wave in fluid, v is flow velocity, and c is the sonic velocity of fluid.

As it is essential that the liquid being measured have sonically reflective particles, doppler flowmeters are not suitable for clear fluids.

2.2 Cross Correlation Flowmeters

This class of ultrasonic flowmeters are based on cross correlation of electrical signals derived from ultrasonic waves which have been modulated by the flow [3], [6].

Turbulent flow systems can be regarded as consisting of a large number of naturally occurring disturbances moving with the stream. As fluid proceeds through pipe, the local velocity at a given point fluctuates in a random manner. If two closely spaced points along a given pathline are selected to observe such fluctuations, it is found that some degree of correlation exists between the two instantaneous velocities. The degree of correlation decreases as the distance between the observation points increases.

Let the signal recorded at point A in Fig. 2.2 be $x(t)$ whose instantaneous value is directly related to the instantaneous disturbance at A and similarly, $y(t)$ is a signal directly related to the instantaneous disturbance at point B, points A and B lying along the same pathline. The cross correlation function $\psi_{xy}(\tau)$ of $x(t)$ and $y(t)$ in terms of a delay τ is given by

$$\psi(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)\, y(t+\tau)\, dt \qquad (2.2)$$

If all turbulent disturbances produce similar signals at A and B, and all spectral components of these disturbances are transported at the same velocity, the maximum value of $\psi(\tau)$ occurs at a value of τ corresponding to the transit time of turbulent disturbances between points A and B. If d is the spacing between A and B, the velocity of flow v is given by

$$v = \frac{d}{\tau_m} \qquad (2.3)$$

where τ_m is the value of τ corresponding to the peak value of $\psi(\tau)$.

2.3 Transit Time Flowmeters

Transit time flowmeters measure the transit time of an ultrasonic beam transmitted across the flow in upstream or downstream direction as shown in Fig. 2.3. There are three methods which are widely employed to measure the transit time.

(a) direct transit time technique,
(b) phase measurement technique, and
(c) sing-around technique.

2.3.1 Direct Transit Time Measurement

If ultrasonic pulses are transmitted in upstream direction the transit time interval of the wave, t_{up} is given by

$$t_{up} = \frac{d}{c - v\cos\theta} \qquad (2.4)$$

where d is transducer separation.

v is velocity of fluid,

c is acoustic velocity in fluid, and

θ is the angle of fluid velocity with respect to the ultrasonic beam.

For downstream transmission, the time of travel t_{dn} is

$$t_{dn} = \frac{d}{c + v \cos\theta} \tag{2.5}$$

Using up or down transmission, velocity of fluid, v can be calculated. But in this method, the measurement sensitivity is less. So as a further development, the ultrasonic signals are transmitted in upstream and downstream directions simultaneously and the difference of transit times is found out.

$$\Delta t = t_{up} - t_{dn} = \frac{2\, v\, d \cos\theta}{c^2 - v^2 \cos^2\theta} \tag{2.6}$$

Since $(c^2 \gg v^2 \cos^2\theta)$,

$$\Delta t = \frac{2\, v\, d \cos\theta}{c^2} \tag{2.7}$$

Eqn. 2.7 shows dependence of Δt on c^2. As the velocity of sound varies with temperature, pressure, and density, velocity of sound compensation is essential in this method for accurate flow measurement. *J. Appel et al.* [7] suggested the following method to eliminate the effect of c on v.

From Eqns. 2.4 and 2.5,

$$\frac{t_{up} - t_{dn}}{t_{up}\, t_{dn}} = \frac{2\, v \cos\theta}{d} \tag{2.8}$$

$$v = \frac{d}{2 \cos\theta} \left[\frac{t_{up} - t_{dn}}{t_{up}\, t_{dn}} \right] \tag{2.9}$$

In Eqn. 2.9, v is independent of c.

2.3.2 Phase Measurement Technique

In phase measurement technique, phase of the acoustic wave travelling upstream or downstream, between the two transducers is measured. If the fluid is stationary, the phase corresponds to the sound speed in the fluid. However, if the fluid moves, the phase will change indicating a change in apparent sound speed in the fluid.

Let the transmitted signal be

$$V = V_m \sin(\omega t) \tag{2.10}$$

The change in phase angle of the received signal, compared to the transmitted signal, will be $\omega d / (c \mp v \cos\phi)$. The difference of the phase changes in upstream and downstream directions, $\Delta\phi$ is

$$\Delta\phi = \frac{\omega\, d}{c - v \cos\phi} - \frac{\omega\, d}{c + v \cos\phi} \approx \frac{2\, \omega\, d\, v \cos\phi}{c^2} \tag{2.11}$$

From Eqn. 2.11, velocity of fluid can be calculated.

Thus the phase comparison of received acoustic signals in the upstream and downstream directions, gives the velocity of fluid. But as $\Delta\phi$ is dependent on c, compensation for changes in velocity of sound is essential in this technique.

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

The phase measurement technique suffers from the problem of phase ambiguity since if $\Delta\phi \gg 2\pi$, the phase difference is no longer unique. This places restriction on the pipe sizes and velocities over which this technique can be used. Also, if there is any acoustic coupling between the transmitting and receiving transducers through pipe walls and housing, addition of the wave received thus with the wave travelled through water causes undue phase change, causing error in the reading.

2.3.3 Sing-around Technique

In the sing-around method [5], [9] ultrasonic pulses are transmitted through the fluid at an angle to the flow axis. The received pulse is used to trigger the transmitter, resulting in a pulse repetition frequency (prf). When the pulses are transmitted in upward direction, prf is

$$f_{up} = \frac{c - v\cos\theta}{d} \tag{2.12}$$

In downward transmission, prf is

$$f_{dn} = \frac{c + v\cos\theta}{d} \tag{2.13}$$

In both Eqn. 2.12 and Eqn. 2.13, velocity of fluid, v is dependent on c. This dependence of v on c can be avoided by finding out the difference between f_{up} and f_{dn} [10]. The frequency difference between f_{up} and f_{dn},

$$\Delta f = \frac{2v\cos\theta}{d} \tag{2.14}$$

Thus the measured value of v becomes independent of changes in acoustic velocity of fluid, c.

2.4 Various Types of Sing-around Flowmeters

Various types of sing-around ultrasonic flowmeters have been developed over the years. Some of them are described below.

2.4.1 Flowmeter with Single Transmission Path

A flowmeter with measurement of flow and automatic recording was developed by *M. Greenspan & C.E. Tschieg* [9]. The block diagram of the system is given in Fig. 2.4. In order to define uniquely the time difference between the pulses, the pulse position is specified by the instant at which the received signal begins to rise from noise.

In this system, pulse repetition frequency is measured for either upward or downward transmission only. So the accuracy is affected by changes in acoustic velocity. The system needs calibration for the particular class of liquids with which it is to be used.

2.4.2 Dual Transmission Path Ultrasonic Flowmeter

Dual path flowmeter developed by *A.E. Brown* [10] overcomes the drawback of the previous one. Ultrasonic waves are transmitted in both upstream and downstream directions. The difference in pulse repetition frequencies is calculated. This difference is independent of changes in acoustic velocity of the liquid. This flowmeter additionally provides an output that is proportional to the actual speed of sound in fluid.

$$f_{up} + f_{dn} = \frac{2c}{d} \qquad (2.15)$$

So by calculating $(f_{up} + f_{dn})$ value of c also can be found out.

Block diagram of another system reported by *Forgacs* [11] is shown in Fig. 2.5. The transmitter is triggered initially by means of a start button. The acoustic signal is launched into the sample, strikes the opposite face, and is reflected a number of times before being completely attenuated. A train of electrical signals is generated by the receiving quartz crystal. The echoes are amplified, then passed into selection circuit which is controlled by an adjustable gate to permit a selected cycle of an echo to pass through. The gated signal retriggers the transmitter and the sing-around cycle repeats indefinitely. As the ratio of acoustic-to-electronic delay is increased, errors due to electronic delay variations becomes less important.

2.4.3 A Narrow Band Sing-around System

In this method, an ultrasonic pulse of narrow bandwidth (quasi continuous wave) is transmitted through the fluid and the triggering of the succeeding pulse is obtained from a pre-selected zero crossing of the received signal [12].

Sufficiently long tone bursts were used for excitation of the transmitter element to ensure that the structure of the radiated field was essentially that produced under continuous wave conditions. Fig. 2.6 shows the timing diagram of the system. The sing-around loop was retriggered by counting up the number of zero crossings in the received signal until a pre-selected number was reached and then generating a retriggering pulse. By including a highly stable delay in the sing-around loop, the reverberations were allowed to die away before a fresh transmitter excitation was initiated.

The advantage of this technique stem from the avoidance of the problems involved in the conventional use of short pulses (broad-band), which are particularly acute in high dispersive area. The use of quasi continuous wave ensures stability of the sing around loop as the sing-around is not lost even when a particular peak of the received signal is missed due to some changes in amplitude levels. But the accuracy will be affected in that case.

2.4.4 Two Pulse Phase Comparison Technique

One of the major difficulties experienced by sing-around technique is that any obstruction between transmitter and receiver will cause errors in the sing-around frequency. *Hoene* [13] has described a technique by which this problem can be eliminated. This technique, known as the two pulse phase comparison technique, is described below.

Fig. 2.7 shows the sing-around flowmeter using the two pulse phase comparison technique. The sing-around pulses are generated by division of the output of a voltage controlled oscillator. The train of pulses generated by transmission of ultrasonic signals through the fluid is phase compared with the output of the voltage controlled oscillator. Depending on which arrives first, the voltage controlled oscillator is incremented or decremented. A similar system operates in the other direction. In the absence of a received signal, the output of the the voltage controlled oscillator is maintained at its previous value. In this way, it has been claimed that only 2% of the pulses need be received in order to achieve the required accuracy. Thus this method eliminates any error due to obstruction of ultrasound from transmitter to receiver.

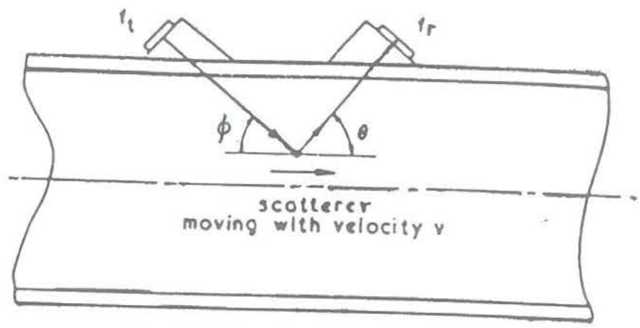


Fig. 2.1. Principle of doppler frequency shift flowmeter

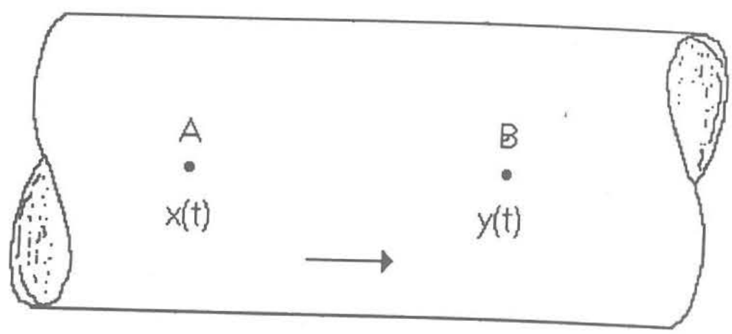


Fig. 2.2. Principle of cross correlation flowmeter

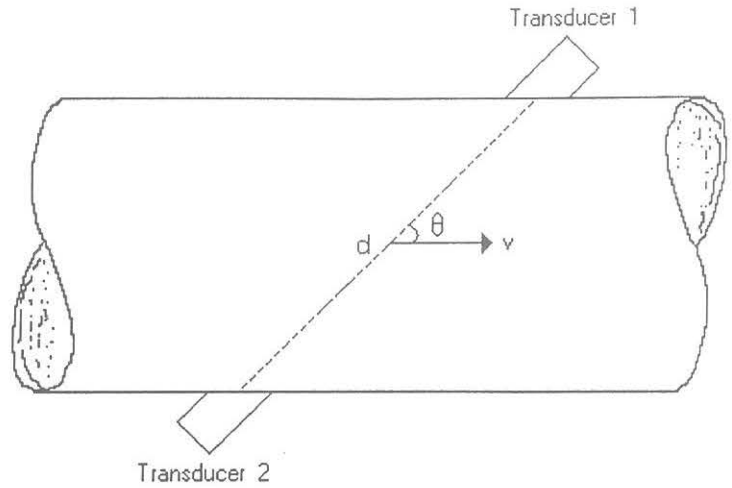


Fig. 2.3. Transducer arrangement in a transit time flowmeter

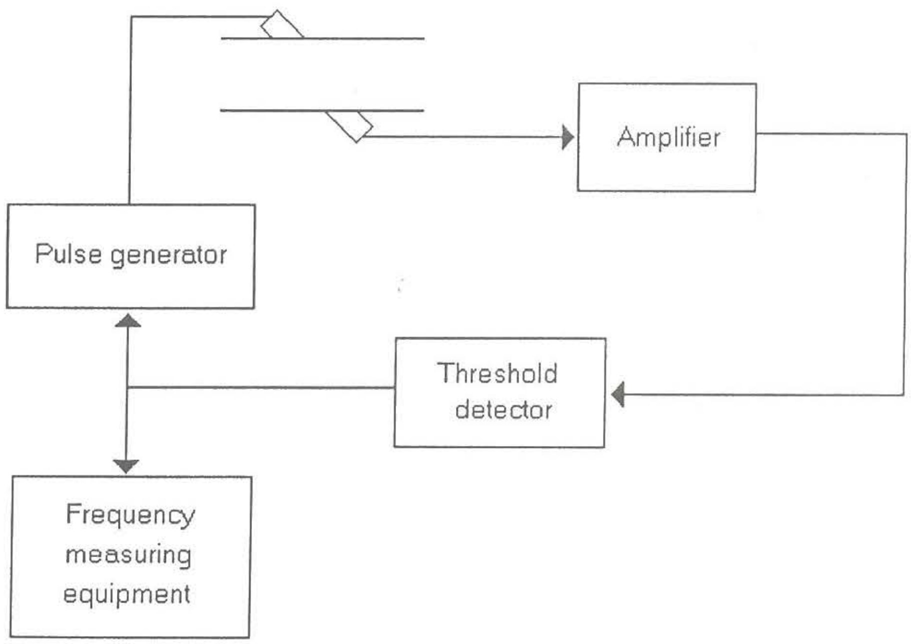


Fig. 2.4. Block diagram showing sing-around principle

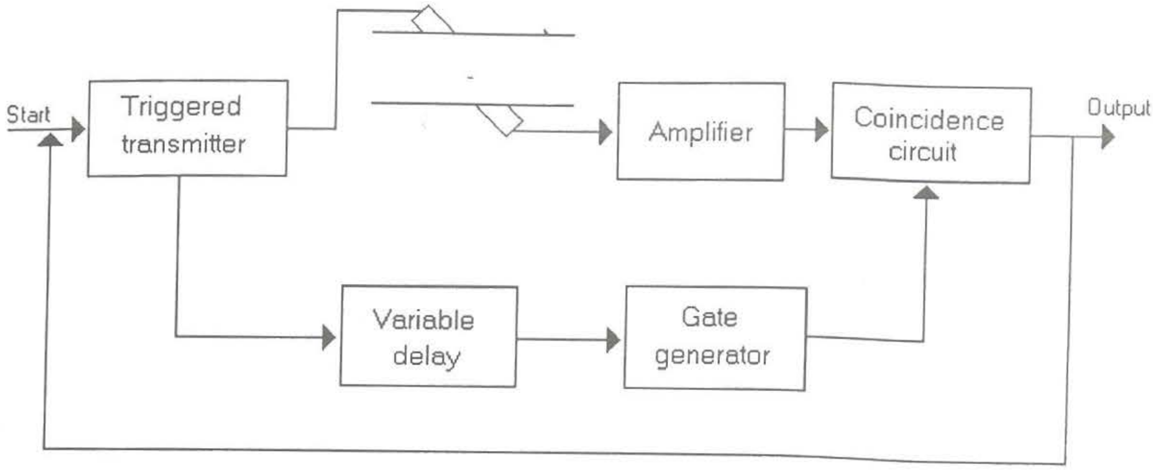


Fig. 2.5. Sing-around system developed by *Forgacs*

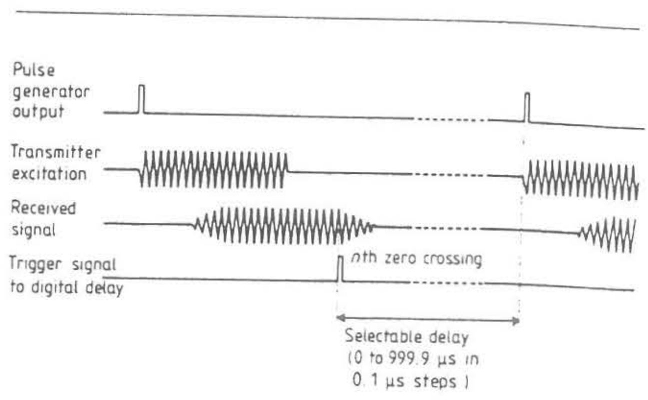


Fig. 2.6. Timing diagram of the narrow-band sing-around system

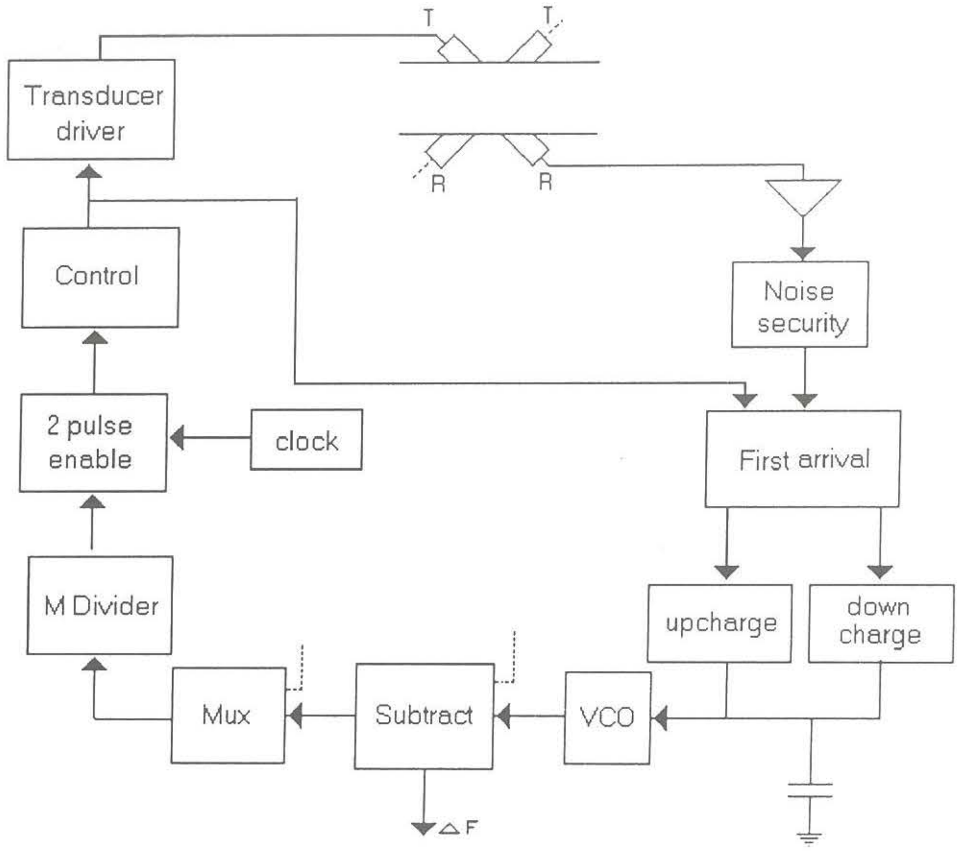


Fig. 2.7. Two pulse phase comparison method

Chapter 3

Sing Around Ultrasonic Flowmeter, SAF-1

The ultrasonic flowmeter developed by B.P.Parmar [4], referred to as SAF-1 in this report, measures single phase liquid flow through a closed pipe using dual path sing-around technique. A detailed testing of the system has been done in the laboratory. A discussion on the hardware and measurement set up of this flowmeter is given in this chapter. Test results and scope of improvement of its performance are also discussed.

3.1 Description of SAF-1

The block diagram of SAF-1 is shown in Fig. 3.1. Piezoelectric crystals with a frequency of 2.2 MHz are used as transducers. Two pairs of transducers are used to transmit the ultrasonic signals in upstream and downstream directions. A transistor pulser circuit is used to excite the pulsed type ultrasonic transducer. The received signal is amplified and a fixed instant of the amplified signal is used to trigger the transmitter. A monostable and a differentiator circuit are used to generate sharp edge pulses to trigger the transmitter. The difference between the upstream and downstream sing-around frequencies is measured with a phase coincidence circuit, which is used to calculate the liquid flow. The actual flow is found out using a calibration system.

3.1.1 Amplifier

As the ultrasonic wave emitted from the piezoelectric crystal passes through the liquid, it gets attenuated. A transistor single stage RC coupled amplifier is used to amplify the received signals. It has a bandwidth of 4.4 MHz. A pre-amplifier (Model D1000) is used to amplify the received signal before feeding it into the RC coupled amplifier. Amplifier output is fed to the pulse shaping circuit.

3.1.2 Pulse Shaping Circuit

In SAF-1, a specific instant of the received signal is used to trigger the transmitter. This is achieved by comparing, the received signal after amplification, with a constant reference voltage. Facility for adjusting the reference voltage is provided so that it can be set above the noise level. When the amplifier output is higher than the reference voltage, a high to low transition results at the output of comparator, which is used to trigger the monostable.

The output of the monoshot is fed to a differentiator to have sharp rising edge. The differentiator output is used to drive the transmitter, through an emitter follower. Another monoshot is coupled with the first one. The time period of the second monoshot is adjusted in such a way that it gives a trigger pulse whenever 'sing-around' is lost. Also, there is no need to give a starting pulse.

3.1.3 Transmitter

The function of the transmitter is to generate a high voltage pulse of short duration for energizing the piezoelectric transducer to emit a pulse of ultrasonic energy. The transmitter consists of a capacitor connected to the output of a transistor switch. The capacitor previously charged to a high voltage, is discharged instantaneously across the transducer by means of the transistor switch. Damping of the transducer can be adjusted by a potentiometer.

3.1.4 Frequency Difference Measurement

To measure the difference of the pulse repetition frequencies of upstream and downstream transmissions, phase coincidence method is used. Let the phase coincidence between the two pulse repetition frequencies f_{up} and f_{dn} occur at interval T.
It was shown [4] that

$$\Delta f = f_{dn} - f_{up} = \frac{1}{T} \tag{3.1}$$

Therefore, the frequency difference is given by the frequency of the periodic pulse output from the phase coincidence circuit. Multiple period averaging method is used to find out the frequency of the output of phase coincidence circuit.

Phase Coincidence Circuit

The phase coincidence detection circuit is realized using a D flip-flop. The two prf signals are given to Schmitt triggers to provide sharp rising and falling edges of square pulses. Now, the signal of higher frequency is given to the D input and the other to the clock input of a D flip-flop. When the two signals are in phase coincidence, output of D flip-flop changes state. Thus at the output of D flip-flop, square pulses of frequency $(f_{dn} - f_{up})$ is obtained. The circuit will work only if the frequency difference is less than one third of the higher frequency of input frequencies.

3.1.5 Calibration System

To calibrate the flowmeter, the liquid passing through the flowmeter is collected in a calibration tank. The time taken to raise the level of the tank by a fixed height is measured. Lower and upper levels are sensed by electrodes fitted in the tank. The volume of the liquid corresponding to this height is known. From this, the actual flow rate is calculated.

3.2 Test Results of SAF-1

The flow measurement system was set up. Measurements were taken with two pairs of transducers for upward and downward transmissions for different flows. The flow rate was calculated using the values of the experimental setup. The actual flow was determined by using a calibration system (as described in Section 5.1.2).

It was observed that as the flow increases, SAF-1 gives erratic readings. At higher flows the transmitter was getting erratic triggering which causes instability of the sing-around loop. Further efforts were made to investigate the reasons behind this instability of the sing-around loop.

The ultrasonic signal obtained at the receiver transducer was observed for various flow rates. The received waveforms at various flow rates are shown in Fig. 3.2. At low flow rates, there is not much change in the amplitudes of the received ultrasonic signal. But as the flow rate increases, the relative amplitudes of the peaks of the signal change. It was observed that the change in amplitude levels is not consistent, it varies with transducer alignment.

The received signal for different flow rates were recorded and are shown in Fig. 3.2 (a)-(f). The causes of instability in the sing-around can be seen from the difficulty in setting the comparator level for some of these waveforms. For flow rates corresponding to Fig. 3.2 (a)-(c) the system will work without any triggering problem if the triggering point is set at point A. But at a flow rate of 440 lpm, as seen in Fig. 3.2 (e), the triggering point may shift from point A to point B, causing false triggering. As the relative amplitudes of the peaks of the signal are not constant at all flows, intermittent shifting of triggering point between the peaks occur. This undesired shift in triggering point causes instability of the sing-around loop. It is not possible to increase the value of threshold further, as it might cause loss of triggering at lower flow rates (Refer Fig. 3.2 (a), (b)), and decreasing the threshold might cause false triggering by noise and reflected signals.

The exact reason for the change in waveshape could not be found out. One possible reason could be that some part of ultrasonic signal passing through the pipe and reaching the receiver transducer a little earlier than that reaching through water. This might cause a change in waveshape due to the phase addition of the two signals. Another reason could be the effect of turbulence. The change in waveshape might also be due to the shearing action of ultrasonic wave by the flow .

Even at low flows, when there is no change in waveshape, there is fluctuation in amplitudes of the received signal. As triggering of the transmitter is done at a particular level of the received signal, this amplitude fluctuations will cause fluctuations in the detected receiving instants. Apart from that, it imposes a restriction that the system be calibrated and used on a class of liquids within which the attenuation characteristics are not too variable [9].

In the flow measurement system, it is assumed that the time delay introduced in non-flowing liquid parts of the flowmeter and electronic circuits, is negligible. But it was found that in SAF-1, there is a pocket of non-flowing liquid between the transducer and flowstream, in the transducer assembly, which causes an extra delay in the acoustic path. As the ICs used in the circuits are not of fastest type, it causes an electronic delay. These undesired delays affect the performance of the system.

The output pulse of the transmitter of SAF-1 is having a pulse width of the order of 2.3 μs. This relatively large pulse width increases the energy transferred to the transducer which might cause damage to the transducer.

In SAF-1, an RC coupled amplifier was used to amplify the received signal. The bandwidth of the amplifier was found to be 4.4 MHz. This limited bandwidth caused distortion at the output when 5 MHz transducers were used. The amplifier has a gain of 22 dB at 2.2 MHz. This gain is not sufficient to amplify the signal to the desired level. So a standard pre-amplifier had to be used.

A new system, SAF-2, with modifications to overcome the problems faced in SAF-1, has been developed, and will be described in Chapter 4.

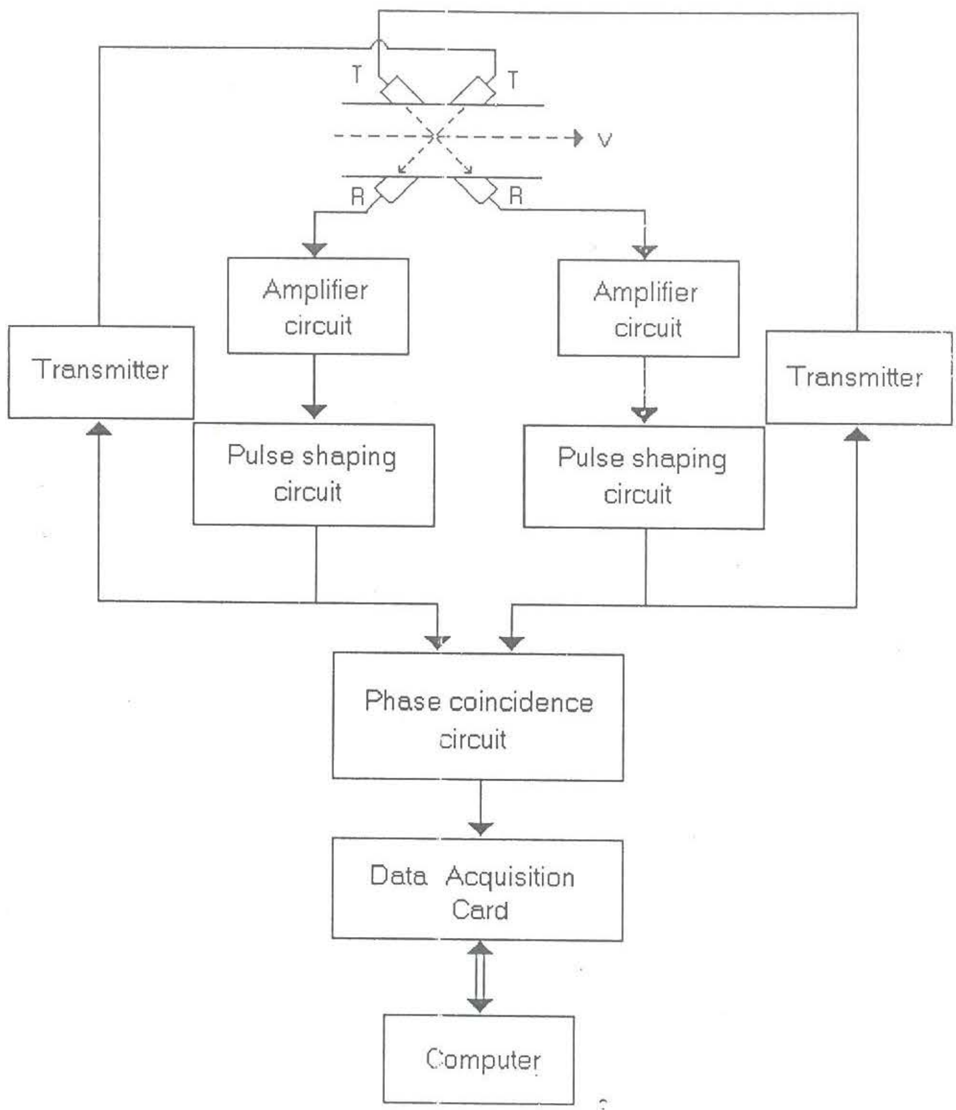


Fig. 3.1. Block diagram of SAF-1

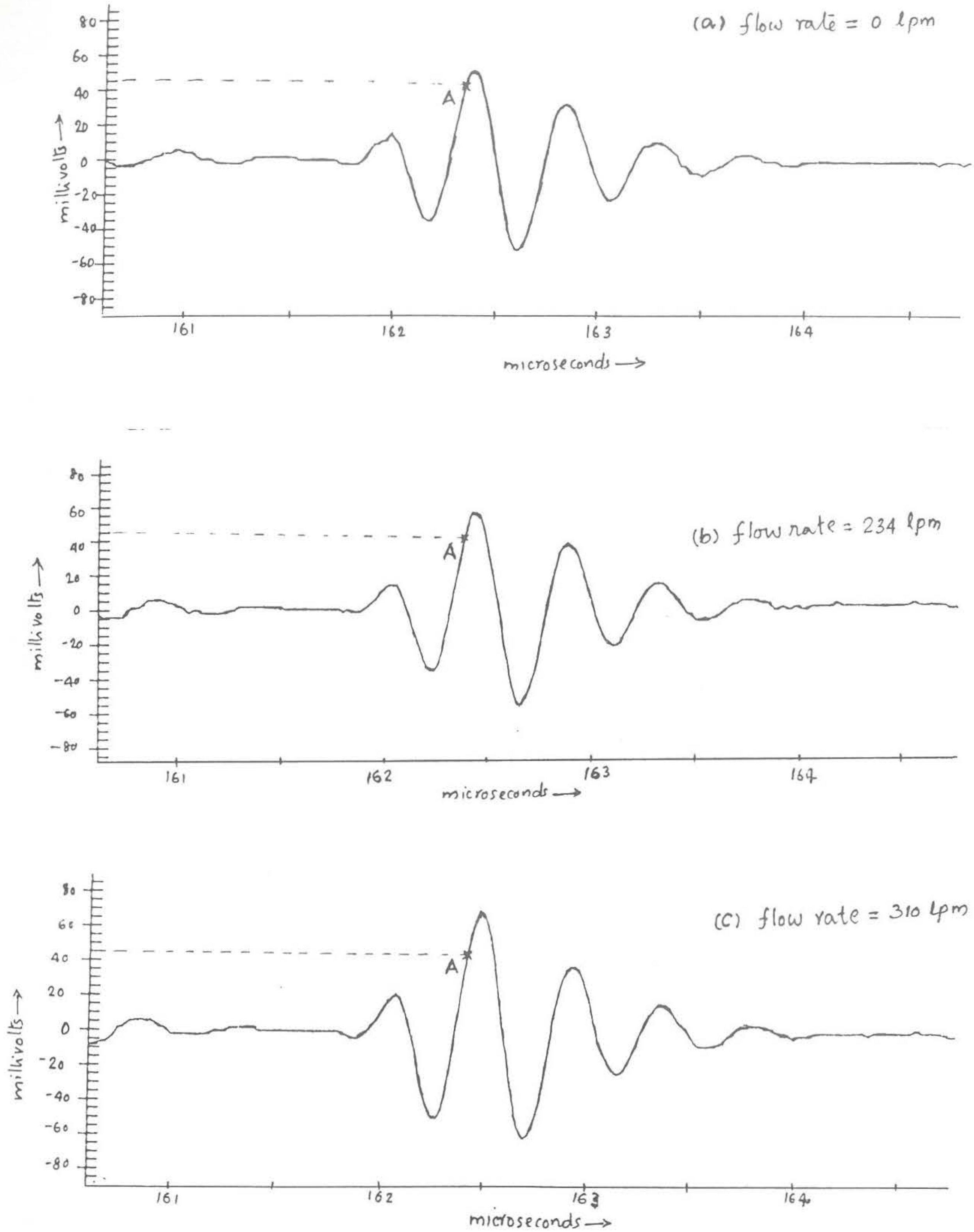
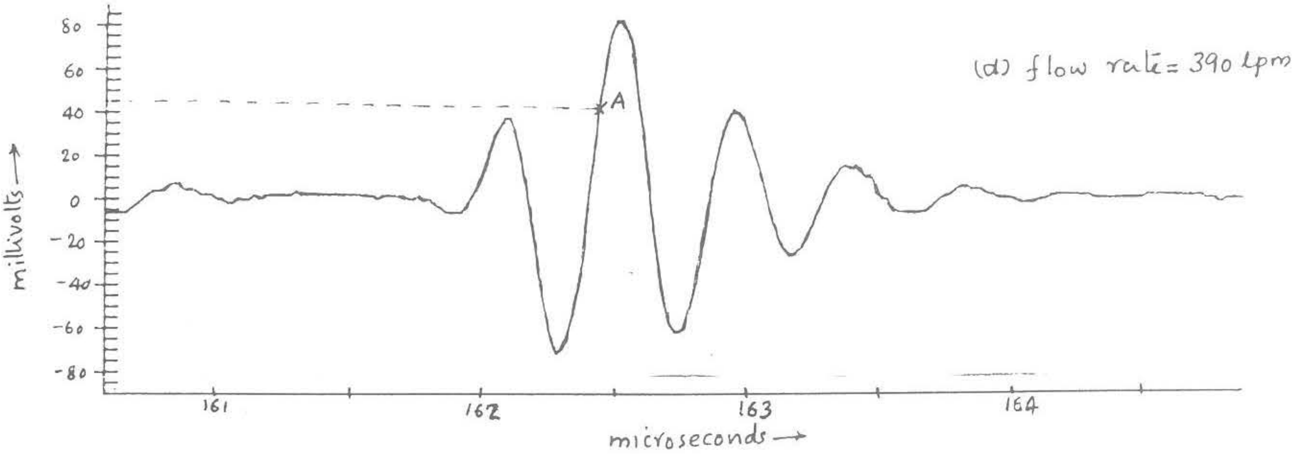
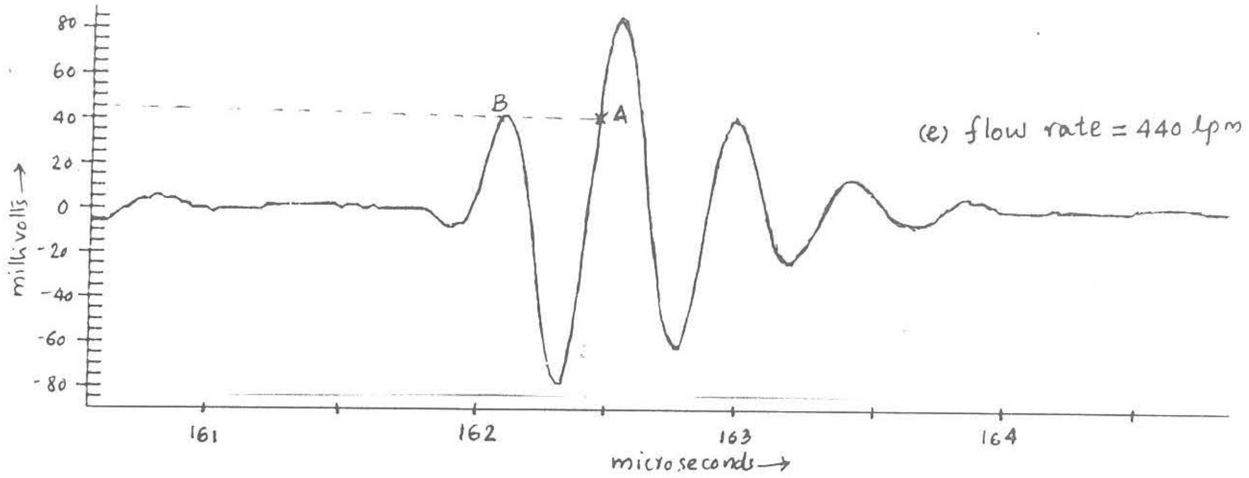
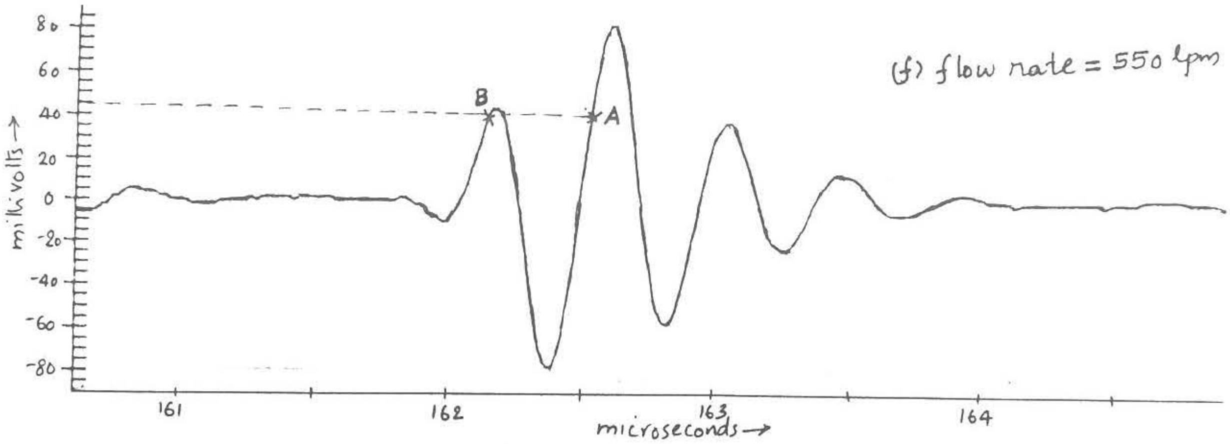


Fig. 3.2. Ultrasonic signal received at the transducer, at different flow rates


(d) flow rate = 390 lpm
millivolts →
80
60
40
20
0
-20
-40
-60
-80
A
161
162
163
164
microseconds →


(e) flow rate = 440 lpm
millivolts →
80
60
40
20
0
-20
-40
-60
-80
B
A
161
162
163
164
microseconds →


(f) flow rate = 550 lpm
millivolts →
80
60
40
20
0
-20
-40
-60
-80
B
A
161
162
163
164
microseconds →

Chapter 4

System Description

The details of the sing-around ultrasonic flowmeter developed by B.P.Parmar, referred to as SAF-1, were described in Chapter 3. A thorough testing of this flowmeter was done in the laboratory. The possible causes of malfunctioning were discussed in Chapter 3. A new flowmeter, referred to as SAF-2, with suitable modifications, has been developed. These modifications, set-up of SAF-2, and the factors affecting accuracy of the system are discussed in this chapter.

4.1 Required Modifications

The main problem encountered in SAF-1 was that the changes in relative amplitudes of peaks of the received signal with flow, causing undesired shift in triggering point of the transmitter. Another cause of error in the reading was small amplitude fluctuations in the received signal causing fluctuations in the detected receiving instants.

Several methods of detecting the exact arrival of pulse have been suggested [14], [15] to overcome the effect of amplitude fluctuations of the received signal, on the performance of the system. In one of the methods, a voltage threshold is used, but the trigger point is not the first crossing with rising amplitude, but the mid-point of the section between this and the second crossing, now with falling amplitude. In another method, the detector is enabled if the leading edge of the pulse exceeds two levels, and gives the trigger at the following zero crossing. Implementation of these methods require complicated electronic circuits. Further, a new approach for solving the above problem has been discussed.

To nullify the effect of change in amplitude levels of the peaks of received signal, the received waveform was amplified to such an extent that output of the amplifier reaches saturation. Thus small amplitude fluctuations will not affect the level of output. But, it was observed that the noise and echoes also getting amplified causing false triggering of the transmitter. So this method does not yield any specific advantage. Therefore, we devised an alternative circuit in which the received signal is connected to a pre-amplifier with variable gain. A diode clipping circuit follows this amplifier. The gain of the amplifier is adjusted such that voltage level of the noise and echoes, even after amplification, is less than the cut-in voltage of the diode. So the signal after the diode clipping circuit, would be free of noise and echo signals. Now, the signal is connected to another amplifier and the gain of this amplifier is adjusted to make the output at saturation level. Thus, small changes in amplitude levels of the received signal does not have any effect on the amplifier output. Hence the performance of the system is not affected by the waveshape change.

Since the small amplitude fluctuations of the received signal do not affect the output of amplifier, this system can be used for different liquids having different attenuation characteristics.

The pulse width of the transmitter output of SAF-1 was found to be 2.3 μs which might cause damage to the transducers. Also, if the duration of the pulse is higher than the period of the wave, it can result in distorted waveform [16]. A transmitter circuit has been developed which would give pulse width of approximately 200 nS.

To reduce the delay occurring in electronic circuits, high speed ICs have been used in the system hardware. A new set-up for assembling the transducers is developed. This set-up ensures that the transducers are perfectly aligned and the non-flow liquid part of the system is minimum. Proper care has been taken to avoid the transmission of ultrasound through pipe. A rough layer of epoxy putty is created in the inner surfaces of the pipes to increase the attenuation of ultrasound signals striking the pipe wall.

The bandwidth of the amplifier in SAF-2 is 45 MHz, which ensures that the amplified waveform is not distorted, in contrast to the amplifier in SAF-1.

One of the drawbacks of the sing-around technique is that any obstruction between the transmitter and receiver causing errors in the sing-around frequency. To reduce the effect of this sudden change in frequency, a low pass RC filter is incorporated at the output of the phase coincidence circuit.

4.2 Circuit Description

The block diagram of SAF-2 is given in Fig. 4.1. The hardware includes a video amplifier, diode clipping circuit, triggering circuit, phase coincidence circuit, transmitter, and the power supply unit. The received ultrasound signal after amplification and diode clipping is used for triggering the transmitter, resulting in a pulse repetition frequency (prf). This is being done in upstream and downstream directions. A phase coincidence circuit is used to find the difference between the pulse repetition frequencies. The output of the phase coincidence circuit is fed to the PC through a data acquisition card to calculate the flow rate using the parameters of the system.

4.2.1 Amplifier Circuit

When ultrasonic signals are passed through the liquid, they get attenuated. These signals received by the transducer have to be amplified to the saturation level before feeding it into the triggering circuit. The circuit diagram of the amplifier section is shown in Fig. 4.2. It consists of a pre-amplifier followed by another amplifier with a diode clipping circuit connected between them. The frequency response characteristic of the amplifier is shown in Fig. 4.3. It has a bandwidth of 45 MHz. The gain of the pre-amplifier is set in such a way that the noise and echoes in the received signal are not amplified beyond the cut-in voltage of the diode. Hence the output of the centre-clipping circuit is free of noise and echo signals. Typical waveforms before and after the clipping circuit are shown in Fig. 4.4. The second amplifier boosts the signal from clipping circuit to the saturation level.

The amplifier is built using NE592, a differential input, differential output, wide band video amplifier [17]. Gain of this differential amplifier can be adjusted by varying the value of the resistance connected between pins 4 and 11.

4.2.2 Triggering Circuit

The function of the triggering circuit is to detect the arrival of the ultrasonic signal and provide a trigger pulse to the transmitter.

The trigger circuit is shown in Fig. 4.5. It consists of a high speed comparator (NE521), a monostable circuit (74LS123), and a transistorized (2N2222) switching circuit. The comparator detects the instant at which the amplifier output crosses a constant reference voltage, set much above the noise level. The comparator thus detects the arrival of pulse, and gives a low to high transition at the output, which in turn is used to trigger the monoshot. The monoshot output excites the transmitter through a driving circuit.

The pulse width of monoshot A is kept smaller than, and that of monoshot B larger than, the pulse repetition period. During sing-around, the Q output of monoshot B will always be at high state, which keeps the comparator enabled. When there is no sing-around, the low state at the output of monoshot B switches the comparator output to high. This triggers monoshot A which in turn triggers monoshot B. Thus at the output of monoshot A, a pulse train of period equal that of monoshot B, is obtained. This arrangement keeps the sing-around at a lower frequency whenever there is loss of received signal. Thus this set-up eliminates the application of an external start pulse.

The $\bar{Q}$ output of monoshot A is fed to a transistor switch. This is for increasing the high state voltage level of the pulse from TTL to +12 V so as to drive the MOSFET in the transmitter stage. A common collector driver stage is used for driving the MOSFET.

4.2.3 Phase Coincidence Circuit

A phase coincidence circuit, as described in Section 3.1.4, is developed for the measurement of difference between the prf's in upstream and downstream directions. The prf's are given to a Schmitt trigger to have sharp rising and falling edges of square pulses. Then they are fed to D and CLK input of a D flip-flop to detect the phase coincidence. Circuit diagram of the phase coincidence circuit is shown in Fig. 4.5 along with the trigger circuit.

The output of phase coincidence circuit is connected to a low pass RC filter. This is to remove any jitter in frequency caused by temporary loss of sing-around due to some obstructions in the liquid. The cut-off frequency of the low pass filter is designed to be 10 times the maximum frequency of phase coincidence output.

4.2.4 Transmitter

The function of the transmitter is to excite the transducer to emit a short duration pulse of ultrasonic energy. This is done by applying a transient electrical pulse to the transducer. The circuit diagram of transmitter is shown in Fig. 4.7. The transmitter consists of a capacitor, connected to the output of a MOSFET switch. When MOSFET is off, the capacitor is charged to +200 V. When the trigger signal is applied to the gate of the MOSFET, it goes to on state and acts virtually as a short circuit. This results in a large negative spike voltage across the transducer. By means of this electric pulse, the transducer is excited to produce a mechanical pulse which is transmitted into water via a coupling layer.

The amplitude and shape of the transmitter pulse have a great effect on the transmitted ultrasonic pulse. The width of the pulse and hence the energy transferred to the transducer can be increased by choosing higher value capacitance. The damping of the transducer can be adjusted by the trimmable resistance R_4. Pulse width vs damping resistance and pulse amplitude vs damping resistance characteristics of the transmitter circuit are given in Fig. 4.8 and Fig. 4.9 respectively.

4.2.5 Power Supply Unit

The power supply unit feeds the necessary d.c. voltages required for each circuit. It consists of a step down-transformer, rectifier, capacitor filter and regulator for each of the required supply. Separate ± 6 V have been used for the amplifiers. For the trigger circuit, ± 5 V and +12 V are needed. For producing the high voltage spikes, the transmitter requires a high voltage dc supply. A 1:1 transformer, bridge rectifier, and a zener diode regulator generates +200 V.

The power supply unit of each circuit is shown along with the respective circuit except in the case of trigger and phase coincidence circuit, where it is shown separately in Fig. 4.5.

4.3 Software

The phase coincidence circuit gives a square pulse whose frequency indicates the difference of prf's in upstream and downstream directions. The output of phase coincidence circuit is fed to the data acquisition card PCL-208 [18] interfaced with the PC. A software written in C-language does the initial set-up of the data acquisition card and subsequently reads the frequency of the signal.

PCL-208 is set-up in 'Programmable Interval Timer/Counter' mode where a counter is decremented on receiving pulse on the CTR-0 CLK input. Initially, Counter-0 is loaded with the maximum count. When the output of phase coincidence circuit is fed to the counter, the counter is decremented by one, on each pulse. This is done for a fixed period of time T and the average frequency of the pulse is found out. Using the values of d and θ the velocity of liquid is calculated. Liquid velocity multiplied by the area of pipe gives the flow rate. The actual flow rate is calculated from the differential height obtained across the venturi meter. Differential height is entered through the keyboard. A look-up table, which gives the value of flow for each differential height, is created from the calibration curve of the venturi meter. Thus the software finds out the value of actual flow rate from the look-up table. There is an option in the software to plot the measured flow rate and actual flow rate, on the screen.

4.4 Transducers

Immersion type straight contact piezo-electric transducers having a resonant frequency of 5 MHz have been used in the flowmeter. The specifications of the transducer are given in Appendix A.

Fig. 4.10 gives the schematic of an ultrasonic transducer [15]. It consists mainly of the oscillator disc, a protective layer and the damping block. Electrical matching elements are built into the housing. The disc type crystal is fixed at one end as shown in the diagram. The thickness of the plate corresponds to the required frequency and both its surfaces are metallised to act as electrodes. The damping block absorbs that part of 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 delicate crystal is also used to match the acoustic impedance for optimum coupling to the specimen.

For transmission at various angles to the surface, angle probes are used. Angle probes are fitted with wedge shaped adapter against which piezoelectric transducer is pressed firmly.

4.5 Sources of Error in the Measurement

The flow measurement system suffers inaccuracy as a result of the following assumptions,

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

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

(iii) that there is a uniform flat velocity profile across the pipe diameter. This is true only in fully developed turbulent flow at very high Reynolds number.

(iv) that there is no directional shift in the ultrasound beam when it travels through the liquid. If the frequency of the ultrasound is less, it causes more interference with the medium and thus more directional shift. If the frequency is made high so as to reduce this, it would increase the attenuation in the medium.

4.5.1 Effect of Additional Delay Introduced in the Sonic Path and Electronic Circuits

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 Eqn. 2.4 and Eqn. 2.5. Here $d = (D/\sin\theta)$, where D is the diameter of the pipe. It is assumed that the delays are same in both directions.
The basic equations thus become

$$t_{dn} = \frac{(D/\sin\theta)}{c + v\cos\theta} + \frac{x}{c} + \tau \tag{4.1}$$

$$t_{up} = \frac{(D/\sin\theta)}{c - v\cos\theta} + \frac{x}{c} + \tau \tag{4.2}$$

The difference between the sing-around frequencies, $\Delta f'$ will be [19]

$$\Delta f' = \left[1 + \frac{2c\sin\theta}{D}\left(\frac{x}{c} + \tau\right) \frac{c^2\sin^2\theta}{D^2}\left(\frac{x}{c} + \tau\right)^2\left(1 - \frac{v\cos\theta}{c}\right)^2\right]^{-1} \tag{4.3}$$

In the perfect case where x=0 and $\tau = 0$,

$$\Delta f = \frac{v\sin(2\theta)}{D} \tag{4.4}$$

The relative error may be defined as,

$$e = \frac{\Delta f' - \Delta f}{\Delta f} \tag{4.5}$$

$$e = \frac{-2c\sin\theta}{D}\left(\frac{x}{c} + \tau\right)^2 - \frac{c^2\sin^2\theta}{D^2}\left(\frac{x}{c} + \tau\right)^2\left(1 - \frac{v\cos\theta}{c}\right)^2 \tag{4.6}$$

As v is small compared with c, $(1 - (v\cos\theta)/c) \to 1$. Hence

$$\frac{E}{100} = 1 - \left[1 + \frac{c\sin\theta}{D}\left(\frac{x}{c} + \tau\right)\right]^2 \tag{4.7}$$

It may be noted that

1. Error is always negative (unless $(x + c\tau) < 0$, i. e. x is negative.)
2. Error is composed of both geometric and time dependent variables.
3. Error is dependent on sonic velocity and hence temperature and pressure sensitive.
4. If unequal time delays exist in the two sonic directions, it can be shown that the error will be dependent on flow velocity also [19].

4.5.2 Effect of Unequal Angle of Inclination of Transducers to the Flow Axis

Let θ_1 and θ_2 be the angles of inclination of the transducers to the flow axis. It can be shown [4] that the error in the frequency difference,

$$\Delta f - \Delta f' = (1 - \cos(2\,\Delta\theta))\left(\frac{v\sin(2\theta)}{D}\right) + \frac{2\,c\,\cos\theta\,\sin(\Delta\theta)}{D} \tag{4.8}$$

where $\Delta\theta = (\theta_1 - \theta_2)/2$, and $\theta = (\theta_1 + \theta_2)/2$.
If e is the relative error,

$$e = 1 - \cos(2\Delta\theta) + \frac{c\,\sin(\Delta\theta)}{v\,\sin\theta} \tag{4.9}$$

Error, e consists of two parts, one constant part which depends solely on the error in angles, and the other part which reduces as fluid velocity increases. If $\Delta\theta$ is small, then the first term in Eqn. 4.9 can be neglected and,

$$e = \frac{c\,\sin(\Delta\theta)}{v\,\sin\theta} \tag{4.10}$$

It can be seen from Eqn. 4.10 that a slight error in the angle of inclination of the transducers will cause considerable inaccuracy in the measurement.

4.5.3 Effect of Velocity Profile

The ultrasonic flowmeter is subject to velocity profile errors if velocity profile skewing occurs. Velocity profile skewing is imparted to the fluid due to an asymmetrical obstruction or curve in the pipeline. Even in a long straight pipe the velocity profile varies with Reynolds number. *Y.A.Al-Khazraji et al.* [20] 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 %.

The ultrasonic flowmeter measures the mean flow velocity of the fluid along the sound path. However, true rate of flow is determined by the mean speed of the flow across its cross section. As a result, an error of approximately 30% can occur in the measurement using ultrasonic technique [2] .

4.5.4 Effect of Transducer Frequency

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

It may be shown [21] that for a disc of diameter d 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 $0 < \alpha < \frac{\lambda}{d}$

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 d it is necessary that $\lambda \ll d$ where λ is the wavelength of sound in the medium. If c is the velocity of sound in the medium $\lambda = (c/f)$ so then the condition for beaming becomes $f \gg (c\ /d)$ and the angle of divergence of the beam, $\alpha = c/(f d)$. 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 between the transducers via the wall.

The attenuation in clean fluids increases with the square of the frequency [2]. So high frequencies result in more attenuation of the sound signals.

The best frequency in a particular application is therefore one which is not so 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 3-5 MHz are the best [2].

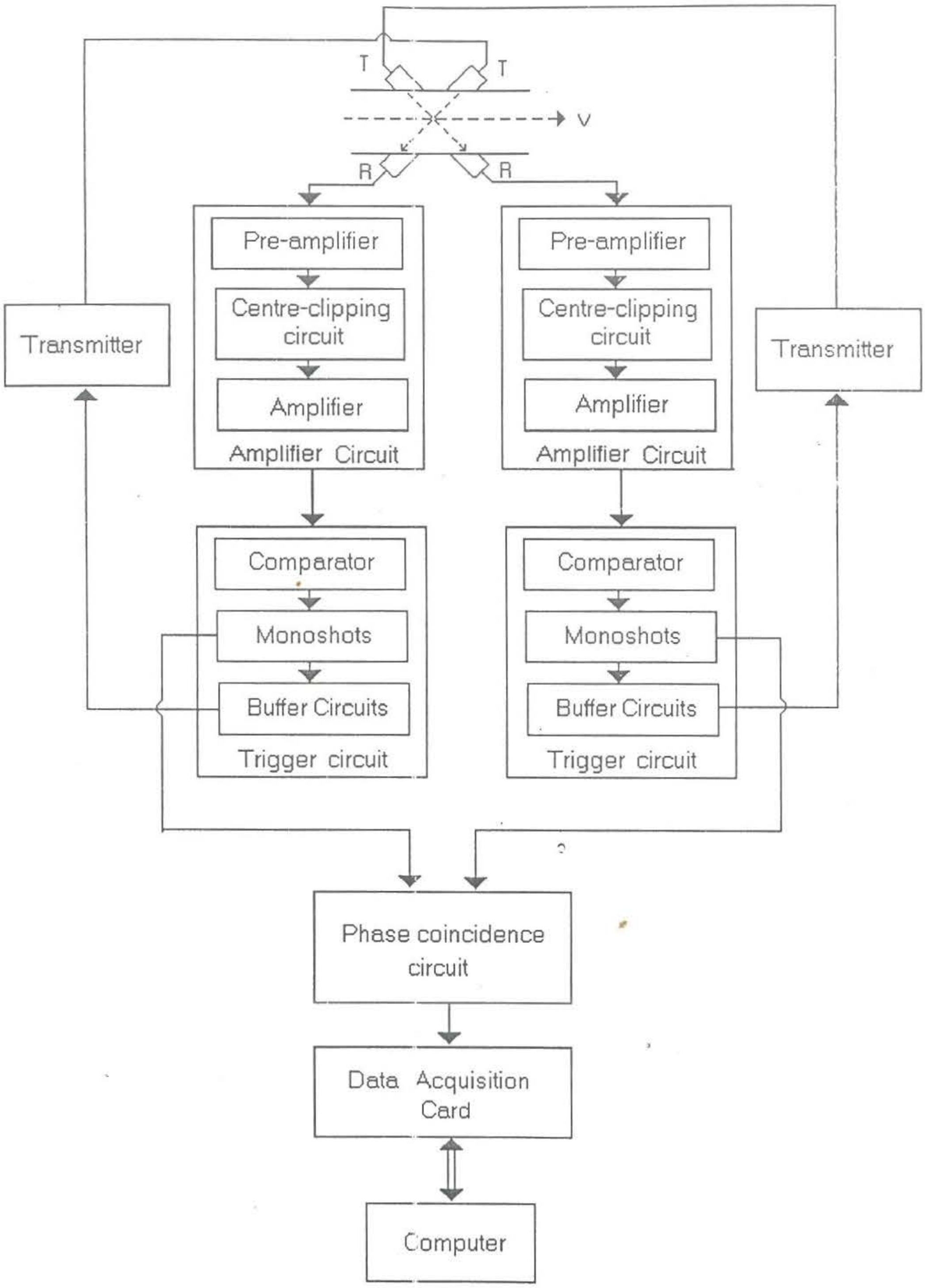
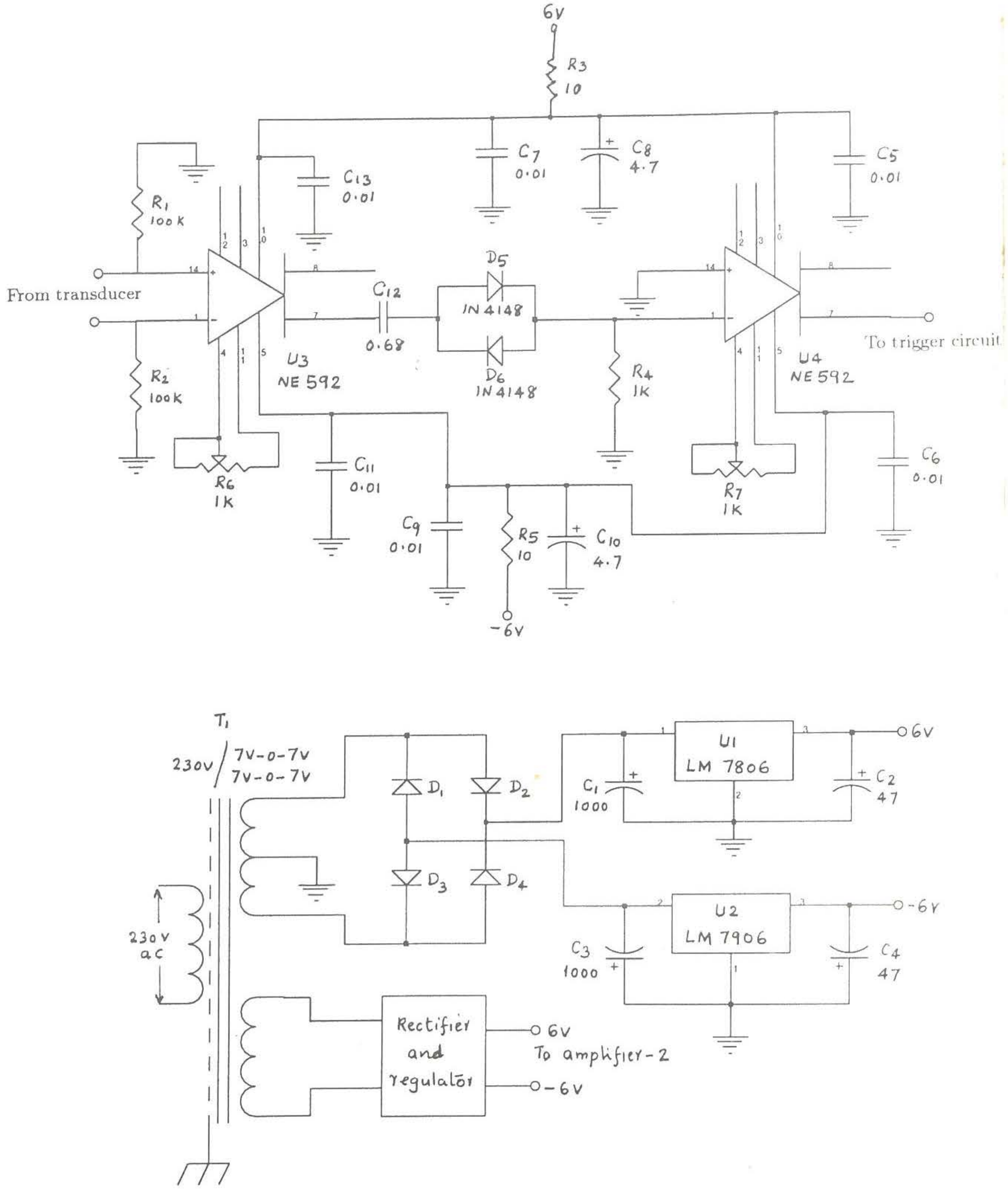


Fig. 4.1. Block diagram of SAF-2



NOTE: UNLESS OTHERWISE SPECIFIED

1. All resistors are 1/4 W, 1%, value expressed in ohms.
2. All capacitance expressed in microfarads.
3. All diodes are 1N4007.

Fig. 4.2. Ampifier circuit

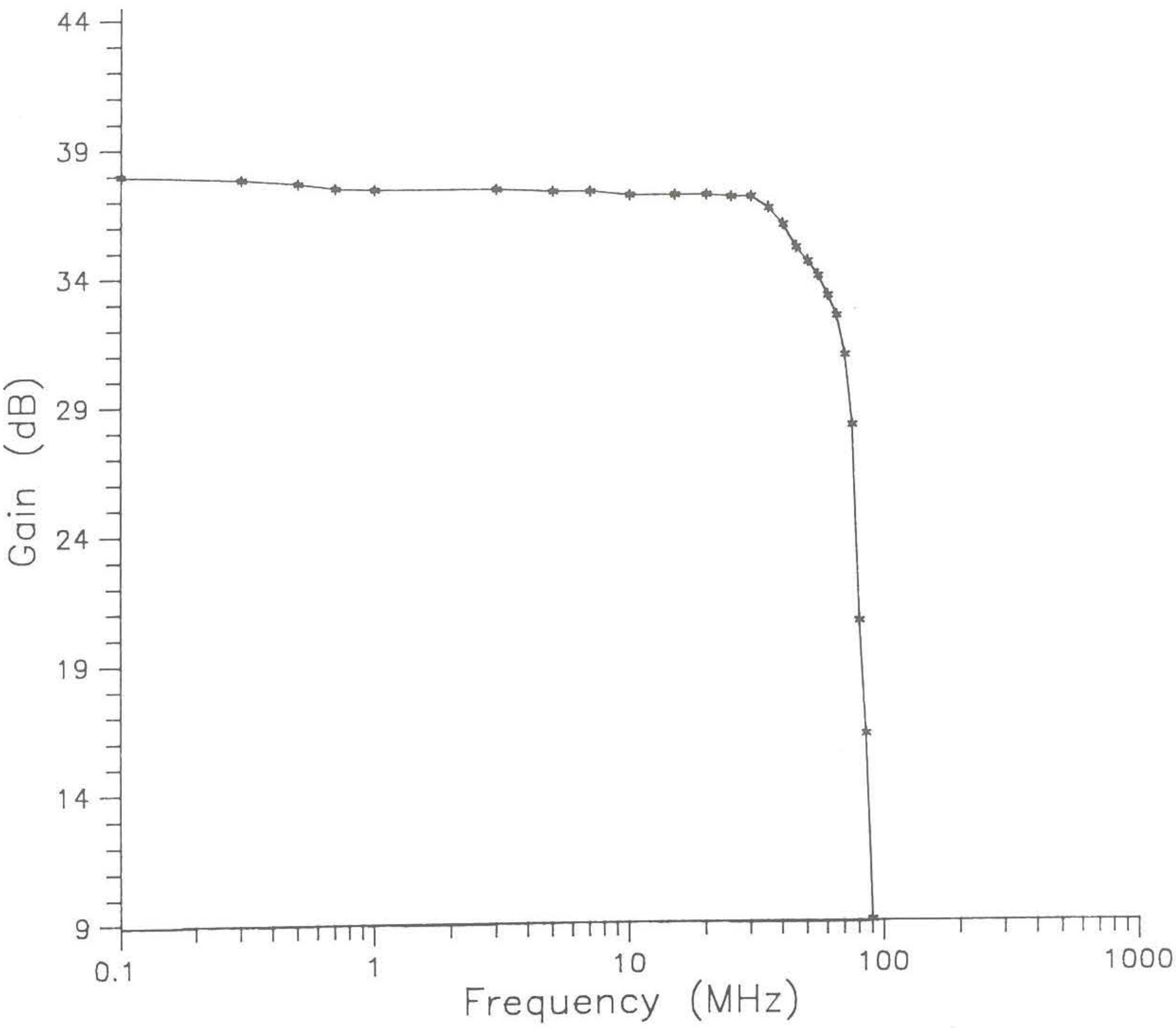


Fig. 4.3. Frequency response characteristic of the amplifier

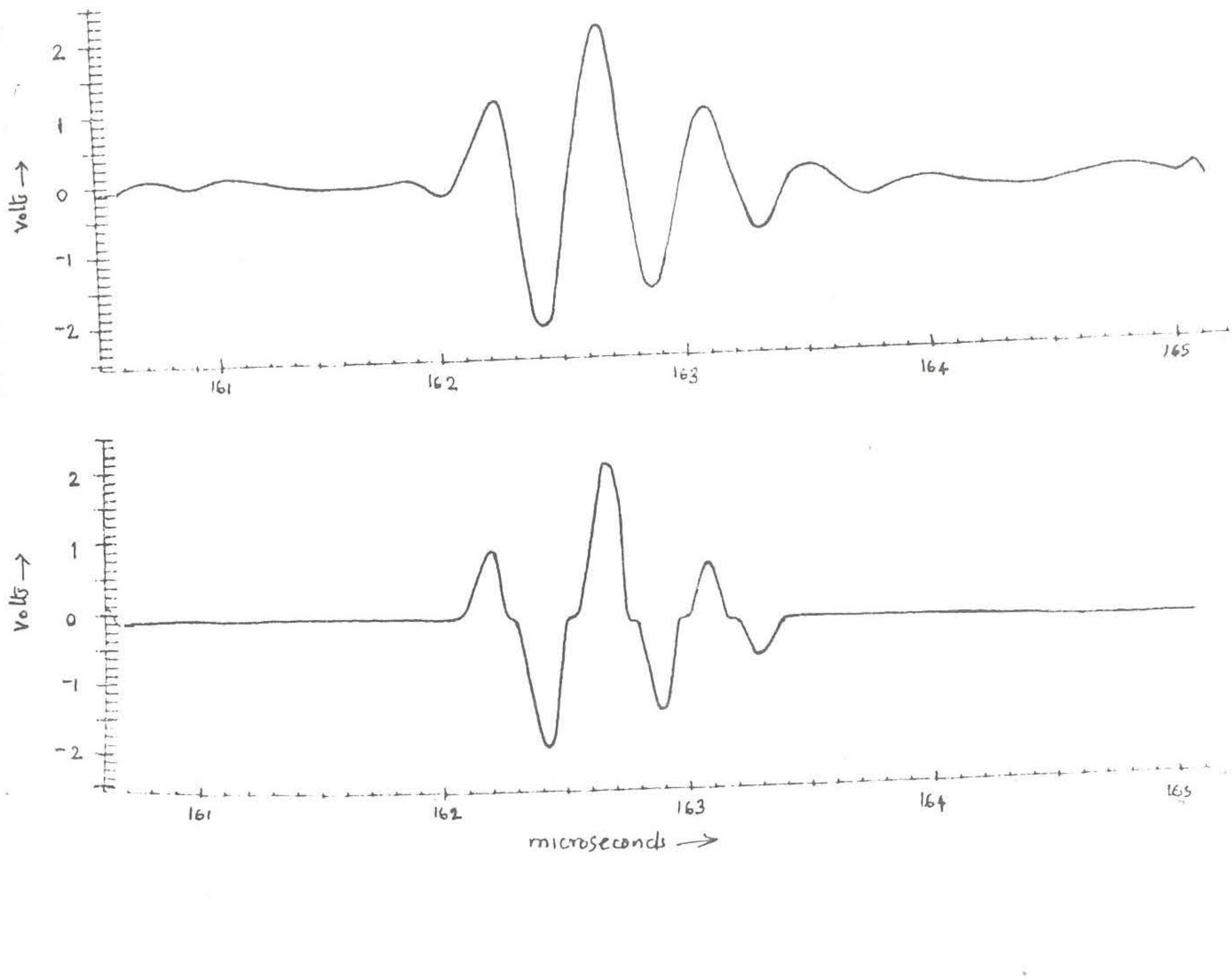
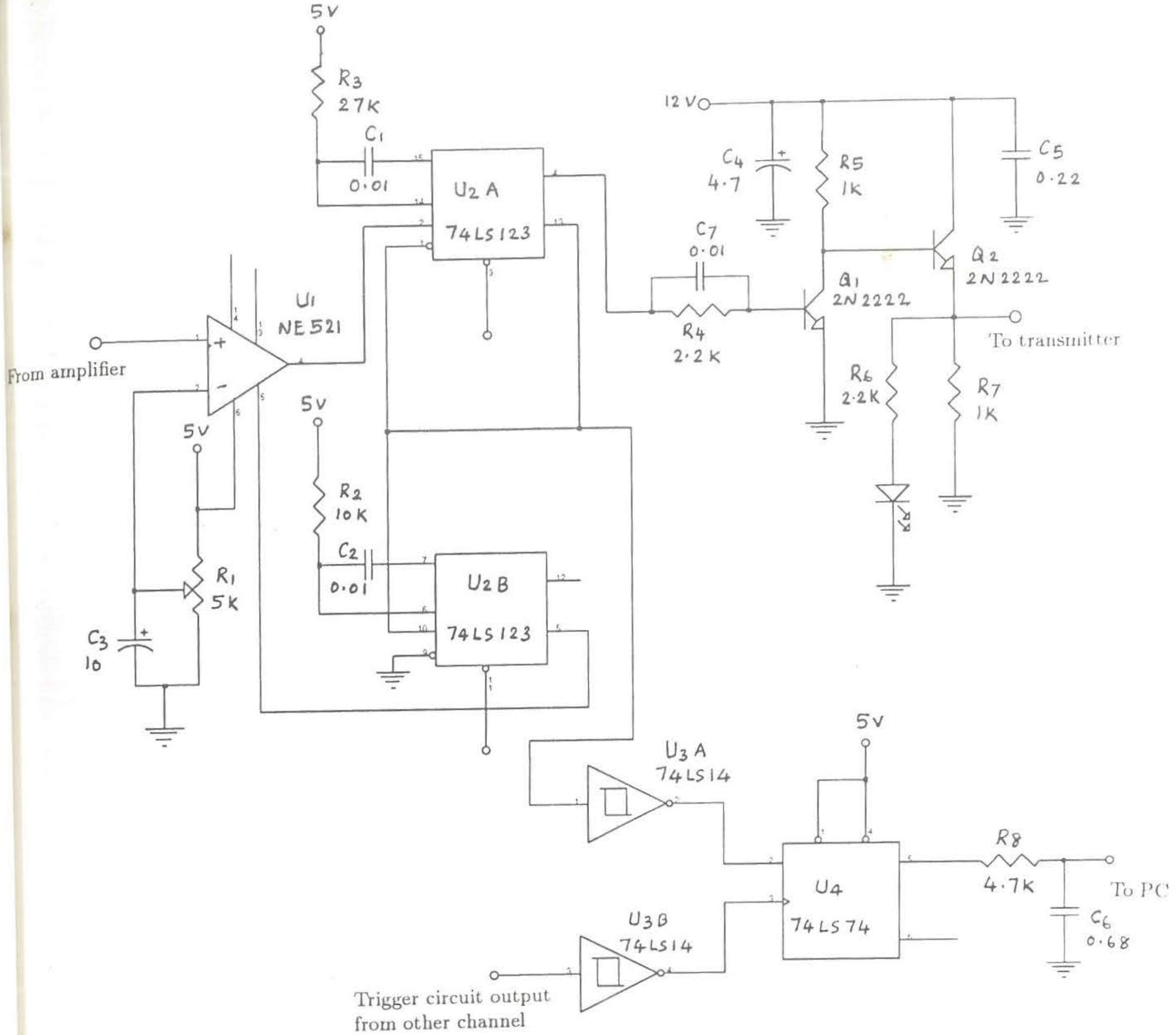


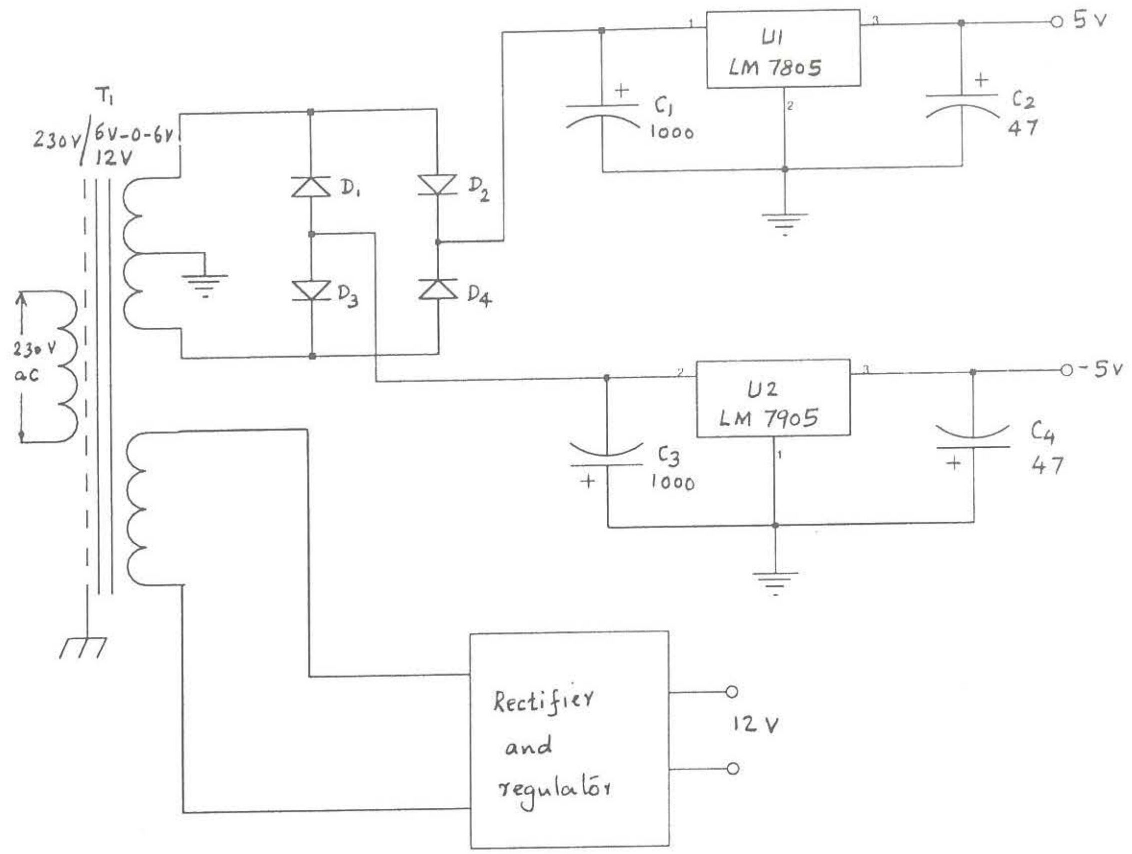
Fig. 4.4. Typical waveforms before and after the centre-clipping circuit



NOTES: UNLESS OTHERWISE SPECIFIED

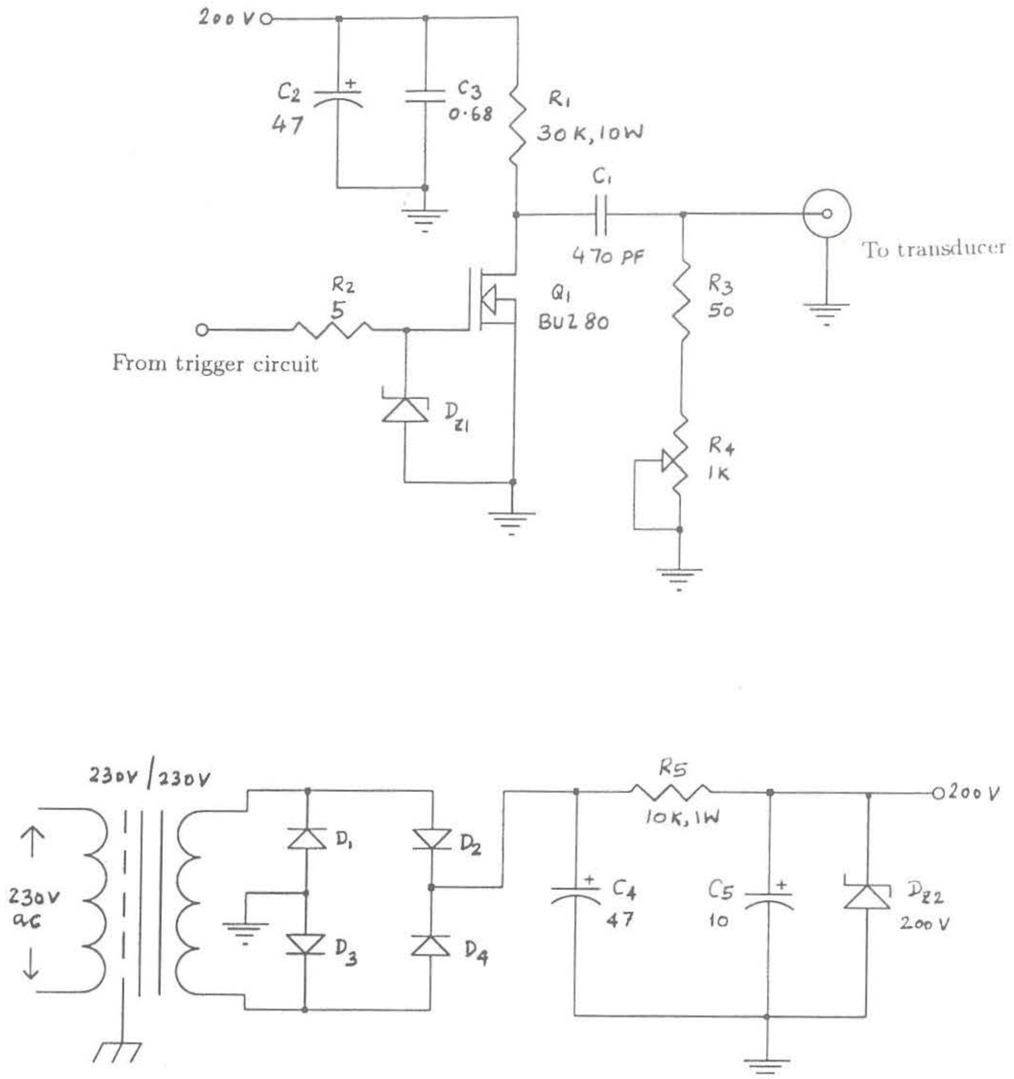
1. All resistors are 1/4 W, 1%, value expressed in ohms.
2. All capacitance expressed in microfarads.
3. Capacitors of value 0.1 μF are connected between the power supply and ground pins of each IC, for power supply decoupling.

Fig. 4.5. Trigger and phase coincidence circuit



NOTE: UNLESS OTHERWISE SPECIFIED
1. All capacitance expressed in microfarads.
2. All diodes are 1N4007.

Fig. 4.6. Power supply for trigger and phase coincidence circuit



NOTE: UNLESS OTHERWISE SPECIFIED
1. All resistors are 1/4 W, value in ohms.
2. All capacitance in microfarads.
3. All diodes are 1N4007.

Fig. 4.7. Transmitter circuit

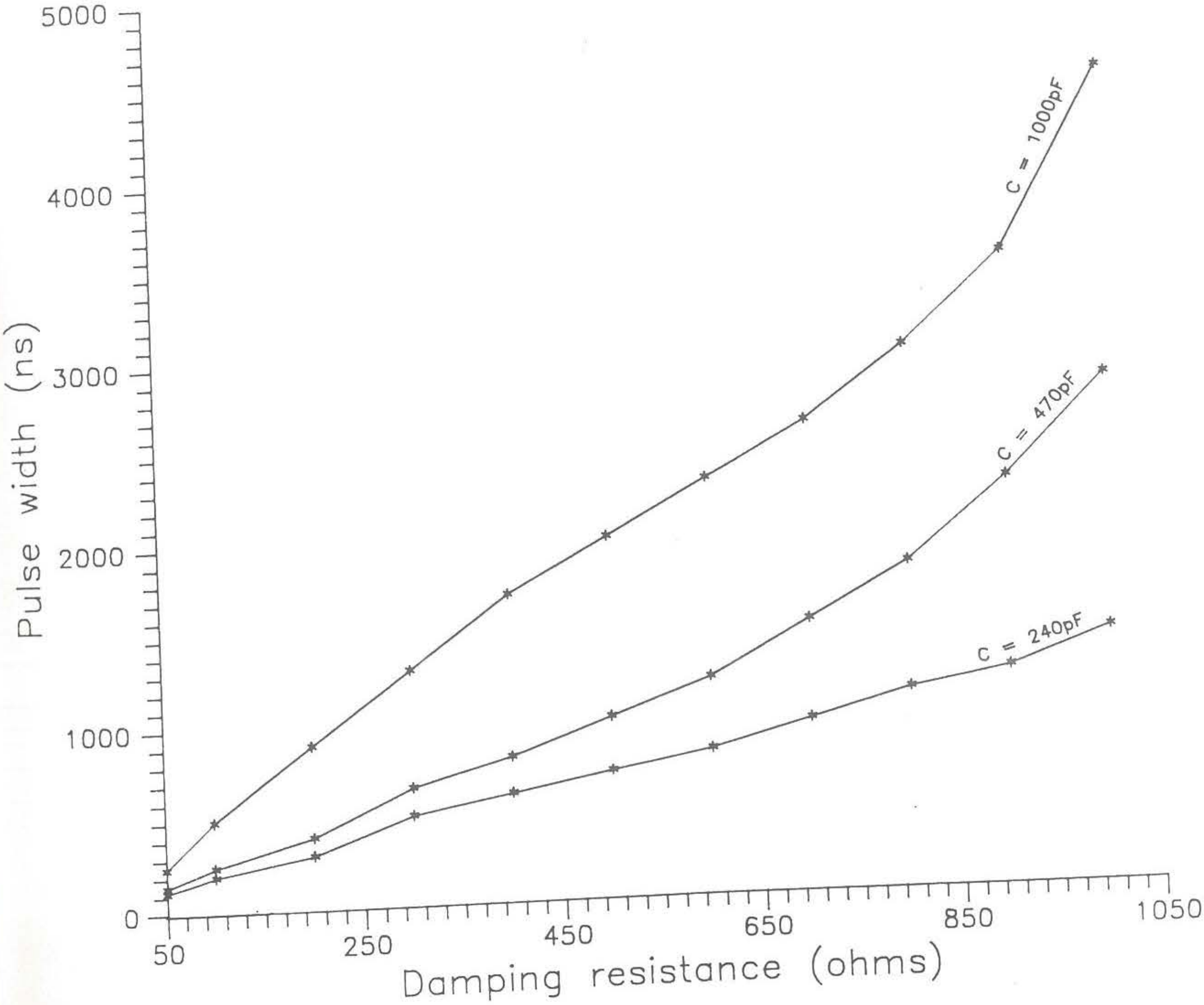


Fig. 4.8. Pulse width vs damping resistance characteristics of the transmitter

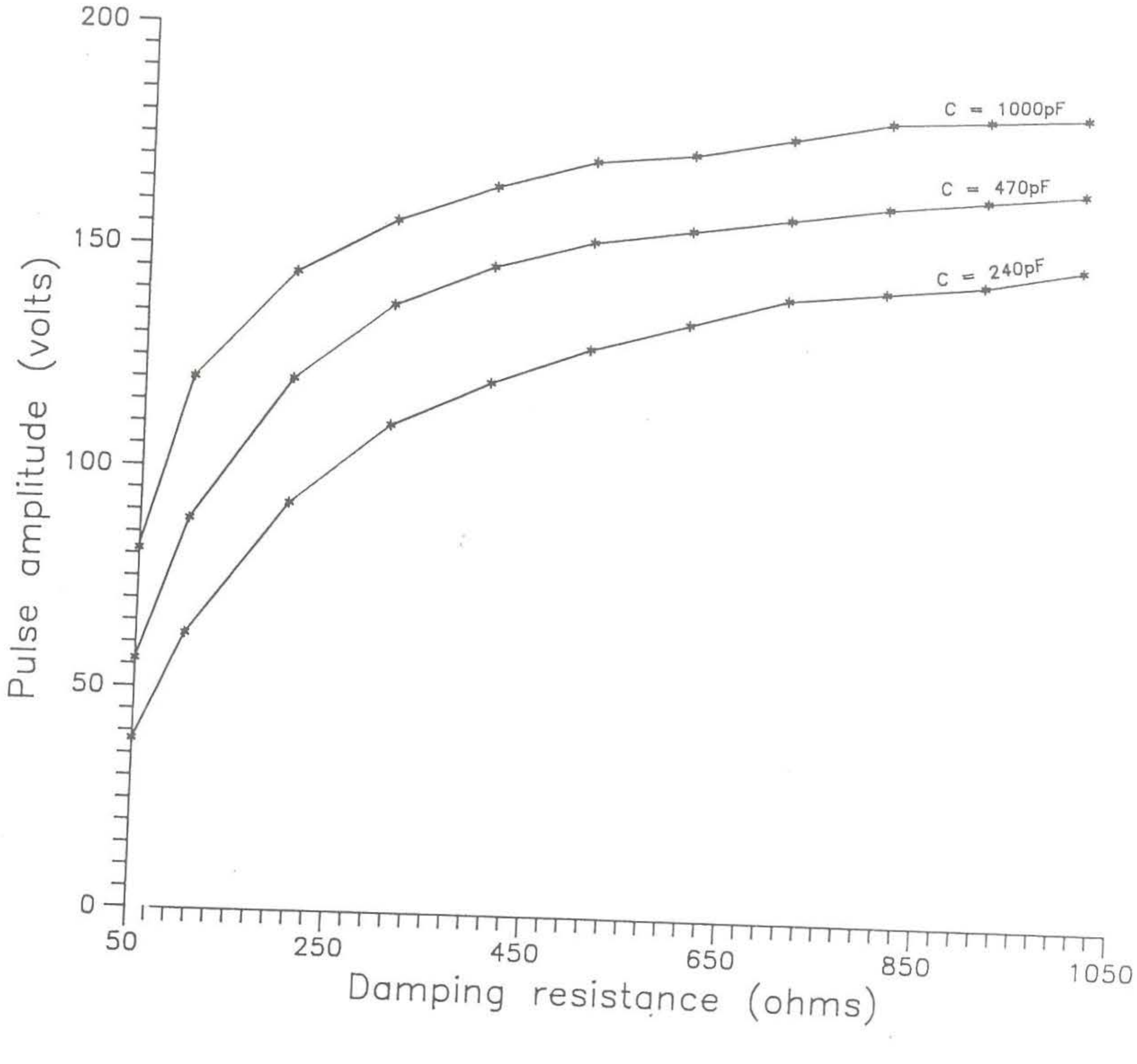


Fig. 4.9 Pulse amplitude vs damping resistance characteristics of the transmitter

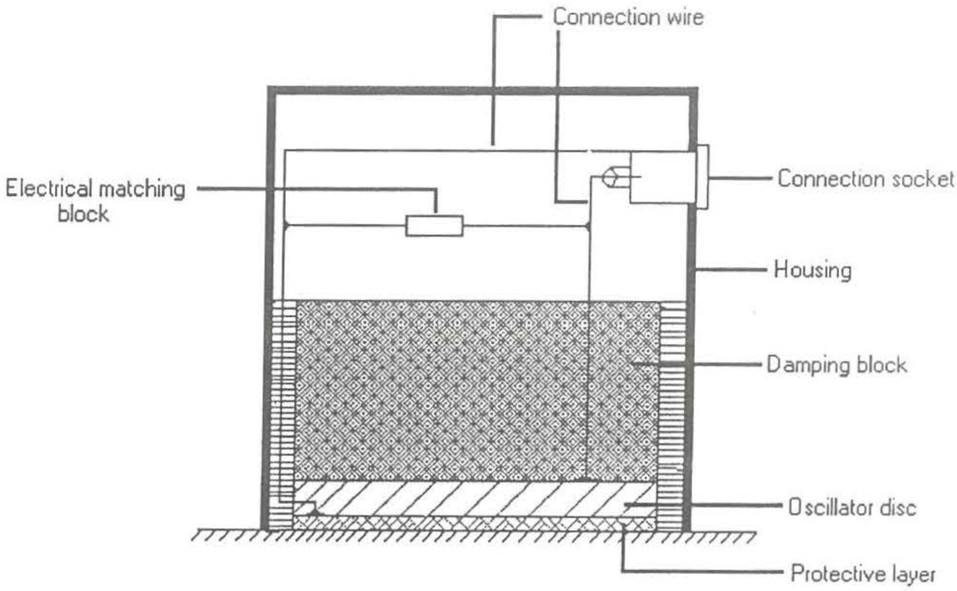


Fig. 4.10. Schematic of an ultrasonic transducer

Chapter 5

Experimental Set-up and Results

The experimental set-up for the ultrasonic flowmeter consists of water circulation system, transducer assembly, electronic circuits, and calibration system. Details of the electronic circuits were discussed in Chapter 4. In this chapter, water circulation system, transducer assembly, calibration system, and the test results of the electronic circuits are discussed. Finally the overall performance of SAF-2 is presented.

5.1 Experimental Set-up

5.1.1 Water Circulating System

The experiment set-up for water circulation is shown in Appendix B. It consists of a tank, pump set, and a set of pipes of different diameters, whose outlet goes back into the tank. The pump can deliver 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 the valves, the flow through the test pipe can be controlled. This system was built as part of the B.R.N.S. project for development of ultrasonic flowmeters [4]. A venturi meter has been installed in the test pipe for measuring the actual rate of flow of the liquid. The U-tube manometer connected across the venturi meter measures the differential pressure across the venturi meter, which is used for finding the actual flow.

5.1.2 Calibration System

A calibration system using venturi meter is set up for calibrating the ultrasonic flowmeter. A U-tube manometer connected to the venturi meter gives the differential pressure 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 C.

5.1.3 Transducer Assembly

A set up for installing the immersion type piezoelectric transducers has been developed. A schematic diagram of the transducer assembly is shown in Fig. 5.1 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.

5.1.4 Electronic Circuits

The testing of the flow measurement system was done by assembling the electronic circuits in bread boards. The system worked satisfactorily in upstream and downstream modes separately. But as both upstream and downstream loops were put together, both the sing around loops became unstable. The reason behind this was investigated further.

It was observed that the receiver of one channel was getting noise from the other loop. To investigate whether the noise was getting coupled through power supply, separate power supply was used for the amplifiers. Then the amount of noise signal at the output of amplifier was less, but still the transmitter was getting arbitrary triggering. This was due to the radiation noise from the transmitter of the other channel. This problem is overcome by increasing the signal strength by proper alignment of the transducers and setting the gain of the amplifier such that any noise present does not pass through the clipping circuit. Also, separate power supply has been used for the amplifier in each channel. The secondaries of the transformers used in the power supplies are well shielded from the primaries. To eliminate the possibility of oscillation of the amplifiers by coupling through the power supplies, RC filters are incorporated in the power supply lines of the amplifiers [22].

Printed circuit boards have been designed for each of the circuits. Considerable precautions have been taken while designing the layout of the PCB's, to reduce both coupled and radiated noise. Sharp bends of the tracks are avoided as far as possible. Multi point ground system is used to minimize the ground impedance effect. Short tracks have been used as far as possible especially, for analog input and analog output signals. Mylar capacitors, having short lead length, of 0.1 μF are connected close to the supply leads of each IC for power supply decoupling.

5.1.5 Software

The output of phase coincidence circuit is given to the PC/AT through the data acquisition card. A software (as described in Section 4.3) written in C-language reads the frequency of the signal and calculates the flow rate. Actual flow rate is found out from the differential height measured across the venturi meter.

5.2 Test Results

The flow measurement system was set-up. Initially, the system was set-up with transducers for sing-around in one direction and the pulse repetition frequencies at different flow rates are noted down. The flow rates calculated using downstream transmission and the corresponding actual flows are given in Table 5.1. The value of acoustic velocity of water is required for this calculation. It is found out by installing two transducers face to face in a test bench containing water. The schematic diagram of the test bench is shown in Fig. 5.2. One of the transducers is operated as transmitter and the other as receiver. The received signal is fed to the amplifier of the flow measurement system, thus making the system in sing-around. The results of this experiment are summarized below.

Distance between the transducers, $d = 22.41$ cm.
Pulse repetition rate, $f = 6.704$ pulses per second.
Value of acoustic velocity of water, $c = fd = 1502.5$ m/s.

It may be noted that the actual velocity of sound in water, at 27 degrees, as reported by *Lynnworth* [5] is 1501.9.

A plot showing the values of the flow rates calculated using the single path transmission, at different actual flow rates, is shown in Fig. 5.3. Fig. 5.4 gives the percentage error from the best-fit line, at different flow rates. There is a maximum error of 50 lpm from the best-fit line. This large error could be due to the effect of delay introduced in non-flowing liquid part of the system.

Now, both the pair of transducers were connected to the system and were set-up in sing-around. The output of the phase coincidence circuit is given to the PC and the software finds out the frequency of the signal. The flow rate is calculated using this frequency. Actual flow rate is given by the differential height across the venturi meter. Value of differential height is entered through the keyboard, and the actual flow rate is found out from a look-up table. The values of actual flow rate and measured flow rate are displayed on the screen.

The readings of actual flow rate and measured flow rate are tabulated in Table 5.2. A graph showing measured flow rate at various values of actual flow rate is shown in Fig. 5.5. Fig. 5.6 shows the percentage error of the measured flow rate from the best-fit line. It can be seen that the percentage error is less than 5%.

The error in flowmeter reading could possibly be due to non-uniform velocity profile, delay introduced in the non-flow liquid part of the system and electronic circuits, or due to the error in estimating the value of d and θ. Apart from this, the calibration system itself might be contributing towards the error in the reading, as the accuracy, as claimed by the manufacturer of the venturi meter, is only 3%.

From the value of f_{up} *and* f_{dn}, the value of c at various flow rates, can be calculated. Table 5.3 gives the value of c obtained at various flow rates. We see that estimated c, is almost constant. This serves as a verification of the performance of the flowmeter and also its high accuracy. A slight increase in c could be due to changes in velocity profile across the pipe cross section with increasing flow rate.

Although there is a large error between the actual flow rate and measured flow rate, it was observed that the results are repeatable and the relationship is monotonic. Therefore, the curve can be digitized, stored as a look-up table, and used for obtaining corrected readings. A best-fit line approximation to the calibration curve in Fig. 5.6 shows error less than 5%. Hence, a look-up table is really not necessary.
The equation to the best-fit line is

$$y = 0.774x + 23.6$$

Thus the calibration relation becomes

$$Measured\ flowrate = 1.28 * (Observed\ flowrate - 23.6) \tag{5.1}$$

A set of readings were taken and the measured flow rate was calculated using Eqn. 5.1. The readings are tabulated in Table 5.4. A graph showing actual flow rate and measured flow rate with calibration is given in Fig. 5.7. Fig. 5.8 gives percentage error of this measured flow rate at various flows. It is observed from the curve that the error is more at flow rates less than 200 lpm, and from 200 to 600 lpm error is less than 5%. The reason for this increase in error could be attributed to the low accuracy of the venturi meter at lower flow rates.

Table 5.1. Actual flow rate vs. Measured flow rate, using single path transmission

No.	Actual flow (lpm)	prf	Measured flow (lpm)
1	0	8.9982	40.2
2	98.0	9.0012	120.3
3	229.0	9.0091	407.8
4	274.0	9.0121	509.0
5	360.5	9.0145	590.0
6	406.5	9.0159	637.2
7	444.5	9.0165	657.5
8	489.0	9.0179	704.7
9	519.5	9.0192	748.5

Table 5.2. Actual flow rate vs. Measured flow rate in SAF-2

No.	Actual flow (lpm)	Measured flow (lpm)	% error
1	0.0	12.0	2.0
2	40.0	59.0	1.0
3	96.0	110.5	2.6
4	185.0	164.0	0.6
5	229.0	191.4	-1.8
6	304.5	268.7	1.6
7	368.0	315.9	1.2
8	406.0	341.4	0.3
9	436.0	368.9	1.1
10	485.5	402.2	0.1
11	519.5	428.6	0.0
12	560.0	450.9	-0.7

Table 5.3. Value of c calculated at various flow rates

No.	Actual flow (lpm)	$f_{up} + f_{dn}$	Value of c (m/s)
1	0	17.9957	1503.5
2	98	18.0059	1504.4
3	229	18.0061	1504.4
4	314	18.0071	1504.5
5	391	18.0088	1504.6
6	436	18.0090	1504.6
7	468	18.091o	1504.6
8	502	18.0115	1504.8
9	548	18.0118	1504.8

Table 5.4. Actual flow rate vs Measured flow rate with correction

No.	Actual flow (lpm)	Measured flow (lpm)	% error
1	0	-6.5	-1.1
2	27.0	35.4	1.4
3	70.0	91.1	3.5
4	140.0	151.3	1.9
5	229.0	225.1	-0.7
6	274.5	283.7	1.5
7	314.0	319.4	0.9
8	381.5	388.7	1.2
9	421.7	439.7	3.0
10	441.5	450.3	1.5
11	488.5	475.3	-2.2
12	508.5	500.0	-1.4
13	539.0	519.5	-3.3
14	560.0	546.5	-2.3

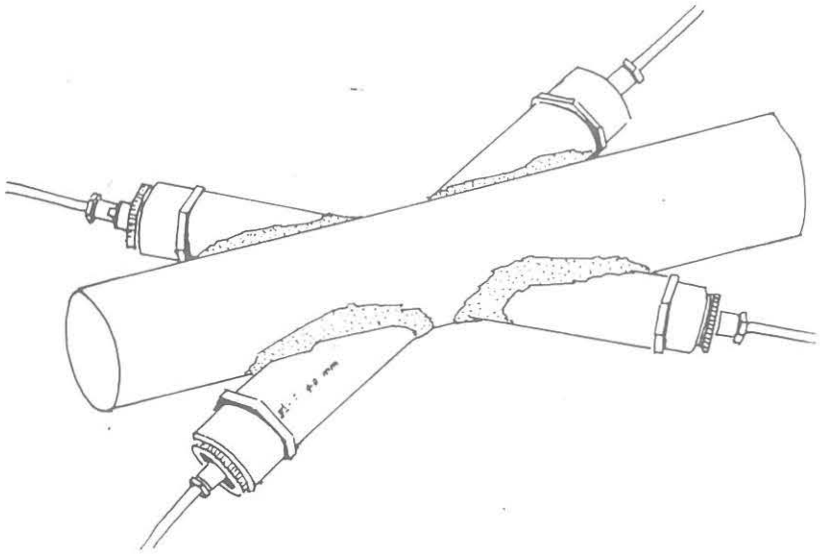


Fig. 5.1. Transducer assembly

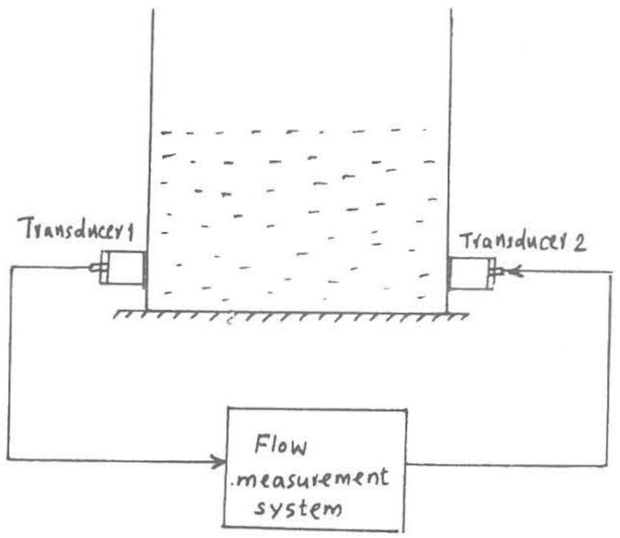


Fig. 5.2. Test bench for measurement of c

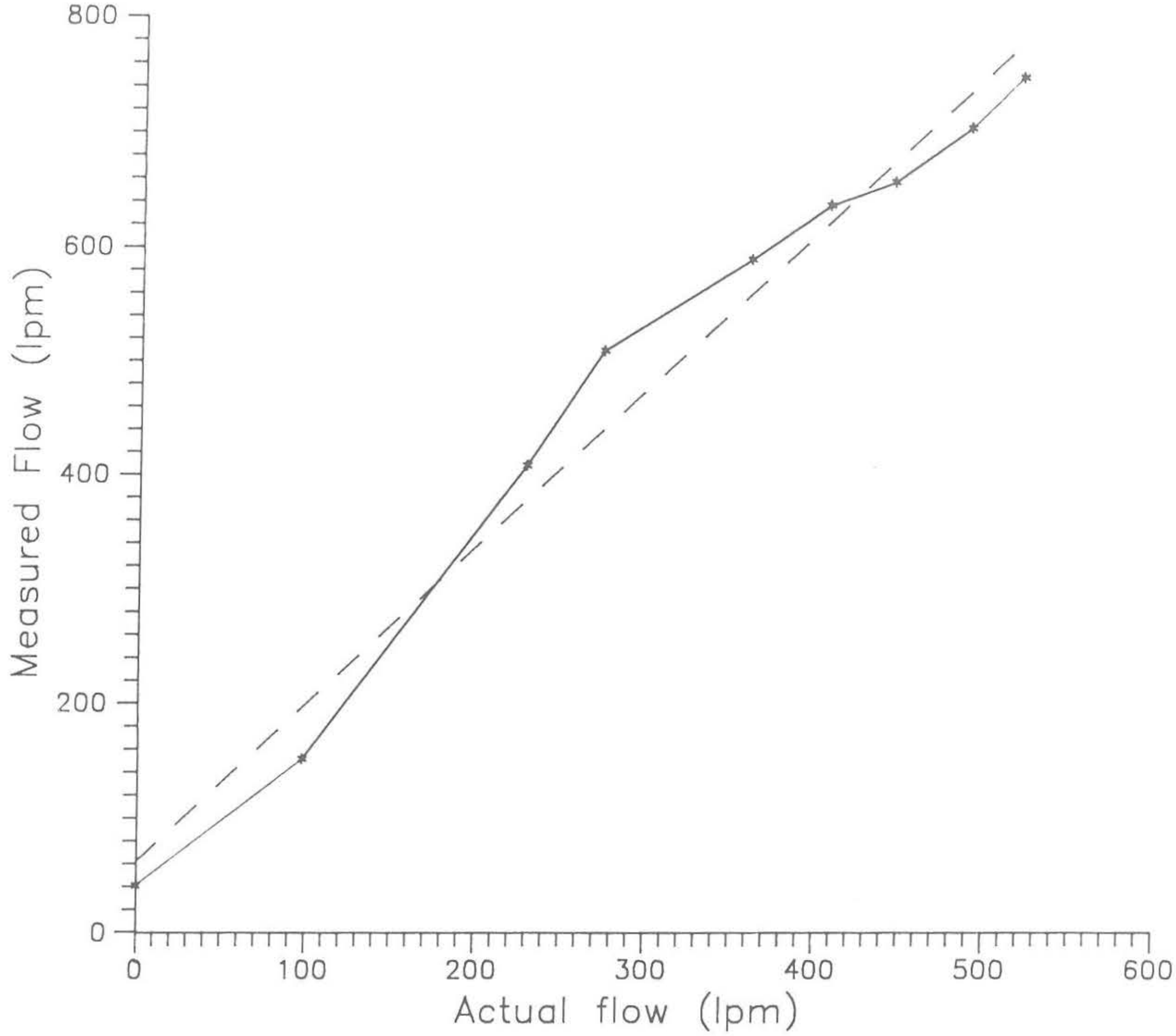


Fig. 5.3. Flow rate measured using single path transmission vs actual flow

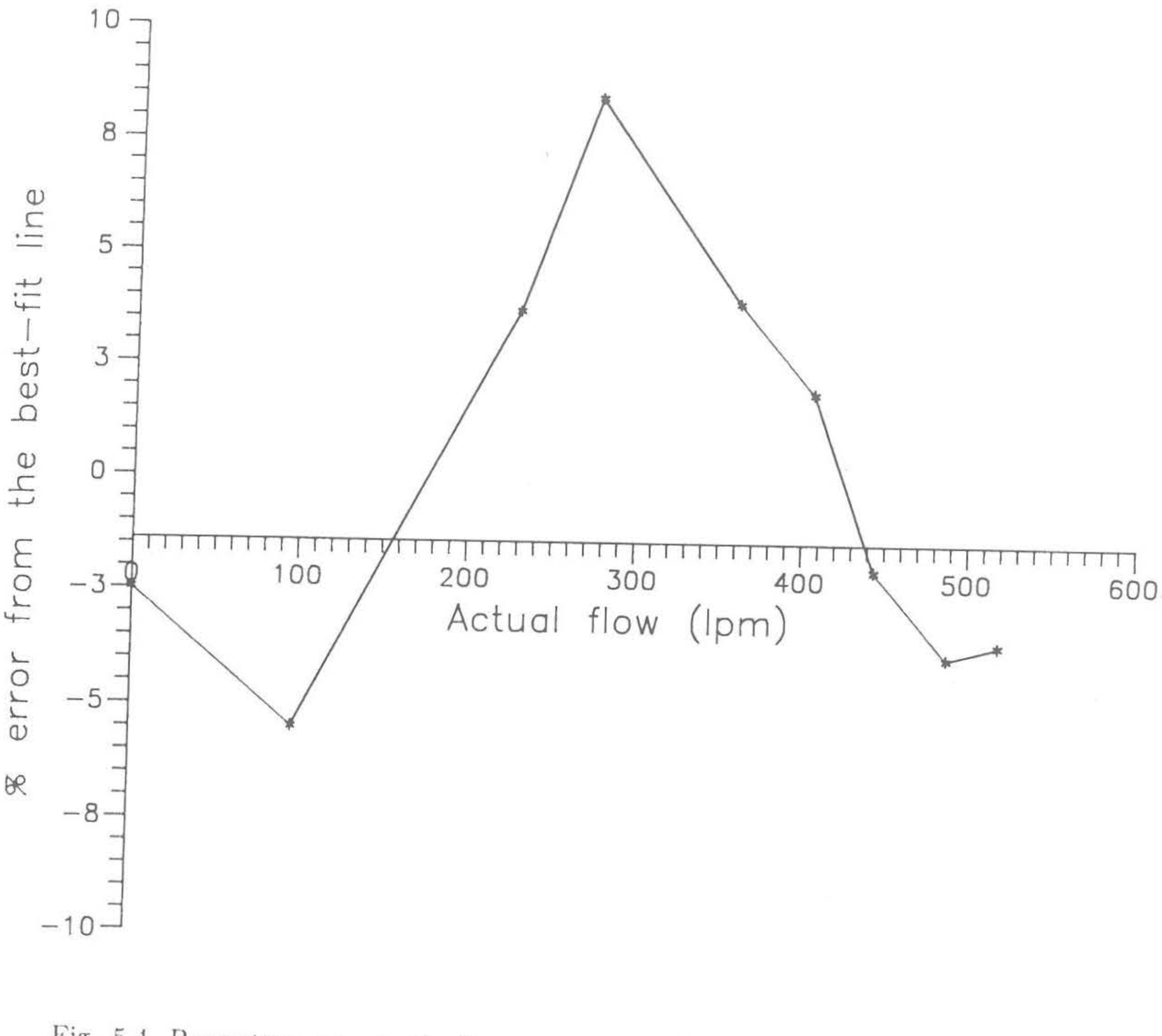


Fig. 5.4. Percentage error in the flow rate measured in single path transmission, from the best-fit line vs actual flow rate

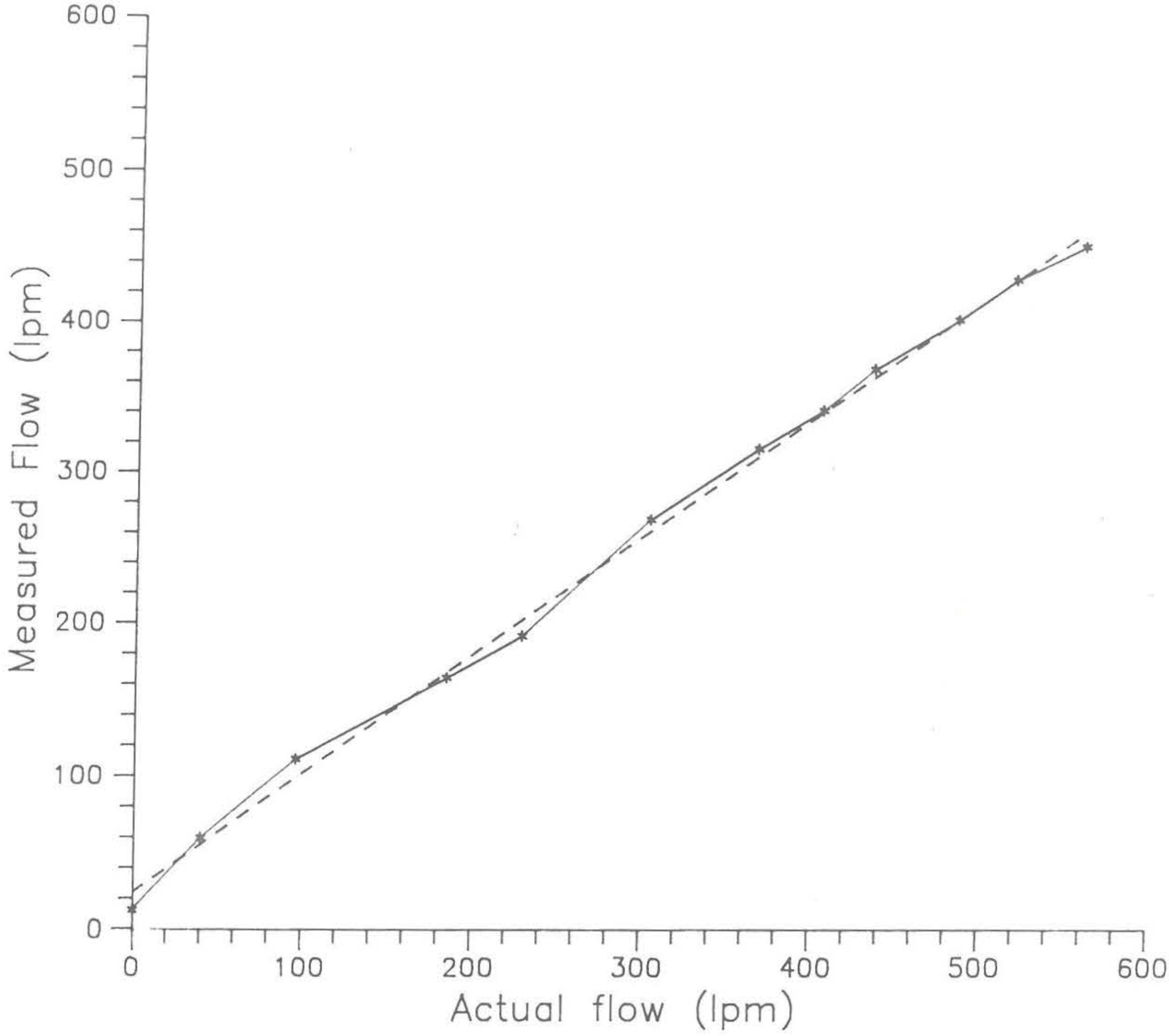


Fig. 5.5. Flow rate measured using dual path transmission vs actual flow rate

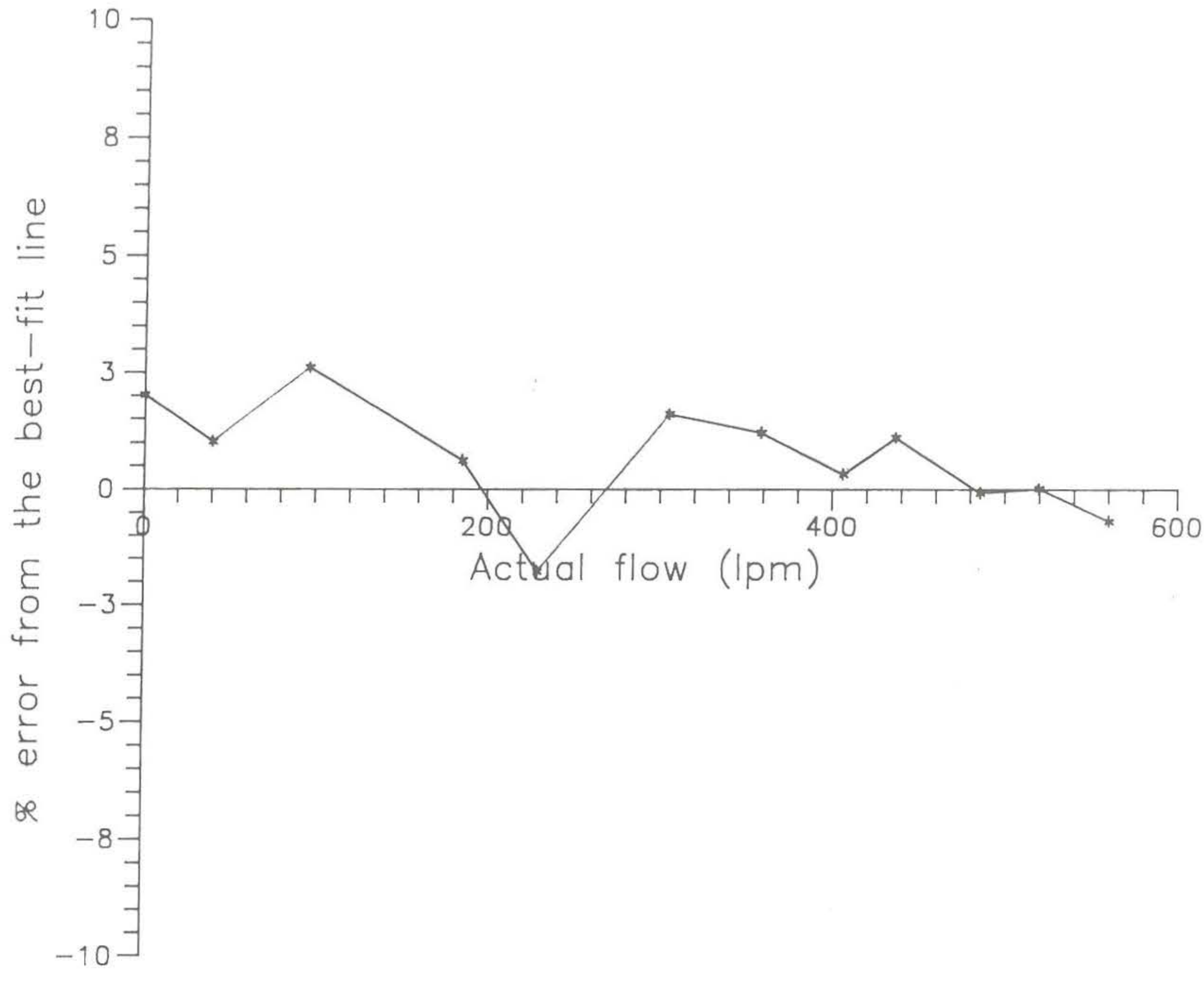


Fig. 5.6. Percentage error in the flow rate measured, from the best-fit line vs actual flow rate

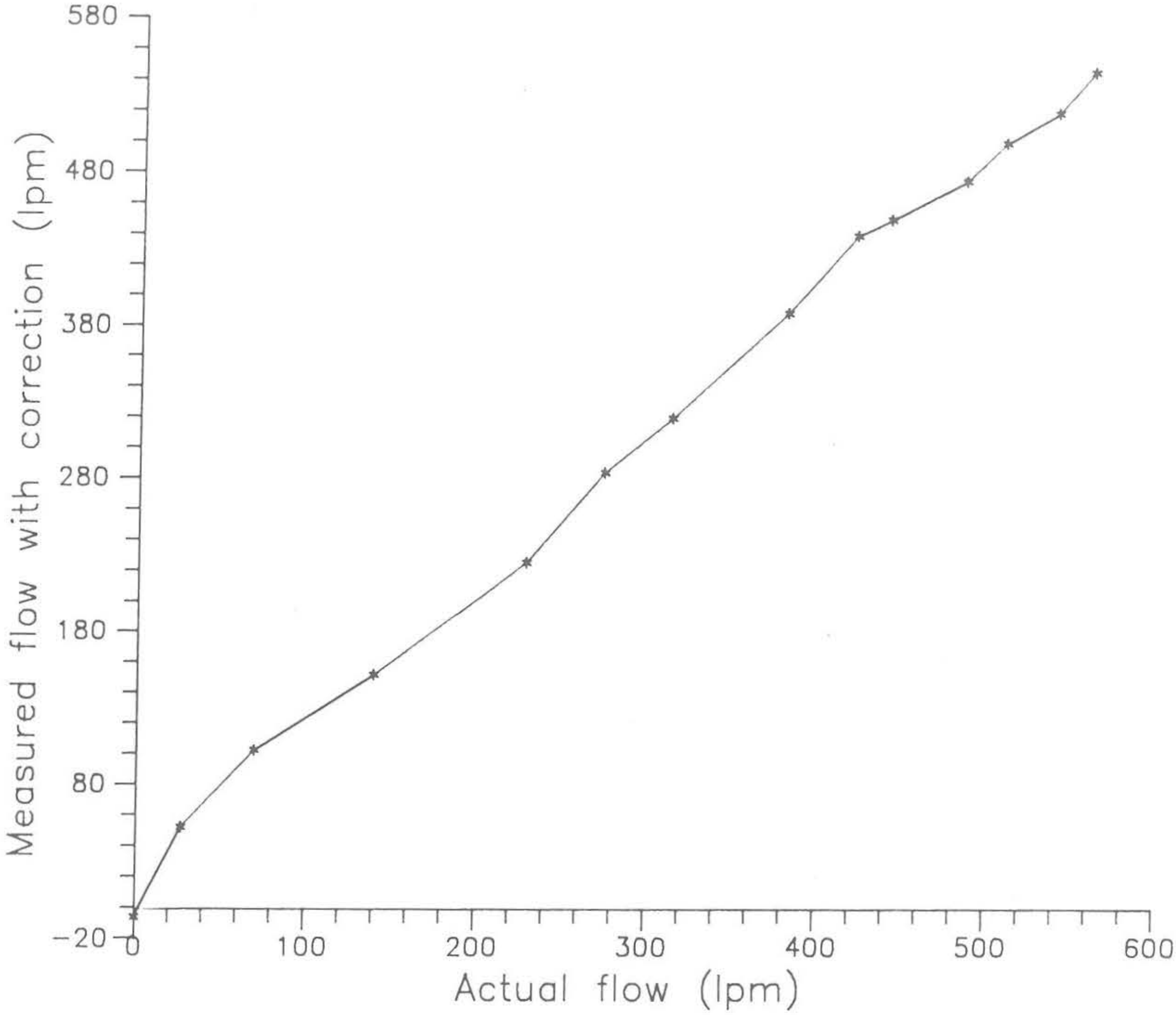


Fig. 5.7. Measured flow rate, with correction vs actual flow rate

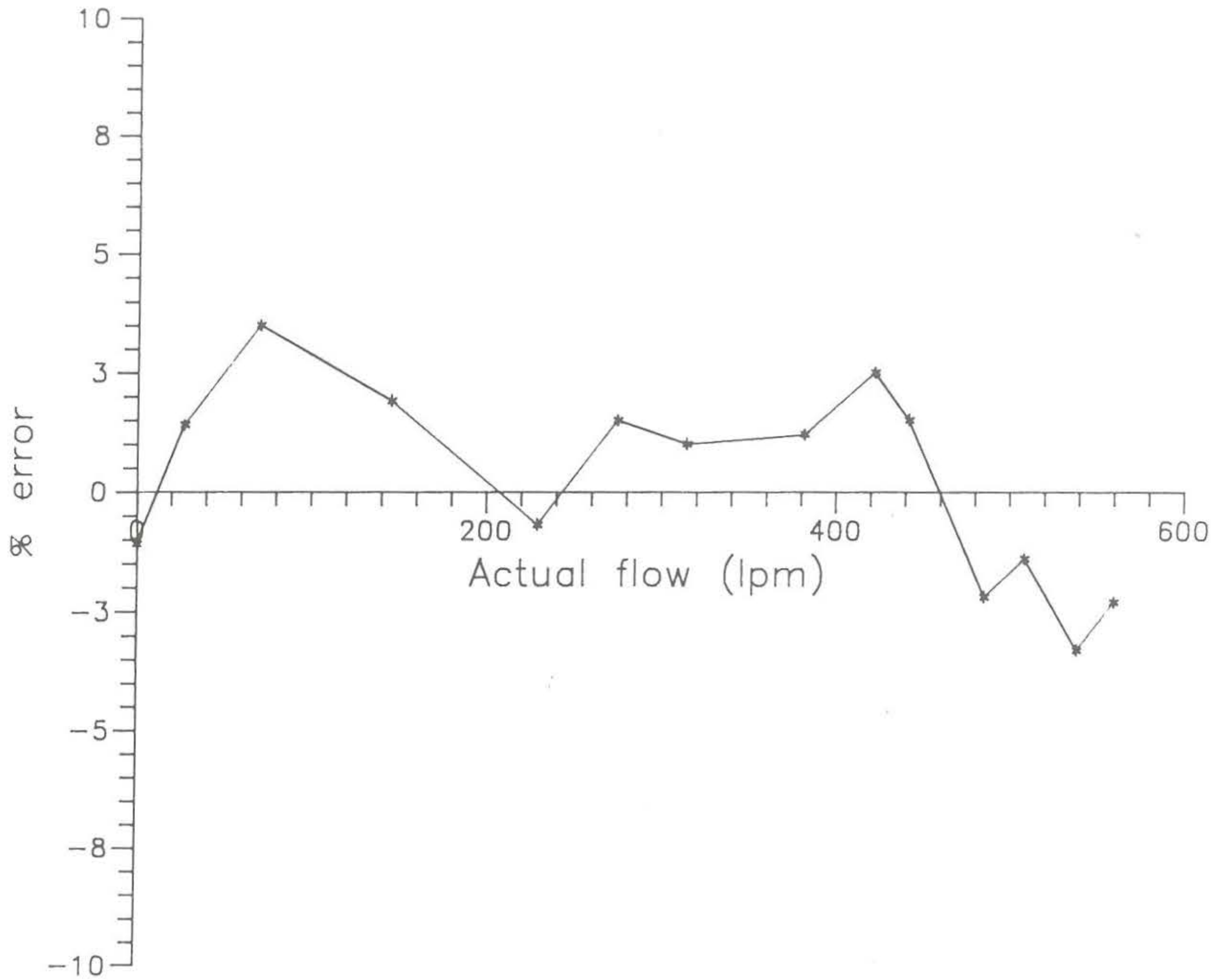


Fig. 5.8. Percentage error in the measured flow rate, with correction vs actual flow rate

Chapter 6

Summary and Conclusions

A thorough testing of the dual path sing-around ultrasonic flowmeter, SAF-1, developed by B.P.Parmar [4], was performed in the laboratory. It was found that the system gives arbitrary reading at higher flow rates. The reason for this instability was, the change in relative amplitude levels of the ultrasonic signal obtained at the receiving transducer, affecting detection of exact arrival of the pulse. Apart from this pitfall, several other drawbacks were detected in the hardware set-up of SAF-1.

A new flowmeter, referred to as SAF-2, with an improved technique for detection of received signal, has been developed. The signal received at the transducer is amplified to such an extent that it reaches saturation level. But as this high amplification results in amplification of noise and echoes, a diode clipping is incorporated to eliminate them after the first stage of amplification. Thus in contrast to SAF-1, amplitude fluctuations of the received signal does not affect the performance.

Complete circuit of the flowmeter has been re-designed and assembled accordingly. The transmitter and amplifier have a much better performance than that were used in SAF-1. The pulse width of the transmitter output is 200 ns. The amplifier has a bandwidth of 45 MHz. This wide bandwidth overrules any chance of distortion even when highly damped transducers of 5 MHz are used. High speed ICs have been used in the circuit to reduce the delay introduced by the electronic circuit. Metal film resistors of 1% tolerance has been used in the timing circuits. In SAF-1, the high voltage required for the pulser was taken by connecting the 0-30 V standard power supplies in series. Instead of this, a high voltage supply of 200 V has been developed.

A set-up for installing the immersion type transducers have been built. In this set-up, the distance between the transducers can be precisely adjusted. Also, precautions have been taken to eliminate the transmission of acoustic wave through pipe.

To reduce the effect of jitter in frequency caused by any obstructions in the liquid, a low pass filter is incorporated at the output of phase coincidence circuit.

Although efforts have been made to eliminate the sources of error, the actual readings given by the system 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. However, it was observed that the results are repeatable and the relationship between actual flow and measured flow is monotonic. When a best-fit line approximation of the curve was taken, the error was less than 5%. So for further calculation of flow rate a calibration factor is evaluated from the best-fit line.

A major source of error in the result could be the delay introduced in non-flow liquid part and electronic circuit. When the flowmeter is operated, with the transducers mounted outside the pipe, an additional delay will be introduced by the pipe wall. One way of getting rid of the effect of these additional delays is by taking the difference of transit times in upstream and downstream directions. It would be worthwhile to try out this method and make a comparison of the results. But in the time difference method, the calculation depends on the acoustic velocity of fluid. As the velocity of sound varies with temperature, pressure, and density, compensation for velocity of sound is necessary in this method.

During the operation of the flowmeter a slight variation in the the pulse repetition frequencies was noticed, even when the liquid is stationary. This could be due to the tolerance of the passive components used in the timing circuits. This has to be investigated further.

Effect of possible error in angles of transducer axis can be eliminated by switching the same pair of transducers in transmit and receive mode. But in this case the pulse repetition frequencies have to be stored to find out the difference of frequencies.

The flow measurement system may develop instability if used in pipes of larger diameter. The magnitude of received ultrasonic signal may become comparable with the noise signals, thus causing spurious triggering. In this case transducers of better sensitivity would have to be used.

The system developed, was tested for flow rates in the range of 0-600 lpm and is having an accuracy of 5 % throughout this range.

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Appendix A

Specifications of the System

A.1 Transmitter

Output: Negative spike voltage
Amplitude: 50 to 180 V
Pulse width: 150 to 2800 ns
Input: +12 V pulse of 3 μs minimuum width
Damping: 50 to 1000 Ω

A.2 Amplifier

Bandwidth: 0 to 45 MHz
Gain: 0 to 45 dB variable

A.3 Transducer

Frequency - 5 MHz
Frequency Tolerance - $\pm 10\%$
Bandwidth - $65 - 100\%$
Rise time cycles - 1
Decay time cycles - Instant

A.4 Calibration system

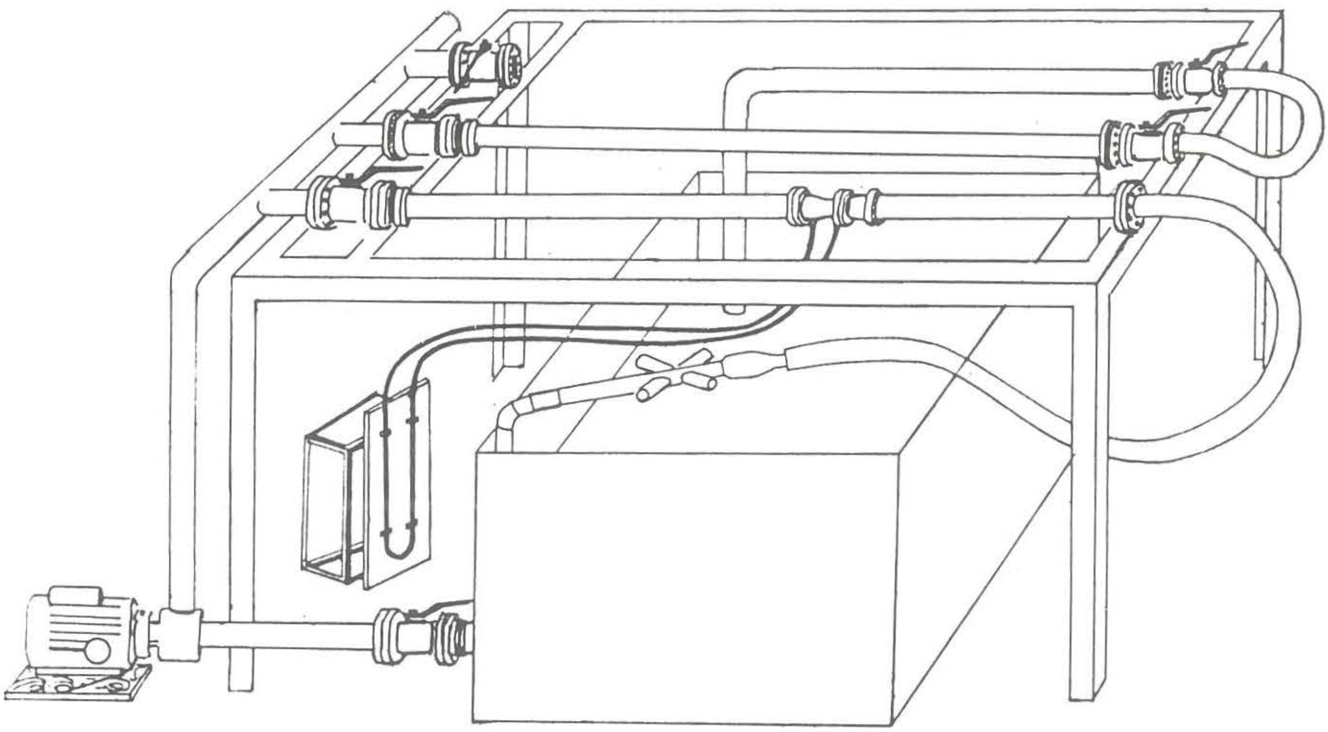
Instrument used - venturi meter
Range - 0 to 1500 lpm
Accuracy - 3%

A.5 Overall specifications

Range - The instrument was tested in the range 0-600 lpm
Accuracy - 5%

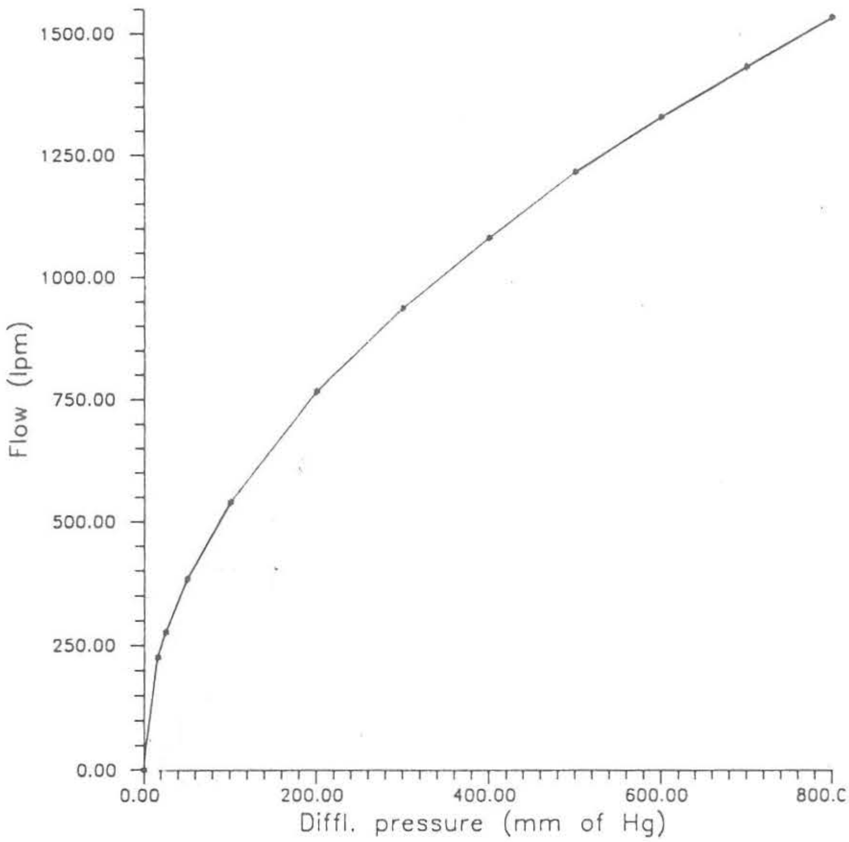
Appendix B

Water Circulation System



Appendix C

Calibration Curve of the Venturi meter



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