SET-UP FOR CROSS CORRELATION FLOW-METER

A dissertation

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for the degree of

Master of Technology

By

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ABSTRACT

In many fluid flow measurement applications, it is required that the flow-meters should not obstruct the flow. In the cross correlation flow-meter, flow is measured by obtaining the time taken by disturbance in the flow to travel from one point to other separated by a known distance. Flow measurement is obtained from transit time, which is estimated by locating the peak in cross correlation between disturbance signals from both channels.

This project aims at developing sensor electronics and correlator for cross correlation flow-meter using ultrasonic transducers. Sensor electronics include RF amplifier, demodulator and band-pass filter. Amplitude demodulation is used to detect the disturbance. The cross correlation is obtained using frequency domain method. The location of the peak of cross correlation is used to estimate the flow rate.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In process industries, a wide range of fluids from clean liquids and gases to toxic, radioactive fluids or fluids containing suspended solid materials are handled. The flow of these fluids can be monitored by flow-meters like mechanical, differential pressure type, ultrasonic, electromagnetic etc. Mechanical flow-meters, and differential pressure type flow-meters [1] like orifice plates, venturi, and pitot tubes are commercially cost effective and more popular for simple flow measurements. But these flow-meters introduce a pressure drop and therefore affect the fluid flow. These are subject to wearing of parts when fluid contains suspended solid materials. Ultrasonic and electromagnetic flow-meters do not obstruct the flow. In ultrasonic transit time flow-meter the difference between transit times of ultrasonic pulse with and against the flow is a measure of the flow. However, because the velocity of sound is much greater than the velocity of the fluid, these devices involve measuring a small difference between two large quantities which is a major source of error. The variation in the velocity of sound due to temperature or density fluctuations of fluid gives rise to considerable error in the measurement. Also to obtain accurate transmission path, ultrasonic transducers have to be in contact with the fluid. Electromagnetic flow-meter does not obstruct the fluid flow, but it can only be used with fluids which have some minimum electrical conductivity.

In contrast to above methods, cross correlation flow-meter with ultrasonic sensor does non-intrusive, non-contact measurements. The cross correlation flow-meter [2,3,4] measures the flow by sensing some disturbance in the flow, usually fluid turbulence and measuring time the disturbance takes to travel from one position to the other. This transit time can be determined by obtaining the cross correlation between the disturbance signals at two different locations. In fact, peak of the cross correlation function will appear for delay equal to the transit time. Knowing the distance between two positions, flow can be determined. Since flow is determined by obtaining delay for disturbance to reach from one position to the other, measurement does not depend on fluid properties. Also transducer calibration is not required for different fluids. Any spurious interferences on the measured signal are rejected since they are not related to the signal. Usually delay measurements are done by digital equipment employing a crystal clock which is precise. Recent developments in hardware and software computation techniques to evaluate cross correlation function have helped to develop this flow-meter.

The cross correlation flow-meter measures the rate at which the disturbance signal travels. To obtain the flow rate, a conversion factor has to be applied. This factor depends on the flow profile across the cross section of the pipe. The flow profile is a function of flow rate and fluid properties and thus conversion factor may be non-linear.

1.2 SCOPE OF THE PROJECT

The aim of this project is to develop sensor electronics and correlator for cross correlation flow-meter using ultrasonic sensors. This project is a part of BRNS-sponsored project at IIT Bombay for developing cross correlation flow-meter. The project comprises of two major parts. Sensor electronics will obtain the signal equivalent to disturbance in the flow which is of interest. This basically involves a high frequency amplifier to amplify received signal, followed by a demodulator to detect the low frequency disturbance signal. A low pass filter gives an output which carries information about disturbance in the fluid. Identical circuits have to be provided to obtain the signals from two positions.

The second part involves the computation of cross correlation function of above signals, obtaining transit time and hence determining the fluid velocity. Developments of digital circuits have made it easier to work with digital signals. Hence the signals are sampled and digitized, and the cross correlation function is obtained using frequency domain method.

1.3 OUTLINE OF THE REPORT

The report describes theory of cross correlation and how it can be applied in the flow measurement. It also gives details of sensor electronics and correlator which have been developed.

Chapter 2 explains how the cross correlation principle can be used for flow measurement. It describes various subsystems involved in a cross correlation flow-meter. Different methods of cross correlation computation are discussed. The design considerations for sensor electronics are explained. Various sensing techniques used to detect disturbance in the flow and different correlators used in cross correlation flow-meters are listed.

Chapter 3 gives details of the hardware set-up. Design and implementation of ~~various~~ sensor electronics ~~is~~ are described in brief. Test results of the individual circuit and performance obtained from overall circuit are discussed.

Chapter 4 explains correlator implementation using frequency domain method. The software is explained using pseudo code. Some test results with delayed sinusoidal inputs and for various signal to noise ratios are also given.

The concluding chapter summarizes work done in this project and gives suggestions for the further work.

CHAPTER 2

CROSS CORRELATION FLOW-METER

2.1 CROSS CORRELATION IN FLOW MEASUREMENT

Cross correlation is a mathematical technique of representing the amount of similarity between two signals. If disturbance is present in fluid flow and if it can be detected then correlation can be used to obtain the flow rate.

2.1.1 Cross correlation principle

Cross correlation is a time domain measure of amount of similarity between two signals [5]. Cross correlation function for a particular delay is obtained by multiplying delayed version of one signal with other signal and averaging it over some time period. Mathematically, it can be represented as

$$r_{uv}(\tau) = \frac{1}{T} \int_{t=0}^{T} u(t-\tau) \times v(t)\, dt$$

between two signals $u(t)$ and $v(t)$ for delay of 'τ', and 'T' is the period of integration. To obtain accurate correlation values, integration period should be as large as possible.

The cross correlation function of two discrete signals $u(n)$

and $v(n)$ [6] is given by

$$r_{uv}[i] = \frac{1}{N} \sum_{n=0}^{N-1} u[n-i] \times v[n]$$

where, integration is replaced by summation and 'N' is the total number of samples.

2.1.2 Application of cross correlation in flow measurement

The cross correlation flow-meters measure the flow by determining the transit time for a disturbance signal to reach from one position to the other [3,7]. Referring to Fig. 2.1, the disturbance signals are detected by sensor 'A' and 'B' separated by distance 'd'. Sensor 'A' is encountered first by the flow or in other words, 'A' is upstream sensor while 'B' is sensor on the downstream. Let the disturbance signal detected by sensor 'A' i.e. upstream signal be denoted by $u(t)$, while the downstream signal by $v(t)$. We are interested in the time taken by the disturbance to travel from 'A' to 'B'. If this transit time is denoted by τ^*, then ideally $v(t) = u(t-\tau^*)$.

The cross correlation function $r_{uv}(\tau)$ is defined earlier as

$$r_{uv}(\tau) = \frac{1}{T} \int_{t=0}^{T} u(t-\tau) \times v(t)\, dt$$

This function will exhibit a maximum value when the cross correlation delay 'τ' is equal to the transit time 'τ^*'.

For the turbulence pattern which is almost frozen, turbulent convection velocity is almost equal to mean flow

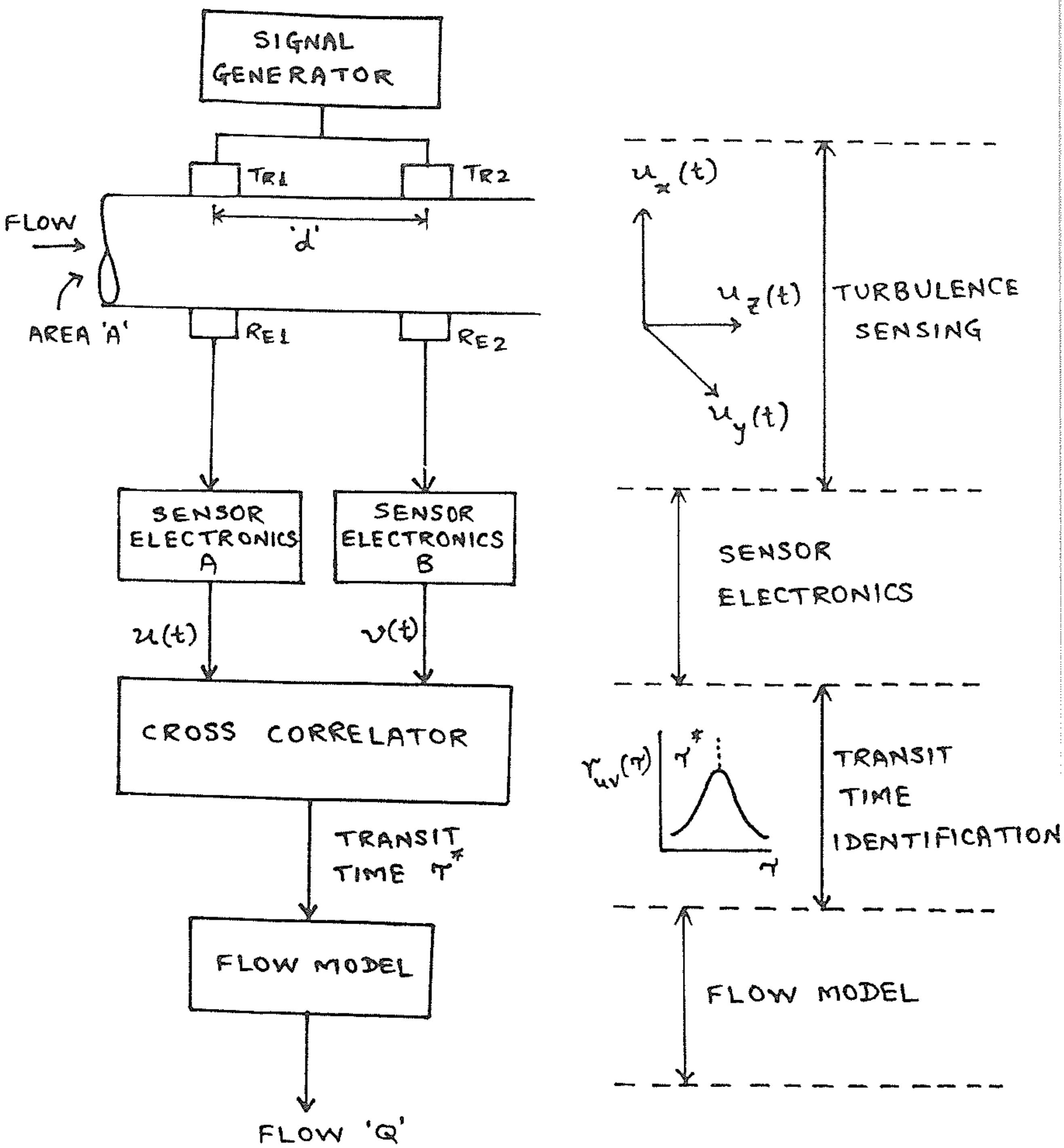


FIG. 2.1 Cross Correlation Flow-meter - Schematic of Subsystems

velocity as stated in [8]. Thus the flow velocity is given by

$$V = \frac{d}{\tau^*}$$

The cross correlation flow-meter actually measures the rate at which the disturbance travels. A conversion factor has to be applied to obtain the flow rate. The factor depends on the flow profile across the cross section of the pipe, which is not uniform. It depends on the flow rate and fluid properties. This makes the conversion factor non-linear. The volume flow rate is given by

$$\begin{aligned} Q &= K \times V \times A \\ &= K \times \left(\frac{d}{\tau^*}\right) \times A \end{aligned}$$

where 'A' is cross sectional area of the pipe and 'K' is the calibration factor which depends on the flow pattern.

2.2 METHODS OF CALCULATING CROSS CORRELATION

Cross correlation function can be obtained in time domain or in frequency domain. The computation in time domain involves delaying of one signal with respect to other, multiplying the two signals, and averaging the product over a suitable time period. This is repeated for different values of delay. The frequency domain computation involves taking DFTs of both signals, obtaining cross correlation function in frequency domain, and then taking inverse DFT to obtain cross correlation function in time domain.

2.2.1 Time domain computation

The cross correlation function of two discrete signals can be written by removing braces for simplicity as follows.

$$r_i = \frac{1}{N} \sum_{n=0}^{N-1} u_{n-i} \times v_n$$

The above equation can be calculated using two different approaches (a) point-by-point calculation and (b) evolutionary calculation [2].

(a) Point-by-point calculation

The cross correlation function can be written as a set of individual equations.

$$r_0 = \frac{1}{N} (u_0 v_0 + u_1 v_1 + u_2 v_2 + \cdot \cdot \cdot + u_{N-1} v_{N-1})$$

$$r_1 = \frac{1}{N} (u_{-1} v_0 + u_0 v_1 + u_1 v_2 + \cdot \cdot \cdot + u_{N-2} v_{N-1})$$

$$\cdot$$

$$\cdot$$

$$\cdot$$

$$r_I = \frac{1}{N} (u_{-I} v_0 + u_{-I+1} v_1 + \cdot \cdot \cdot + u_{(N-1)-I} v_{N-1})$$

An example of cross correlation function is shown in Fig. 2.2[a]. This can be implemented by following two methods [9] and schemes for them are shown in Fig. 2.2[b] and [c].

In series method, both signals are sampled at a particular rate and are stored in an input buffer. One of these is delayed by constant value of delay. The delayed signal and other signal are multiplied and averaged over N samples. This gives cross correlation value for that particular delay. The process is time consuming since it has to be

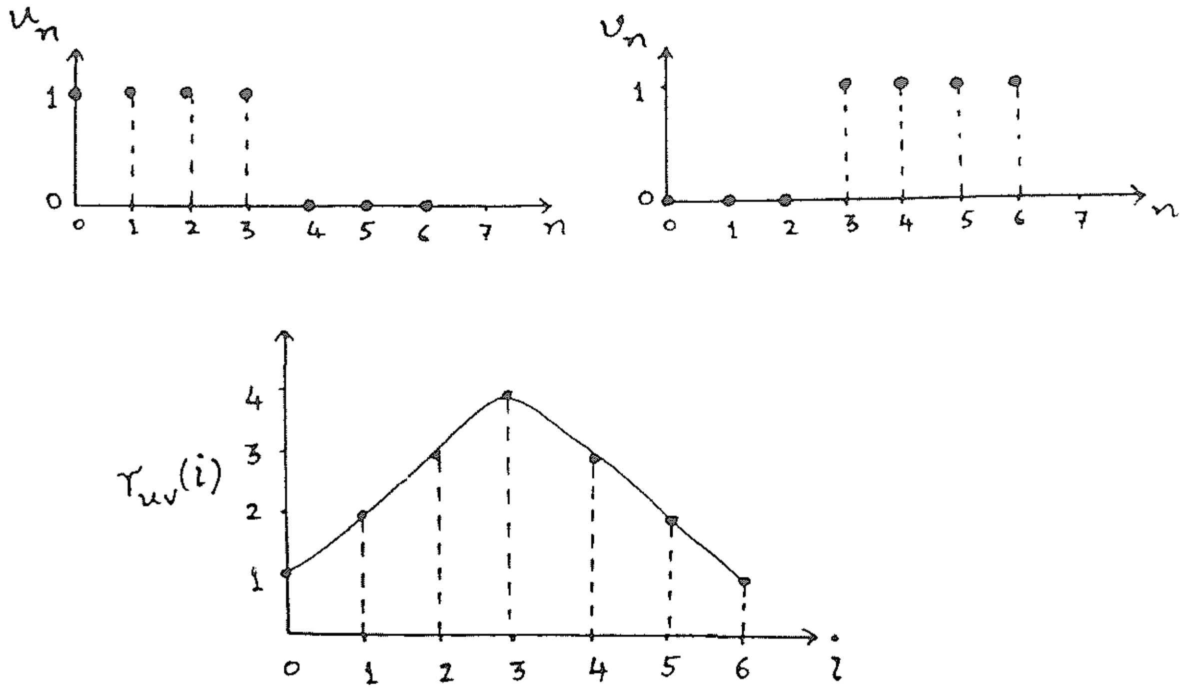


FIG. 2.2[a] Cross Correlation Function

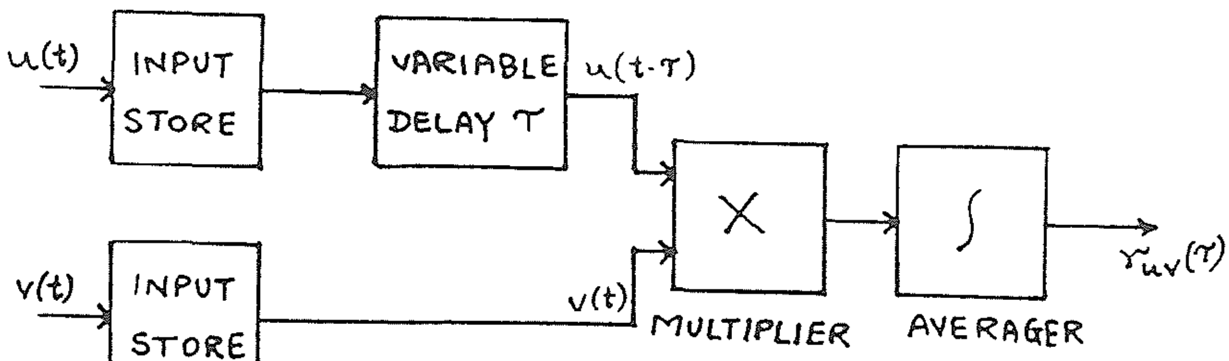


FIG. 2.2[b] Series Method [9]

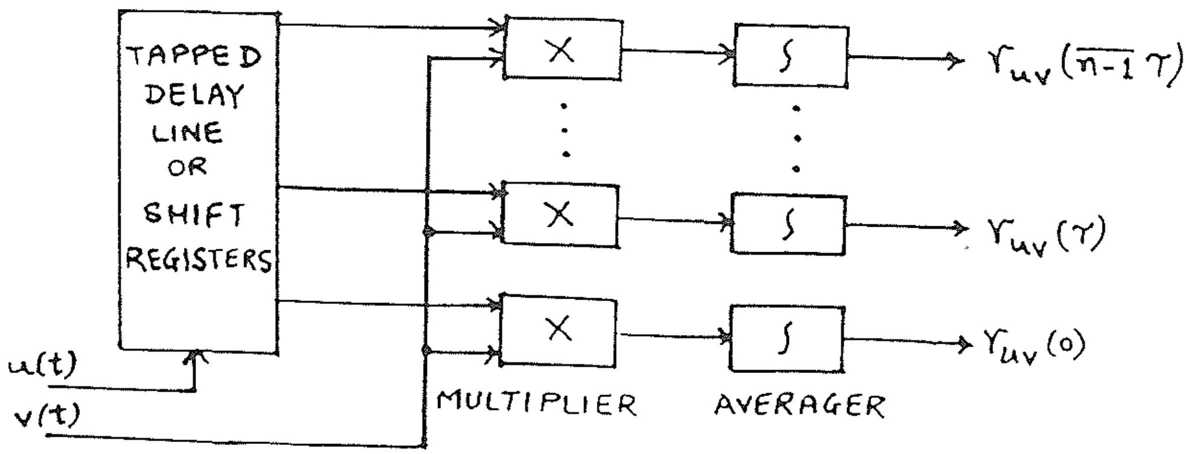


FIG. 2.2[c] Parallel Method [9]

FIG. 2.2 Point-by-point Calculation of Cross Correlation repeated for different values of delay. The only advantage is that it is economical as very less hardware is required.

In parallel method, delay line provides 'N' delayed versions of one signal and hence cross correlation values for different delays are obtained simultaneously. The drawback is that it requires complicated hardware circuitry. The total time required for computation of complete cross correlation function is $\frac{1}{N}$ times that by series method but the cost involved is 'N' times more.

(b) Evolutionary calculation

The individual cross correlation function equations are rearranged as follows.

$$N\begin{bmatrix} r_0 \\ r_1 \\ \cdot \\ \cdot \\ r_I \end{bmatrix} = \begin{bmatrix} u_0 \\ u_{-1} \\ \cdot \\ \cdot \\ u_{-I} \end{bmatrix} v_0 + \begin{bmatrix} u_1 \\ u_2 \\ \cdot \\ \cdot \\ u_{1-I} \end{bmatrix} v_1 + \cdot \cdot \cdot + \begin{bmatrix} u_{N-1} \\ u_{N-2} \\ \cdot \\ \cdot \\ u_{N-1-I} \end{bmatrix} v_{N-1}$$

1^{st} evolution

2^{nd} evolution

In the evolutionary method, the first term in above equation is calculated and then second term is added until final term is added. Thus cross correlation function will evolve in time evolutionary manner. For sequences u_n and v_n considered in point-by-point calculation method, the cross correlation function will evolve as shown in Fig. 2.3[a].

Series parallel correlator configuration (Fig. 2.3[b]) uses evolutionary calculation.

In series-parallel method, delayed samples of one signal and cross correlation function values for different delays are stored in circulating stores. The other signal is multiplied with all delayed versions of first signal and corresponding cross correlation function values are updated. Lower sampling rate is permitted since for one sample, 'N' multiplications and updates are involved. The major advantage of this method is that it can be easily realized by computer software.

2.2.2 Frequency domain computation

The cross correlation function for discrete signals [6] is given by

$$r_{uv}[i] = \frac{1}{N} \sum_{n=0}^{N-1} u[n-i] \times v[n]$$

Taking the discrete Fourier transform of above equation

$$R_{uv}(k) = \frac{1}{N} U^{*}(k) \times V(k)$$

where $R_{uv}(k)$, $U(k)$ and $V(k)$ denote the discrete Fourier transforms of cross correlation function and the two signals.(The proof of above result is given in Appendix A).

Cross correlation function can be obtained by taking inverse discrete Fourier transform of $R_{uv}(k)$. Thus whole task of delaying, multiplying, and averaging reduces to obtaining discrete Fourier transforms, and multiplying the

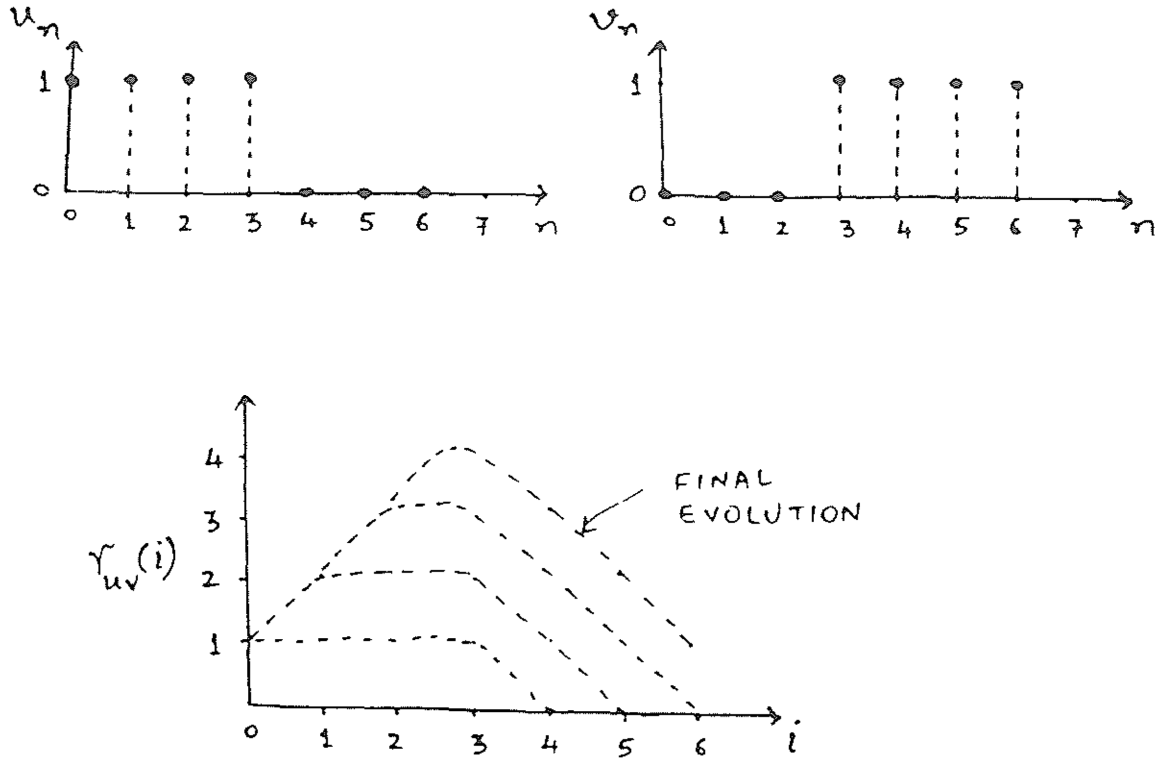


FIG. 2.3[a] Cross Correlation Function

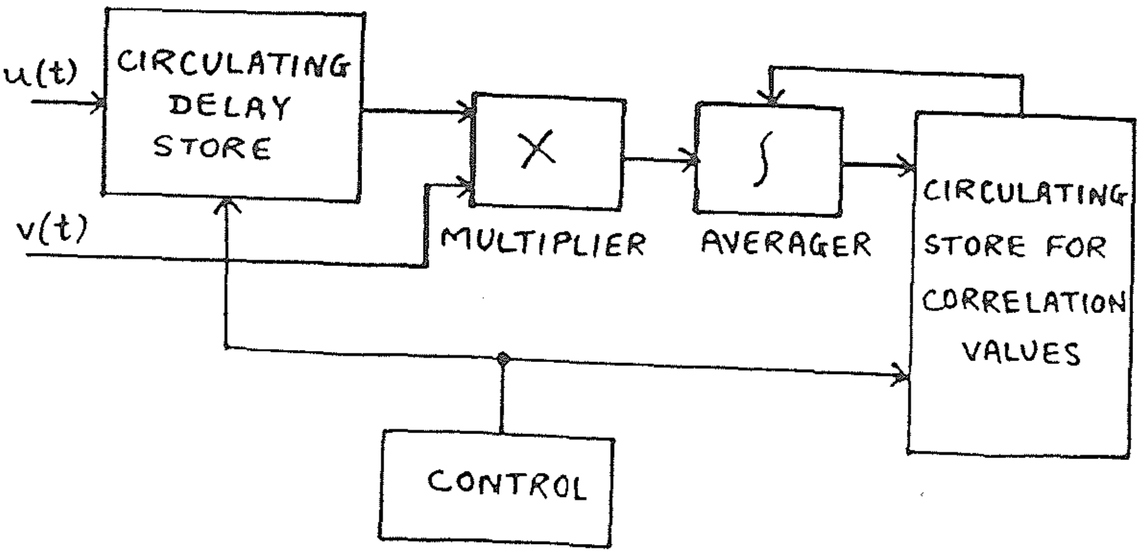


FIG. 2.3[b] Series-Parallel Method [9]

FIG. 2.3 Evolutionary Calculation of Cross Correlation two. Number of samples 'N' is finite and for 'N' point DFT, it assumes that the signal is repetitive with period 'N'. This results into circular convolution [6,10] rather than linear. In this method, linear correlation can be obtained by padding 'N' zeros to 'N' sample values and taking '2N' point DFT. The effect of finite number of samples can be minimized by choosing cross correlation period at least thrice the maximum transit time of interest.

This method is more efficient, as for computing discrete Fourier transforms, efficient FFT algorithms can be used. The efficiency of algorithm is best judged by number of multiplications involved. For computation of cross correlation in time domain, N (number of samples) multiplications are required for cross correlation function at a particular delay. Thus for N cross correlation values N^2 multiplications are required.

In frequency domain, to obtain the same cross correlation values as in time domain, N zeros have to be added to N samples and 2N point DFT has to be considered. Radix '2' FFT algorithm can be used to compute discrete Fourier transform which requires $2N\log_2 2N$ multiplications for 2N point DFT. For complete cross correlation function, $4N\log_2 2N$ multiplications are required for DFTs of two signals; 8N multiplications for multiplying DFTs, and $2N\log_2 2N$ for obtaining inverse DFT. Thus total number of multiplications involved are $6N\log_2 2N + 8N$.

$$N^2 > 6N\log_2 2N + 8N \qquad \text{for} \quad N > 64$$

Thus for obtaining cross correlation function for more than 64 samples, frequency domain method is more efficient.

$$\text{Efficiency factor} = \frac{N^2}{6N\log_2 2N + 8N}$$

$$= \frac{N}{6\log_2 N + 6 + 8}$$

For N = 1024, Efficiency factor = 13.84.

2.3 DESIGN OF CROSS CORRELATION FLOW-METER

The schematic of subsystems of cross correlation flow measurement system [3] is shown in Fig. 2.1. The process of cross correlation flow measurement involves turbulence sensing, sensor electronics, and correlator which will determine transit time. An appropriate flow model is used to obtain the volume flow of fluid. Each of these aspects is discussed below, especially for flow-meter with ultrasonic sensors.

2.3.1 Turbulence sensing

The disturbance signals are usually generated by fluid turbulence. The flow turbulence eddies can be considered as vector velocities in the x- and y- directions perpendicular to the flow axis and the z-direction along the flow axis. These three velocity components are all stationary ergodic processes as shown in Fig. 2.4[a]. The mean values of x-and y- components are zero because there can be no flow of fluid through pipe wall. The mean value of the z- component is the transport velocity of the flow.

A typical spectrum of turbulent eddies [3] is shown in Fig. 2.4[b]. The spectrum is a band limited white noise with its upper frequency limit as high as 10 kHz. Ideally flow sensors in a cross correlation flow-meter should respond over entire range of the bandwidth. This will enable the accurate flow measurement with sharp response time. But this is possible only with point sensing devices which are not feasible for industrial use. The sensors like ultrasonic transducers, capacitive and conductivity sensing plates come across with substantial volume of flow and hence will not respond to high frequency turbulent eddies. The expression for cut-off frequency due to above spatial averaging effect [3] is given as

$$f = \frac{v}{2d}$$

where 'v' is velocity of fluid and 'd' is ultrasonic beam diameter. For ultrasonic sensor with beam diameter of 20 mm and fluid flowing at 4m/s, the cut-off frequency is 100 Hz.

2.3.2 Sensors in cross correlation flow measurement

Sensor selection is an important aspect in design of cross correlation flow-meter for a particular application. The sensing principles fall into three broad categories [3] which are (a) modulation of radiation by flowing fluid,

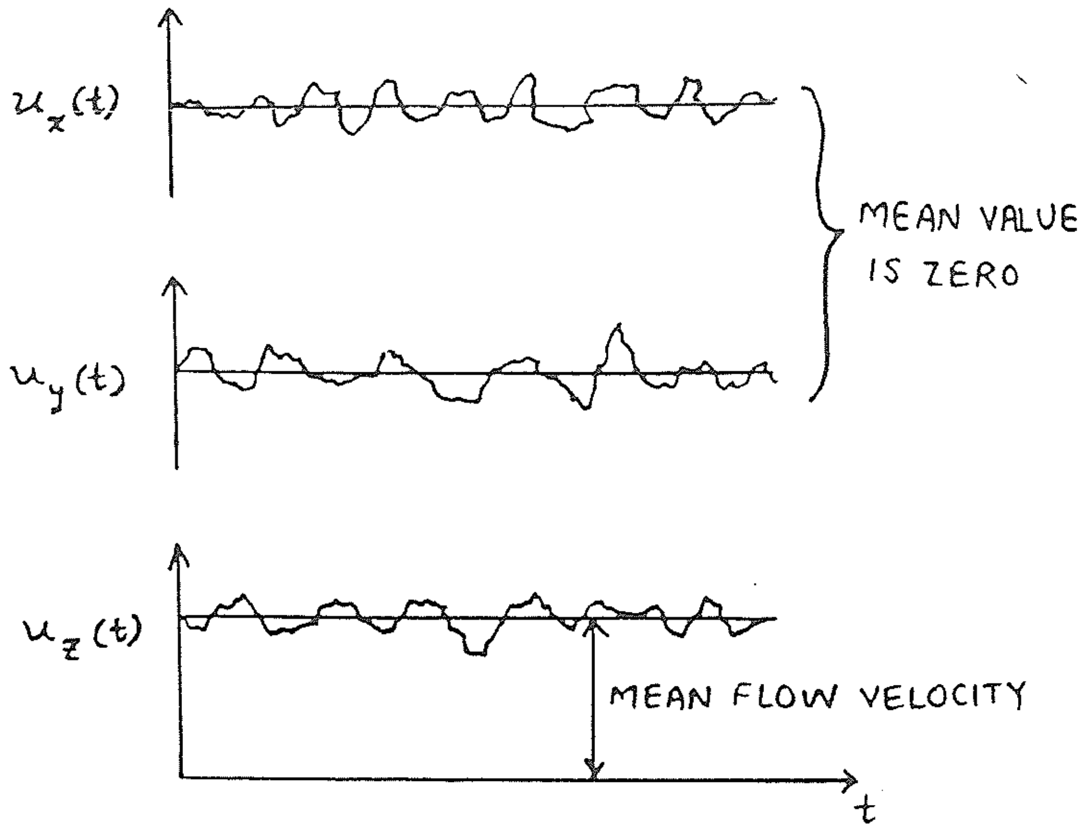


FIG. 2.4[a] Turbulent Vectors

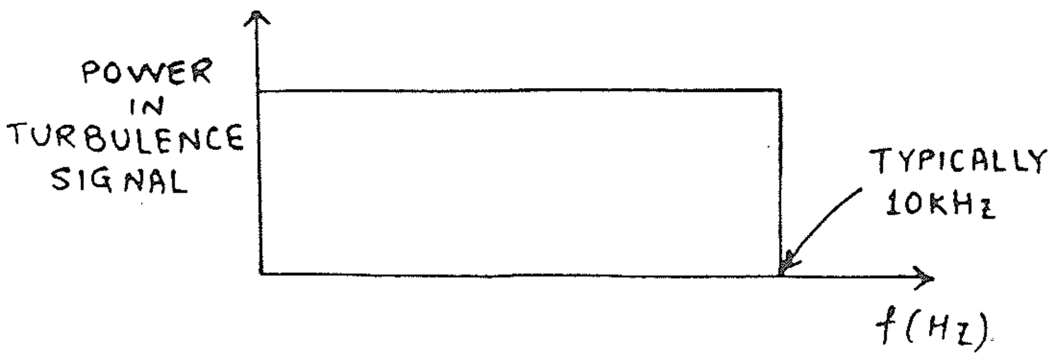


FIG. 2.4[b] Power Spectrum of Turbulence Signals

FIG. 2.4 Turbulence Signals in Cross Correlation [3]

(b) emission of radiation by flowing fluid, and (c) instantaneous measurement of electrical and thermal properties of the fluid.

(a) Modulation of radiation by flowing fluid

This category includes modulation of acoustic (ultrasound) or electromagnetic (visible light, gamma rays) waves. In case of ultrasonic beams, frequencies in the range of 1 MHz are used so that they can penetrate readily through the pipe wall. Optical cross correlation devices have proved successful for measuring flow in open channels. Surface ripples (river flow) or particles suspended in fluid (smoke from a chimney) form the disturbance signal in such case. Modulation of gamma rays is applicable when solid particles are present in a fluid flow. These techniques are attractive since the radiation sensors can be frequently mounted externally to the pipe.

(b) Emission of radiation by flowing fluid

These include thermal and ionizing radiation by the fluids. The turbulence in hot gas flow inevitably leads to variations of temperature in the fluid and these provide good tagging signal which can be used for flow measurement purpose [11]. In case of flow of highly radioactive fluid in nuclear fuel plants, variation in the emitted radiations are caused by either solid particles or gas bubbles in the flowing fluid. These variations can be deteoted by scintillation detectors mounted outside the primary radiation shield.

(c) Instantaneous measurement of electrical and thermal properties of the fluid

Capacitor sensors are particularly useful for measuring two phase flows [7] like the flow of gases with suspended solids. The solids form clouds due to turbulence which modulate the capacitance of the plates which are exposed to the flowing fluid. In electrodynamic sensors, electrostatic charge accumulated on solid particles in a flow is detected by using plates similar to capacitance sensor and voltage developed on the plate is used for cross correlation. In electrical conductivity sensors, the discontinuous phase in the liquid causes instantaneous variations in the electrical conductivity of an electrode exposed to the flowing fluid. These changes can be measured and cross correlated to obtain flow velocity. Constant voltage or current, or constant temperature anemometers are used to detect temperature changes in turbulent eddies. The thermal time constant of the anemometer is large which puts the limitation in frequency response.

2.3.3 Sensor electronics

In case of cross correlation flow-meter using ultrasonic sensors, major blocks in the sensor electronics are RF amplifier, demodulator, and low frequency amplifier and filter. The block diagram is given in Fig. 2.5. The RF amplifier amplifies the signal so that demodulator can detect the disturbance signal. A band-pass filter with center frequency of ultrasonic beam and bandwidth sufficient to pass frequencies which carry information of modulating disturbance signal. This band-pass filter eliminates noise like pipe vibrations, power line frequency etc. The ultrasonic wave gets amplitude modulated or frequency modulated (due to doppler effect) by disturbance signal. Hence to recover disturbance signal, AM or FM demodulator circuit is used. The detected signal is amplified and filtered. The upper cut-off frequency of the filter should be greater than the frequency limit on the disturbance frequencies put by the spatial averaging effect of the sensor. The lower cut-off frequency of the filter should be such that it does not pass very low frequencies which can be considered statistically stationary within the cross correlation averaging period. The sensor electronics for both the signals should be identical.

2.3.4 Correlators for flow measurement

Correlator in flow measurement is used to obtain transit time at which peak of cross correlation function occurs. The early designs of cross correlation flow-meters used hill climbing arrangement [3] so that the correlator time delay was automatically adjusted to give maximum cross correlation function output. But unfortunately when flow

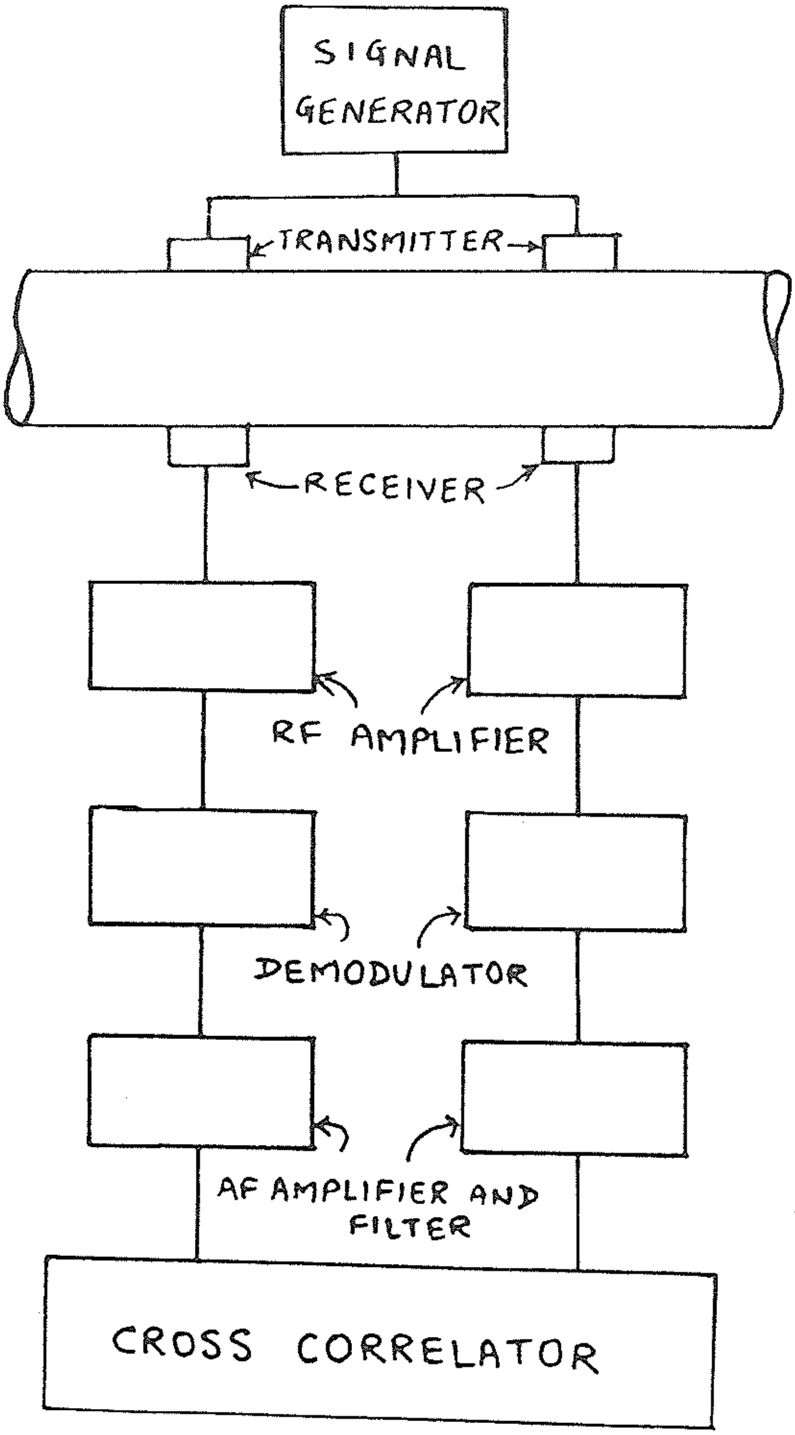


FIG. 2.5 Ultrasonic Cross Correlation Flow-meter - Bloc
Diagram [3]

changes suddenly there are small spurious peaks on the cross correlation function and peak seeking circuit locks on to a subsidiary peak giving error in flow measurement.

Special purpose large scale integrated circuit has been used [12] to obtain flow measurement. The system uses the fact that the cross correlation function grows with increasing delay. An arbitrary level is chosen and cross correlation function is allowed to grow through this level, then the first part of the function to reach this level is the peak.

A reduction in amount of computation of cross correlation function can be obtained by using relay or polarity correlator. Instead of correlating amplitudes of both the signals, amplitude of one signal and sign of the other signal are cross correlated. In polarity correlator, polarity of signals is correlated [3]. The polarity and relay correlators are faster but less accurate. Amplitude information in the signal is lost and the statistical accuracy of the cross correlation will suffer. This can be compensated for by increasing the data observation period. Microprocessor based polarity cross correlator has been used [13].

Cross correlation function can be obtained using frequency domain computation which uses software based FFT technique. A flow-meter using this kind of correlator was reported [4] and results obtained were within $\pm$ 3% for measurements carried out for pipe diameter of 5.25 cm and distance between sensors as 21.7 cm.

2.3.5 Flow model

Model for measuring flow of fluid using cross correlation technique is given by

$$Q = K \times (\frac{d}{\tau^*}) \times A$$

The measured length 'd' and measured cross-sectional area 'A' are subject to constraint of the measuring device. However, there is no varying uncertainty in the measurement of these for non partial flow. This is in contrast to the measurement of transit time 'τ^*' and calibration factor. The error in transit time is due to finite time of integration and limited bandwidth of disturbance signals. Ideally, flow profile should be uniform across the pipe and sensing elements and sensor electronics for both the channels should be identical. But, turbulent eddies have more velocity at center than near the pipe wall, and there exists mismatch between sensing elements. Calibration factor [3] has to be modified according to above factors.

2.4 FLOW RESOLUTION AND RANGEABILITY

Sampling frequency, number of samples, and separation between two sensors together decide minimum and maximum flow rate which can be measured [2].

The flow velocity is given by,

$$\upsilon = d / \tau^*$$

where d is separation between sensors and τ^* is transit time. Differentiation of this equation gives

$$\frac{d\upsilon}{d\tau^*} = \frac{-d}{(\tau^*)^2} = \frac{-\upsilon^2}{d}$$

For sampling time of δ, time discrimination is $\pm\ \delta/2$ and it is the maximum expectation of the error in time delay measurement due to sampling. Corresponding velocity discrimination will be

$$\Delta\upsilon = \pm\ \upsilon^2\delta / 2d$$

Thus fractional velocity discrimination will be

$$\Delta\upsilon / \upsilon = \pm\ \upsilon\delta / 2d = \pm\ 1 / (2n)$$

where n (= $d/\upsilon\delta$) is the sample number corresponding to transit time.

This fractional velocity discrimination deteriorates significantly as the velocity increases. For the maximum measurable velocity, the delay of cross correlation peak corresponds to one sampling unit. This gives discrimination of $\pm$ 50 % which is undesired. Thus for some maximum acceptable discrimination, there is limit on maximum velocity that can be measured.

$$\upsilon_{max} = d / n_{min}\delta$$

For separation of sensors d = 0.2 m and worst case discrimination of 2 % , n_{min} = 25 and υ_{max} = 8 m/sec.

The effect of finite number of samples used for computation of cross correlation function will be less if transit time is within the first one third portion of the correlation period. For correct identification of correlation peak, it must lie in first 1 / 3^{rd} portion of N samples. For 1024 samples and the sampling frequency of 1 kHz, maximum transit time is $\tau_{max} = 1024\delta/3 \cong 0.341$ sec and minimum velocity that can be measured is $\upsilon_{min} \cong 0.59$ m/sec.

CHAPTER 3

SENSOR ELECTRONICS

3.1 INTRODUCTION

In previous chapters, the concept of cross correlation, its application to flow measurement and various correlator configurations are discussed. The main objective of the project is to design sensor electronics and correlator for cross correlation flow-meter with ultrasonic transducers. As described in section 2.3.3, major blocks involved in sensor electronics are RF amplifier, demodulator and low frequency amplifier and filter. RF amplifier is a three-stage RC coupled transistor amplifier with bootstrap stage to increase the input impedance. To detect amplitude modulated signal, envelope detector has been designed. Band-pass filter is second order Butterworth filter. In this chapter, working and testing of above circuits are reported. The details of data acquisition and correlator are described in the following chapter.

As part of the overall system for development and testing of the cross correlation flow-meter, others in the group have designed a water circulation system. This system has been assembled. In this arrangement, an electric pump is used to circulate water through pipes of different diameter. Valves are provided for controlling the flow. A sketch of this arrangement is given in Appendix B.

3.2 OVERALL SET-UP

The scheme of overall set-up is shown in Fig. 3.1. The signals picked up by ultrasonic transducers are input signals at two channels of the signal acquisition unit. The unit has two identical sets of sensor electronics which are RF amplifier, AM demodulator, band-pass filter, and amplifier. The circuits have been assembled on a PCB. The layout of PCB is given in Appendix C. Output from this unit is sampled by add-on data acquisition card put in a PC/AT. A program is developed which obtains cross correlation of these sampled values and displays it on the screen.

3.3 RF AMPLIFIER

In flow measurement system, ultrasonic wave is attenuated and amplitude of received signal is of the order of 50 mV or less. Also this attenuation varies for different factors like pipe diameters, method of mounting of ultrasonic transducers on the pipe. Thus the received signal has to be amplified before information about modulating disturbance signal can be extracted from it and the gain of the amplifier should be adjustable. If low frequency ultrasonic wave is used, attenuation is less but directivity is poor as compared to high frequency ultrasonic wave. A frequency

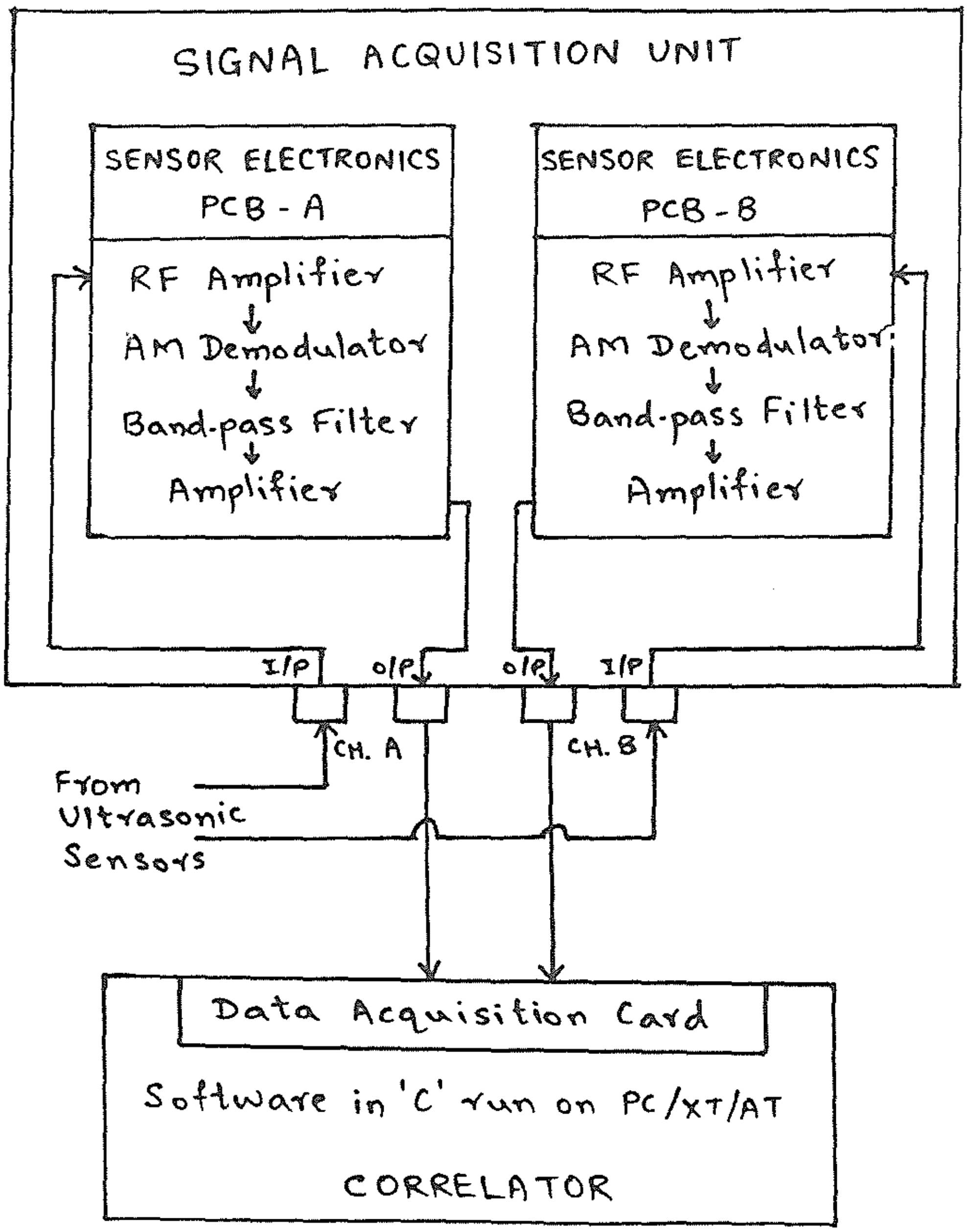


FIG. 3.1 Set-up for Cross Correlation Flow-meter

of 2 MHz is selected as a fair compromise.

A RC coupled amplifier with adjustable gain was designed to operate at frequency of 2MHz. The circuit diagram is given in Fig. 3.2. It is a three-stage RC coupled amplifier. Transistor Q_1 provides bootstrapping circuit to improve input impedance. RF transistor 2N2857 [14] was chosen as its frequency and dc current gain product(f_T) is 1000 MHz, and it is recommended for use in low noise applications. The transistors were biased such that collector potential is near center of the supply voltage. A part of emitter resistance was unbypassed to obtain high input impedance. A potentiometer was provided in the second stage for adjustment of gain of amplifier.

The RF amplifier was designed to have performance equivalent to available commercial unit. A gain of 30 dB was desired in the frequency range of operation. Frequency response of the amplifier is shown in Fig. 3.3. The amplifier gives a gain variation of 29 dB to 37 dB at 2 MHz. The input impedance of equivalent commercial amplifier (Analogic D1000 pre-amplifier) was measured and found to be 5 to 10 KΩ at 2 MHz. The method of measurement is explained in Appendix D. By the same method, impedance of designed RF amplifier was measured, and a plot of impedance as a function of frequency is shown in Fig. 3.4.

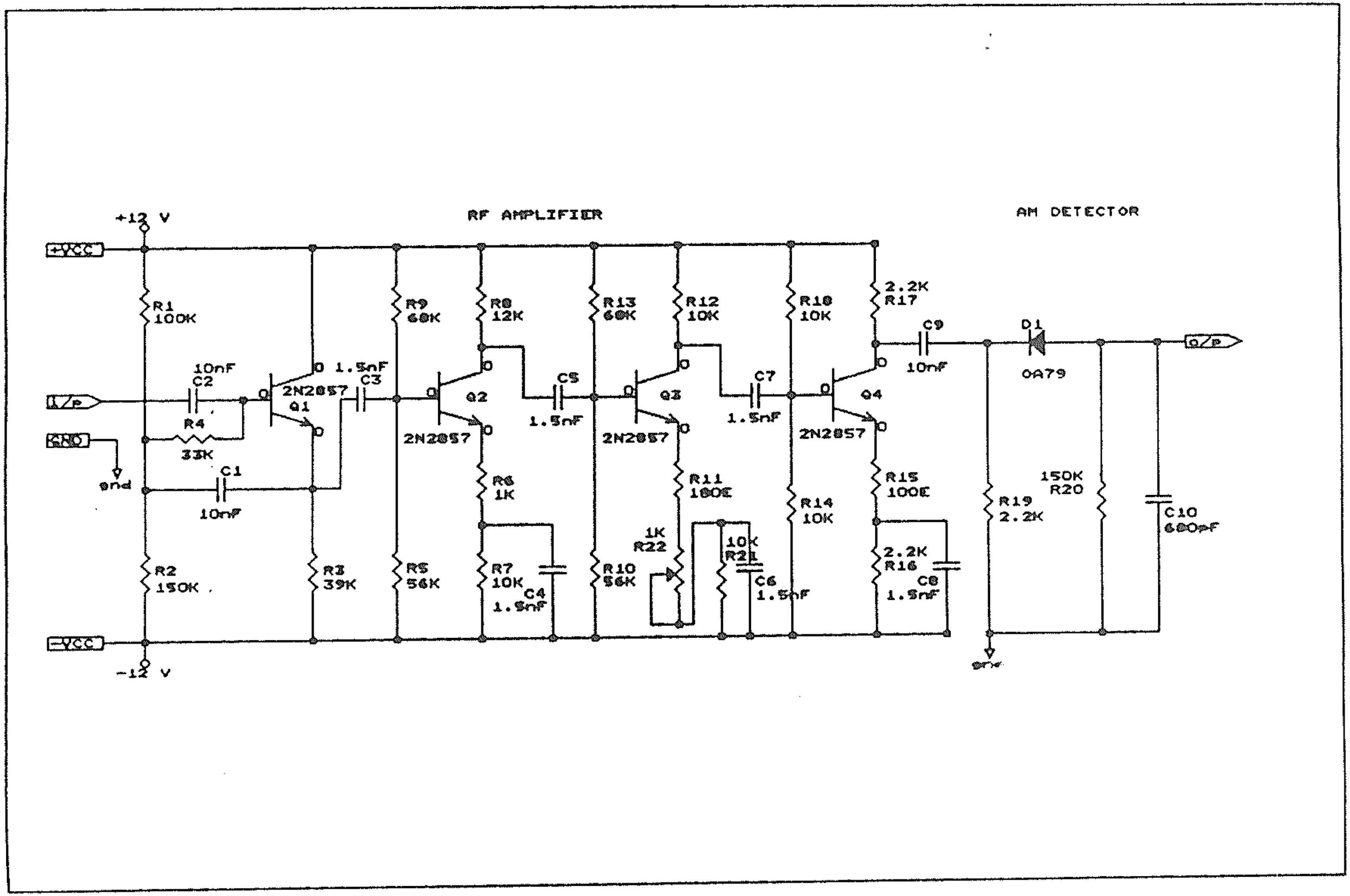


FIG. 3.2 RF Amplifier and Demodulator - Circuit Diagram

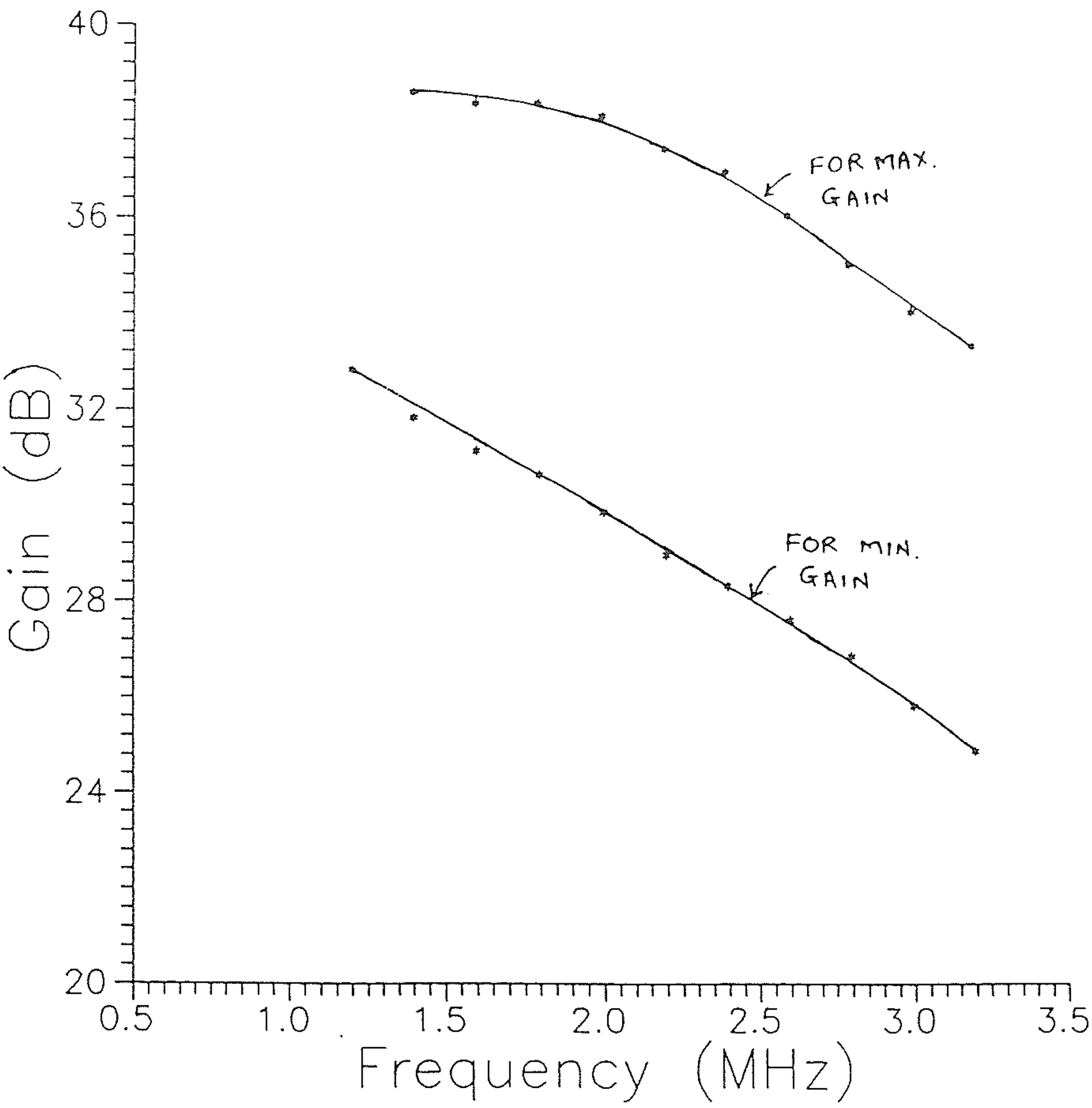


FIG. 3.3 Frequency Response of RF Amplifier

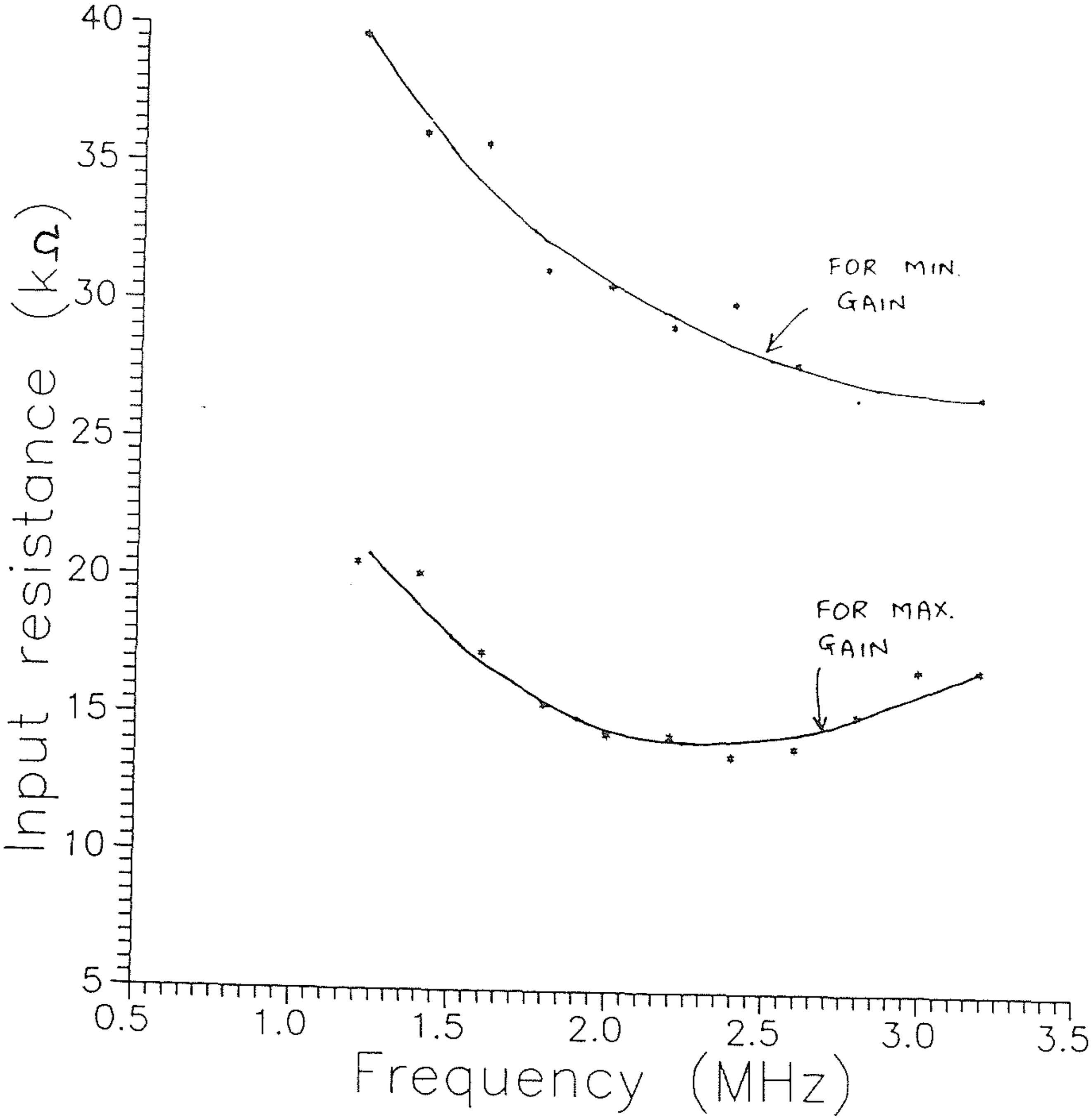


FIG. 3.4 Input Impedance of RF Amplifier

3.4 DEMODULATOR

The designed demodulator is AM envelope detector. The envelope detector is simpler and efficient as compared to synchronous and rectifier detector [15]. In this envelope detector, the output follows the envelope of the modulated signal. It is essentially a half wave rectifier with capacitor across the output terminals as shown in Fig. 3.2. The diode used for rectification is OA79 which is recommended for usage in AM detection applications [16]. The RC time constant was adjusted such that output follows the envelope but RF ripple is less. The carrier frequency, fc, is 2 MHz (time period, Tc = 0.5 μs.) and maximum modulating frequency, fm is 100 Hz (time period, Tm=10 ms). Therefore, RC constant is chosen as 0.1 ms (R = 150 KΩ and C = 680 pF). Carrier frequency ripple gets further filtered out by band-pass filter following the demodulator stage.

3.5 LOW FREQUENCY AMPLIFIER AND FILTER

The amplifier after demodulation should have upper cut-off frequency greater than maximum disturbance frequency of interest. The lower cut-off frequency should be such that it does not pass very low frequencies which can be considered statistically stationary within the cross correlation averaging period. The maximum modulating frequency is 100 Hz. The reasonable choice for sampling frequency is 1 kHz. The cross correlation period will be one second for sampling 1000 samples. Signals with frequency less than 5 Hz will have period in comparison with averaging period and could result into wrong cross correlation function if correlated. Thus a band-pass filter is required prior to the amplification to attenuate the signals with frequency below 5 Hz and above 100 Hz.

Non-linear phase response filter will change the correlation function. But for flow measurement, position of the peak of cross correlation function is important and it remains unchanged. The only requirement is that filter characteristics should be identical. Therefore maximally flat delay Bessel filter is not required which has linear phase response. Instead, easy to design Butterworth filter can be used which has maximally flat amplitude response.

Second order Butterworth filter was designed with following specifications.

Pass band : $5 \text{ Hz} < f < 100 \text{ Hz}$, gain variation < 1.5 dB

Stop band : $f < 1$ Hz and $f > 500$ Hz, Attenuation > 20 dB

The ratio of upper to lower cut-off frequency is greater than two, indicating that it is a wide-band filter. This can be implemented by cascading a high-pass filter and a low-pass filter. The filter design is given in Appendix E. The circuit diagram is shown in Fig. 3.5. The frequency and phase response are given in Fig. 3.6. The filtered output is amplified by a non-inverting amplifier whose gain can be

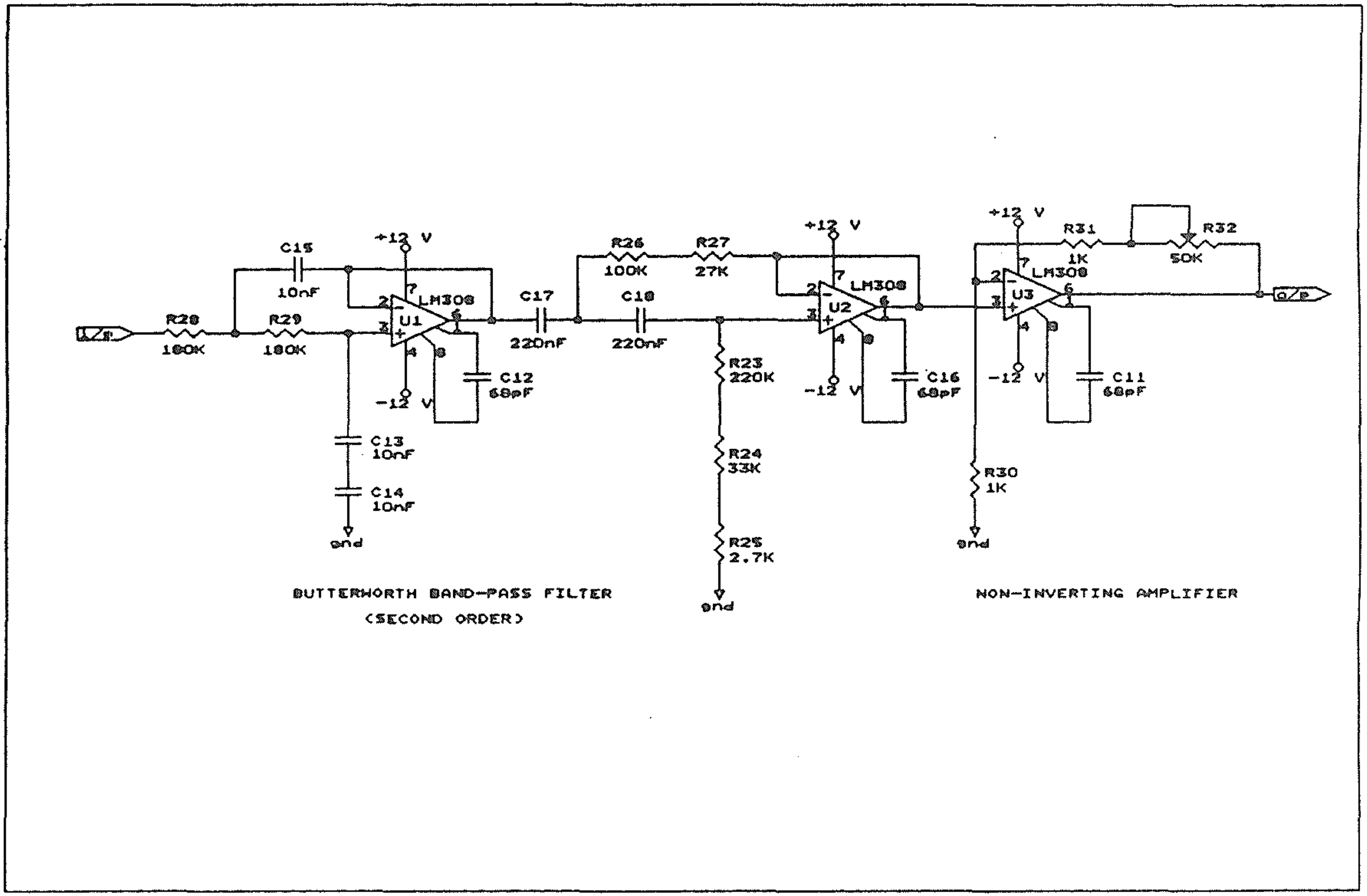


FIG. 3.5 Low Frequency Amplifier and Filter - Circuit Diagram

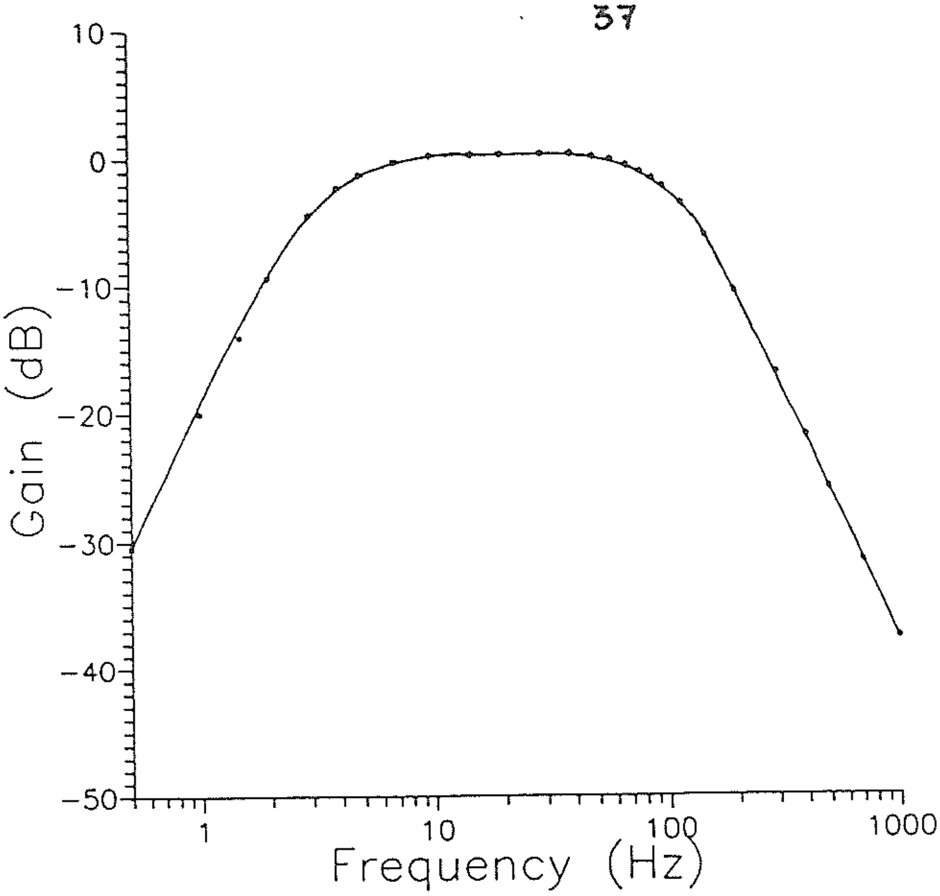


FIG. 3.6[a] Frequency Response of Filter

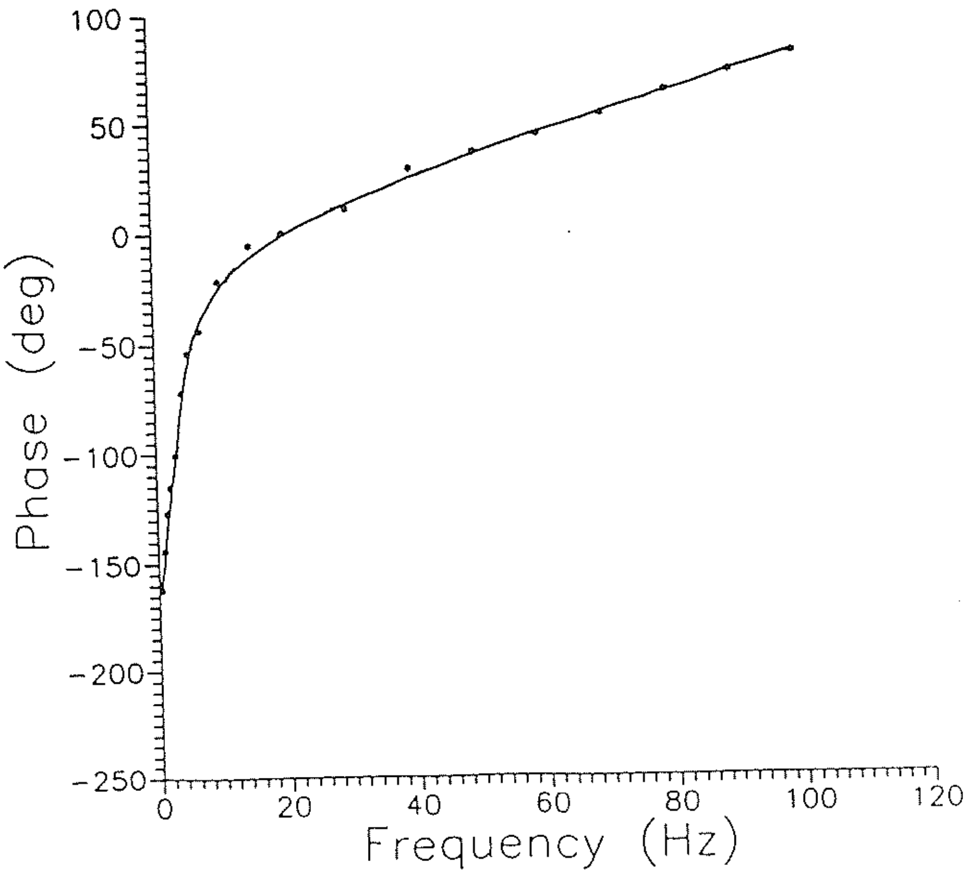


FIG. 3.6[b] Phase Response of Filter

adjusted from 2 to 52.

3.6 TESTING OF OVERALL SET-UP

Both channels of signal acquisition unit were tested using output of AM signal source ('Kikusui 4100' FM-AM signal generator) as test input. The percentage modulation could be varied from 0.5% to 60%, with a facility for varying the modulation frequency. The carrier frequency used was 2 MHz.

By keeping modulating frequency constant, the percentage modulation is varied and output of the circuit is observed. The plot of output against percentage modulation is shown in Fig. 3.7[a]. The relationship between them is linear. Above 14% modulation (for maximum RF and AF gain), the output starts getting distorted for mid-range frequency. Similarly output is plotted as a function of frequency (Fig. 3.7[b]) for different values of modulation indices. The nature of frequency response is due to the band-pass filter.

The set-up was tested with water circulating system. It was observed that ultrasonic receiver output was getting modulated by line frequency of 50 Hz. In presence of this interference, modulation due to turbulence of flow could not be detected. The output of the correlator was found to be essentially due to line frequency interference. For three flow conditions, plots of signals after demodulation,

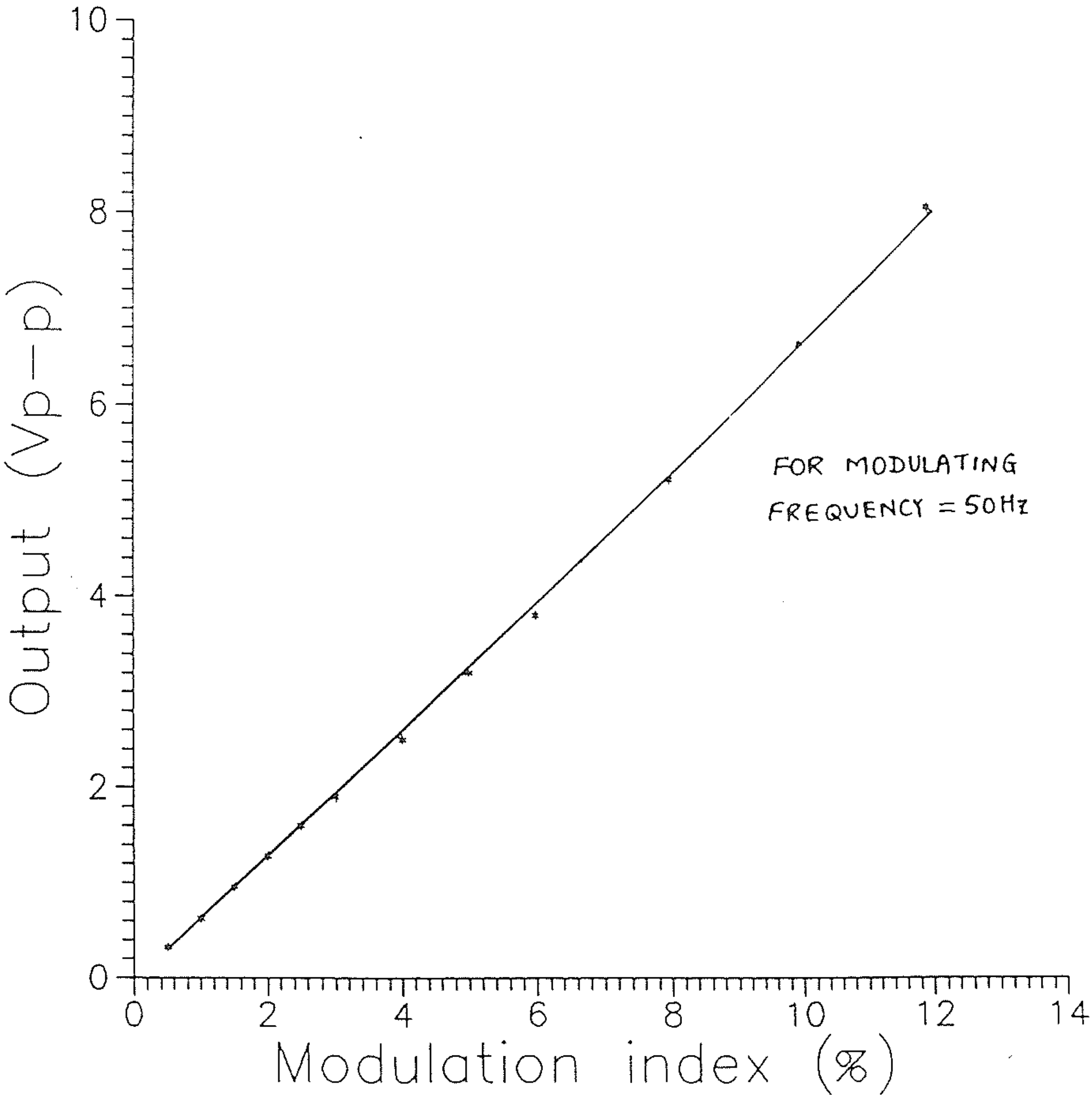


FIG. 3.7(a) Response of Sensor Electronics - Output as a Function of Percentage Modulation

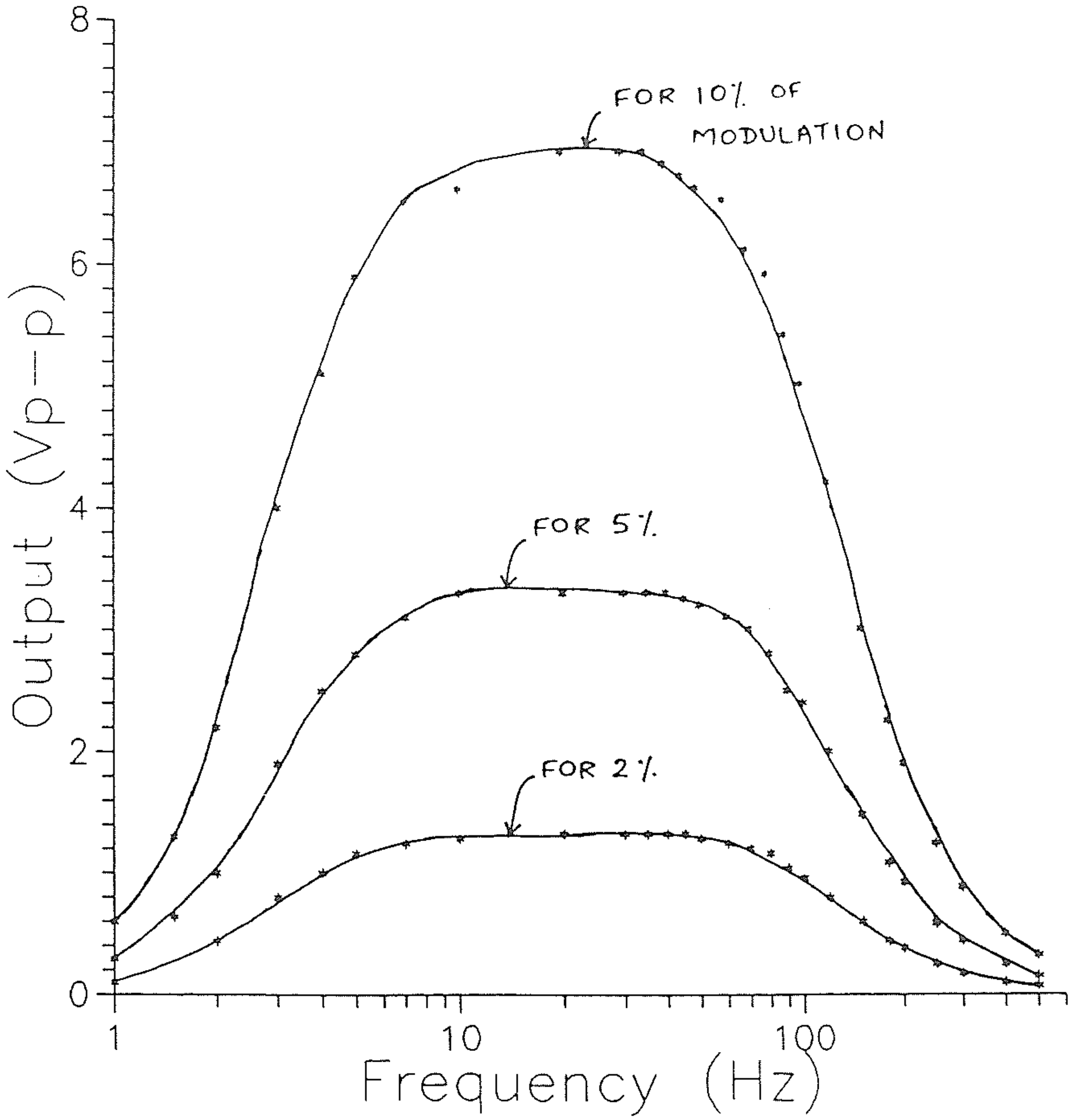
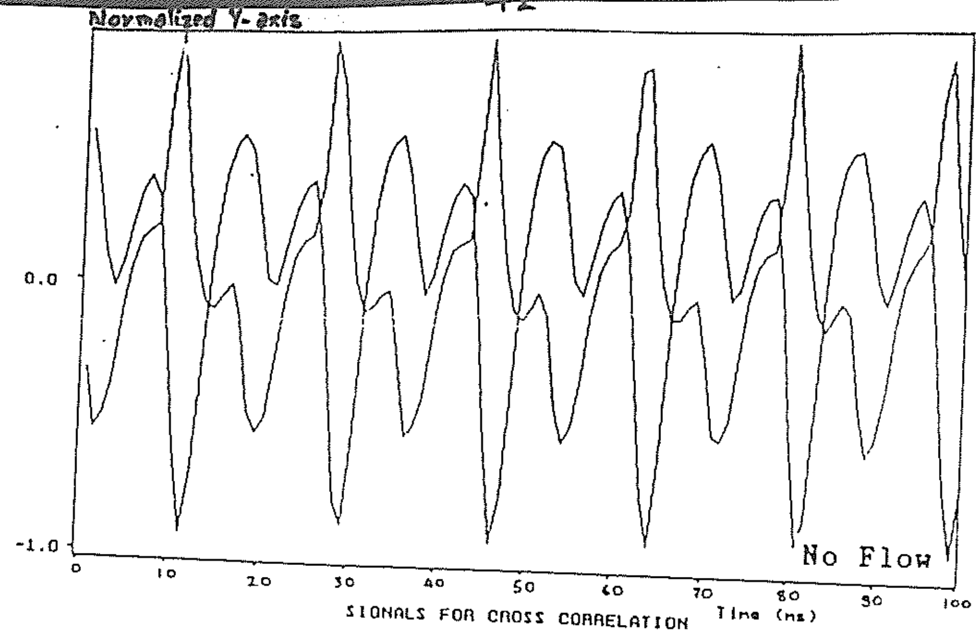
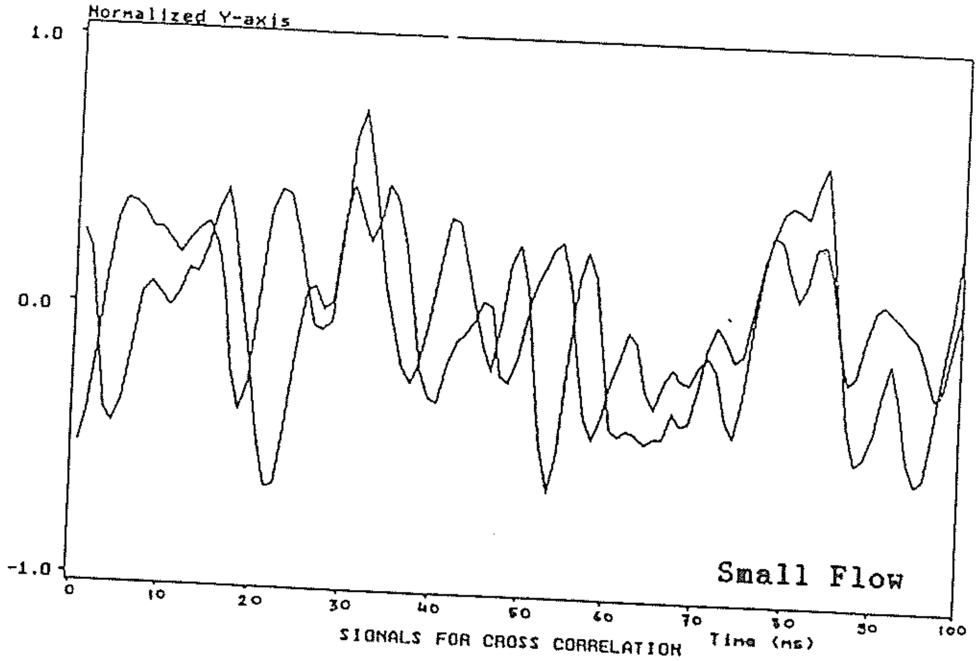


FIG. 3.7[b] Response of Sensor Electronics - Output as a Function of Modulating Frequency with Percentage Modulation as a Parameter

and their cross correlation functions are given in Fig. 3.8[a] and [b]. The 50 Hz modulation of the received ultrasonic wave could be due to vibration of the pipe. More work has to be done on mounting of transducers on pipe wall, rubber padding for entire system for reducing vibration. This may reduce the unwanted modulation of signal due to line frequency. Further, 50 Hz notch filters should be incorporated in both the demodulator channels, so that correlator inputs are free from this interference.





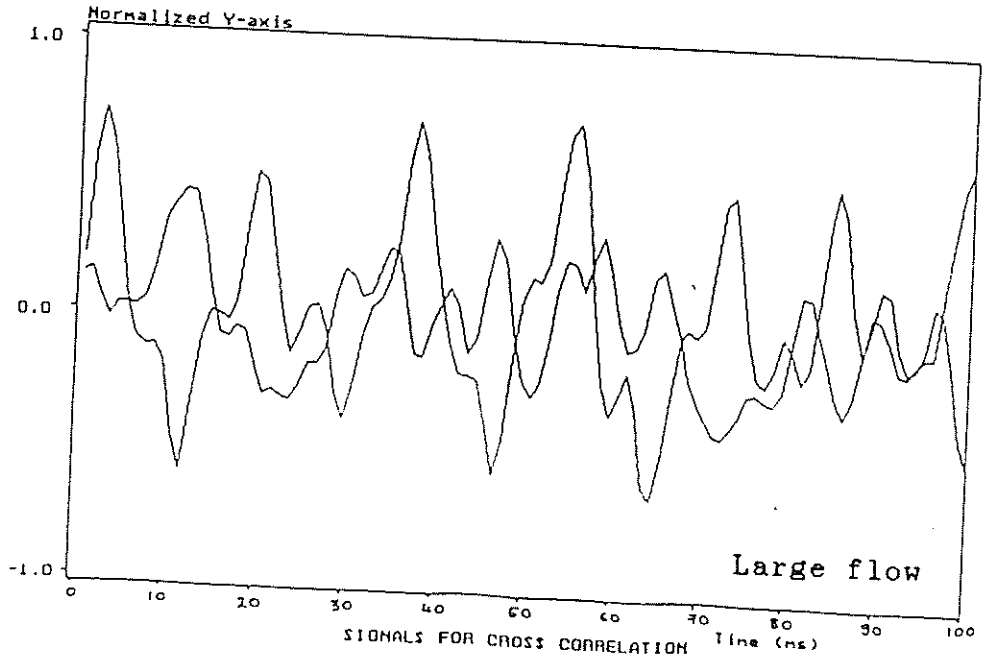


FIG. 3.8[a] Testing of Overall Set-up - Signals after Demodulation

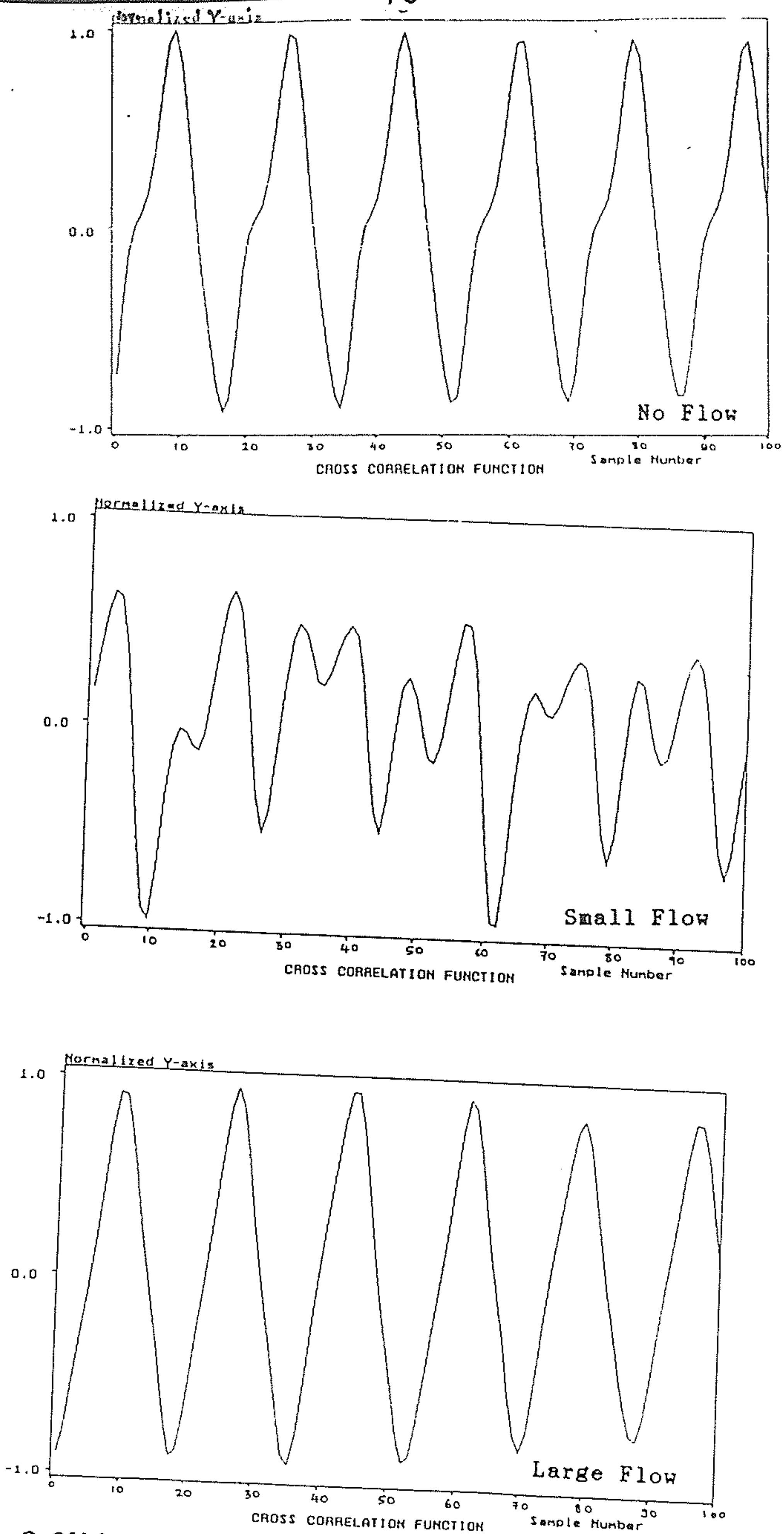


FIG. 3.8[b] Testing of Overall Set-up - Cross Correlation Function

CHAPTER 4

CORRELATOR

4.1 INTRODUCTION

The cross correlation function can be computed in time domain or in frequency domain as discussed earlier in section 2.2. Frequency domain method was used to obtain cross correlation as it is efficient to other methods and it can be easily implemented through digital computation. In this method, cross correlation function was obtained by evaluating DFTs of two signal sequences, multiplying them and obtaining inverse DFT. The correlator scheme is given in Fig. 4.1. The programs for data acquisition, FFT algorithm, computation of cross correlation, and displaying the result on the screen were written in 'C' language. Analysis parameters like number of samples, sampling frequency, power of '2' for radix-2 FFT computation can be set by the user. The program is explained in this chapter with the help of pseudo code. The correlator was tested thoroughly with different test inputs. First, sinusoidal inputs with different phase shifts were used. This was followed by adding white noise to the two test signals, and cross correlation functions were obtained for different signal-to noise ratios.

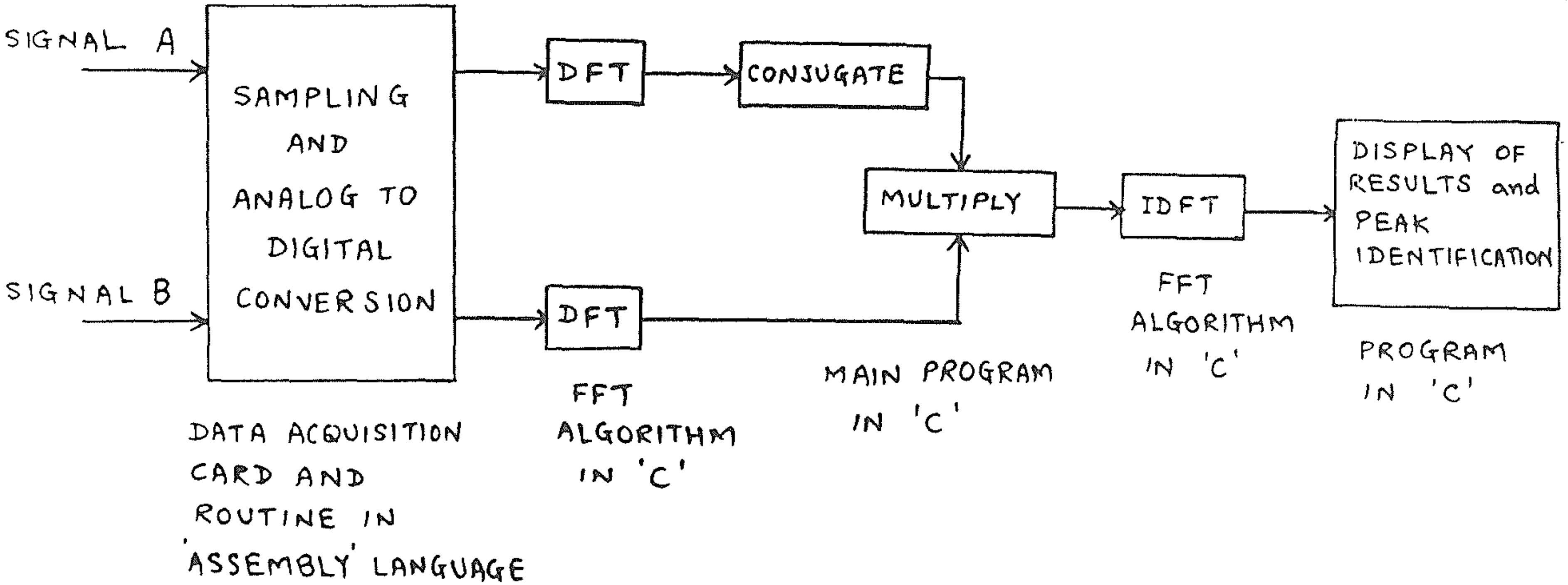


FIG. 4.1 Scheme of Frequency Domain Correlator

4.2 DATA ACQUISITION

Data acquisition involves sampling of data and converting analog signal into digital form. For this purpose, Dynalog Micro Systems data acquisition card PCL 208 [17] was used. This card is a PC/XT/AT add-on card with 16 single ended or 8 differential 12-bit A/D input channels. Features of this card and settings used are given in Appendix F. On-board programmable pacer trigger mode was used for sampling and conversion. The driver for this card was written in assembly language and it was linked with main program which converts digital data read from card into two integer sequences, corresponding to two input signals.

Pseudo code of data acquisition program

```
Get choice about data to be sampled or read from file;
If data to be sampled then
{
    Initialize data acquisition card;
    Check if card is present;
    If card is present then
    {
        Initialize memory for storing data;
        Get channel number to be scanned;
        Set scan channel range;
        Get sampling frequency;
        Initialize pacer trigger timer;
```

```
        Get number of samples;
        Call assembly routine 'ADCON' to sample data;
        Convert 12 bit value (2 bytes) into an integer;
    }
}
```

Assembly routine ADCON

```
Initialize counter for number of samples;
Enable timer;
AGAIN :
Check timer interrupt;
If interrupt has not oocurred then goto AGAIN;
Read lower byte of data from card;
Read higher byte of data from card;
Reset interrupt bit;
Update counter for number of samples;
If all desired samples are not over then goto AGAIN;
```

4.3 CALCULATION OF CROSS CORRELATION FUNCTION

The Fourier transform of correlation function is

$$R_{uv}(k) = \frac{1}{N} U^{*}(k) \times V(k)$$

where $R_{uv}(k)$, $U(k)$ and $V(k)$ denote DFT of cross correlation function and the two signals. The cross correlation function is obtained by taking inverse DFT of $R_{uv}(k)$. Radix '2' fast Fourier transform algorithm which is efficient (as described earlier in section 2.2.2) was used to obtain DFT.

The constraint of this algorithm is that the number of samples should be in power of 2. The choice of number of samples, 'N' and order of DFT, 'n' has been left to the user. If N is greater than 2^n then $(N - 2^n)$ samples are neglected or if N is smaller than 2^n then $(2^n - N)$ zeros are padded to the samples. In the program, maximum value of 'N' and 'n' have been set at 1024 and 11 respectively. Maximum sampling frequency for a single channel achievable with PCL-208 card, is 60 KHz. But maximum frequency of disturbance signal to be correlated is 100 Hz. Therefore limit on maximum sampling frequency for both channels has been set as 10 kHz. These limits can be altered by slight modification in the program. For computation of FFT, standard radix-2, decimation-in-time algorithm (details given in Appendix G) has been used.

<u>Pseudo code of cross correlation computation program</u>

Initialize arrays for storing data and read the data;
Get the order of radix-2 FFT;
Call FFT routine to obtain DFT of first signal, $U(k)$;
Call FFT routine to obtain DFT of second signal, $V(k)$;
Obtain complex conjugate of DFT of first signal, $U^*(k)$;
Multiply $U^*(k)$ and $V(k)$ to obtain Discrete Fourier transform of cross correlation function, $R_{uv}(k)$;
Obtain cross correlation function, $r_{uv}(k)$ by taking inverse Fourier transform of $R_{uv}(k)$;
Store the result into a file;

4.4 DETERMINATION OF PEAK OF CROSS CORRELATION FUNCTION

The position of the peak of cross correlation function is important in cross correlation flow-meter. The peak can be located in two ways (a) direct method and (b) center of mass method [2]. The center of mass method determines the peak of the cross correlation function using following equation.

$$\tau^{*} = \int_{\tau_1}^{\tau_2} r_{uv}(\tau) \times \tau \, d\tau \; / \; \int_{\tau_1}^{\tau_2} r_{uv}(\tau) \, d\tau$$

To obtain the mass moment, the limit of integration τ_1 to τ_2 is decided by the normalized cross correlation values above certain threshold near the peak. The program has been developed to obtain position of the peak automatically. For center of mass method, user can set the threshold for selection of the limit of integration.

Pseudo code of program for determination of peak

```
Get choice; direct method (P) or center of mass method (C);
Obtain peak and its location from normalized cross
correlation values;
If choice is 'P' then
    Display the position of the peak;
If choice is 'C' then
{
    Get the threshold;
    Obtain limit of integration by comparing cross
    correlation values near the peak with the specified
```

threshold;

Obtain position of the peak by mass moment equation;

Display the peak position;

}

4.5 DISPLAY OF RESULTS

The sampled signals and their cross correlation function can be displayed on the screen of PC. All samples of both the signals and the cross correlation function were normalized by respective maximum. Either the two signal waveforms together, or the cross correlation function can be displayed at a time. Maximum 600 samples can be displayed on one screen. By pressing 'escape' key, the present screen gets cleared and other samples can be viewed by specifying proper window. A cursor can be moved along the waveform displayed with the help of arrow keys. The value of the function at present cursor position and the maximum value are displayed on the screen for easy identification of the peak. Hard copy of the waveform can be taken on a printer.

Pseudo code of display program

Initialize arrays and read data for two signals and the cross correlation function from a file;

Obtain maximum of two signals and cross correlation values and normalize them with respective maximum;

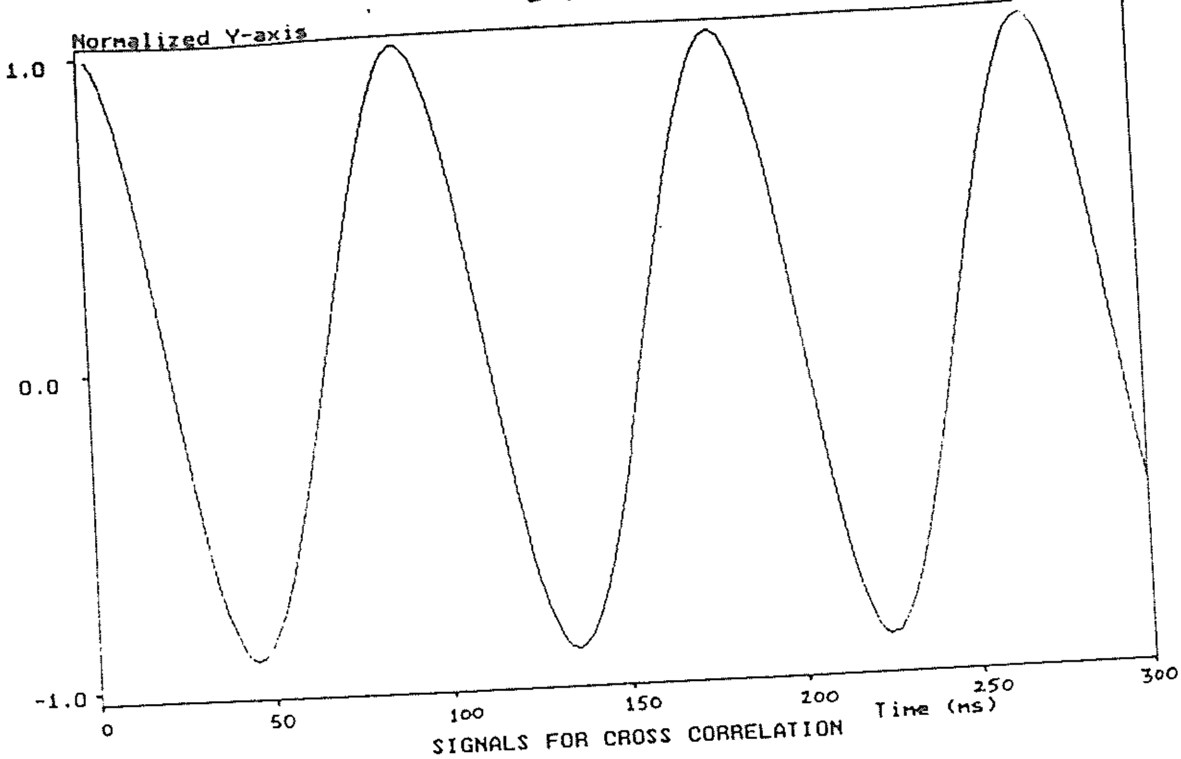
```
GET_CHOICE:
Get choice; quit(1) or display signals(2) or display  cross
correlation function(3);
If choice is 2 or 3 then
{
    Get start and end sample number of  the  window  to  be
    displayed (Maximum window length = 600);
    Initialize graphics mode;
    Set size of viewport and draw the boundary on screen;
    If choice is 3 then
    {
        Display specified cross correlation function values
        by joining consecutive values after proper scaling;
        Draw vertical line as a cursor;
        Display sample number, value of  cross  correlation
        at current position of cursor and maximum;
GET_KEY_1:
        Read key from keyboard;
        If key is 'escape' then
            goto END_DISPLAY;
        If key is right or left arrow then
        {
            Shift cursor right or left by one position;
            Update value of cross correlation function;
            Goto GET_KEY_1;
        }
    }
```

```
    If choice is 2 then
    {
        Display both the signals  in  specified  window  by
        joining consecutive samples after proper scaling;
        Draw vertical lines as cursors;
        Display sample number, value of signals at  current
        position of cursor and maximum;
GET_KEY_2:
        Read key from keyboard;
        If key is 'escape' then
            goto END_DISPLAY;
        If key is right or left arrow then
        {
            Shift cursor right or left by one position;
            Update value of signals;
            Goto GET_KEY_2;
        }
    }
END_DISPLAY:
    End graphics mode;
    Goto GET_CHOICE;
}
```

4.6 TESTING OF CORRELATOR

The correlator was tested with test signal of sinusoidal wave with various phase shifts. The results for sine wave of 10 Hz frequency are plotted in Fig. 4.2[a]-[c]. It can be observed that as phase difference increases, position of the peak of cross correlation function shifts towards right. It can also be observed that the shift in peak of cross correlation function is equal to the time shift between the two test waveforms. The cross correlation of two sine waves over infinite period should be sinusoidal with constant amplitude. But finite cross correlation interval causes windowing effect which results into decreasing cross correlation function.

The correlator was tested for different signal-to-noise ratios (SNR) by injecting random white noise into the signal. Output from random noise generator of 'HP-3561A', dynamic signal analyzer was sampled and stored in a file. Similarly signal of 10 Hz of sine wave was sampled and stored in another file. A program was written to obtain power of both, noise and signal. The samples of signal and noise were scaled and added to obtain various SNRs. This was given as an input file to the correlator program. The results for 20 dB, 10 dB, 0 dB and -10 dB SNR are given in Fig. 4.3[a] to 4.3[d]. It is observed that the nature and peak of cross correlation function remains same. The auto-correlation of random noise is an impulse function. As the noise level increases (SNR decreases), the impulse becomes predominant, which is observed as a large pulse at first sample in the graph. For SNR of -10 dB or less, the



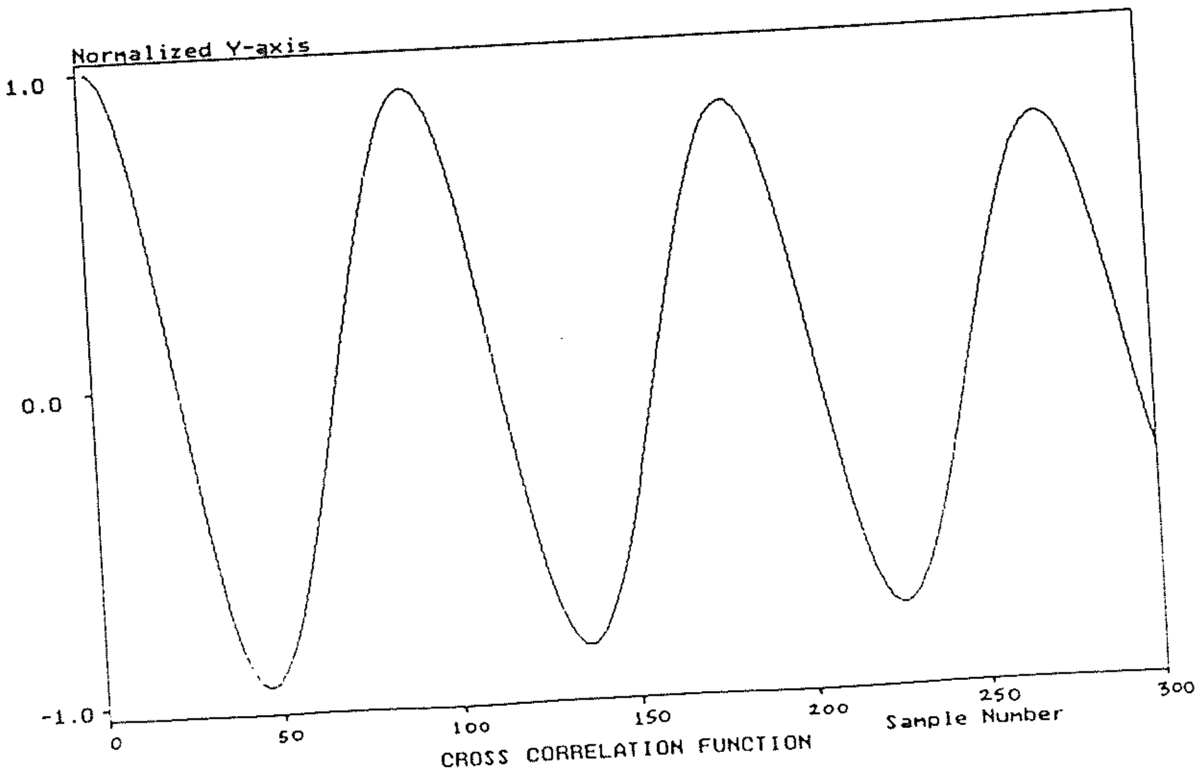
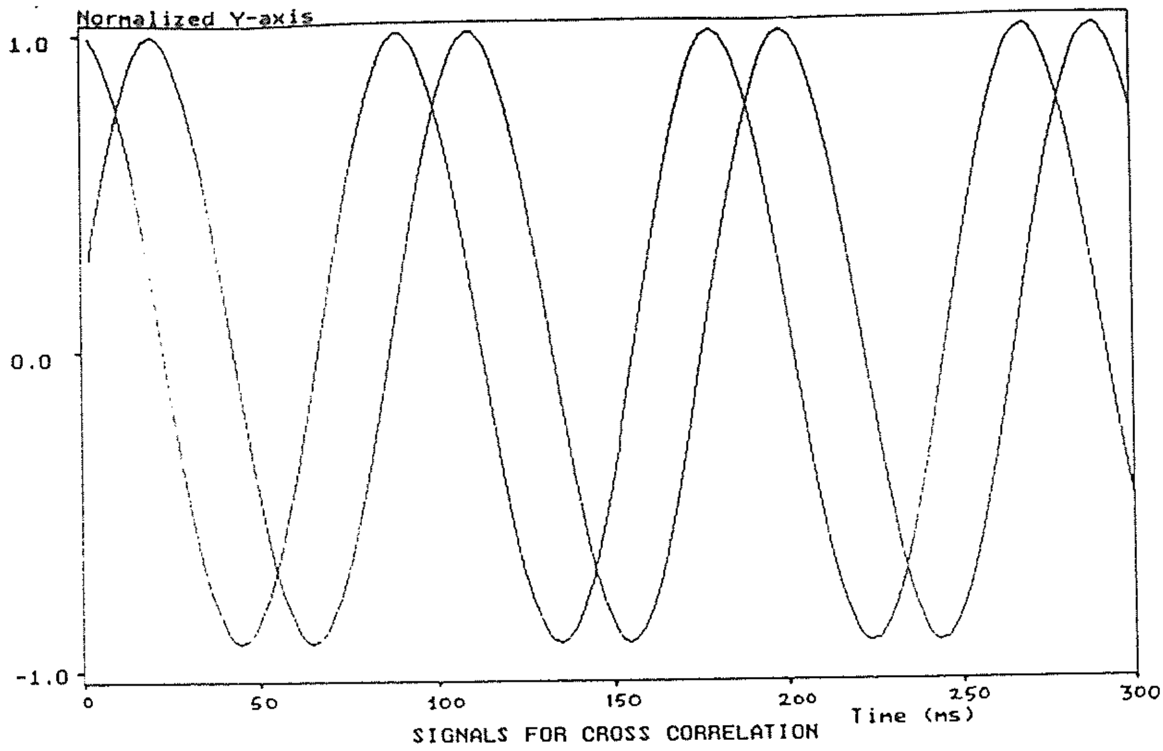


FIG. 4.2[a] Cross Correlation Function - With No Phase Shift between Two Inputs



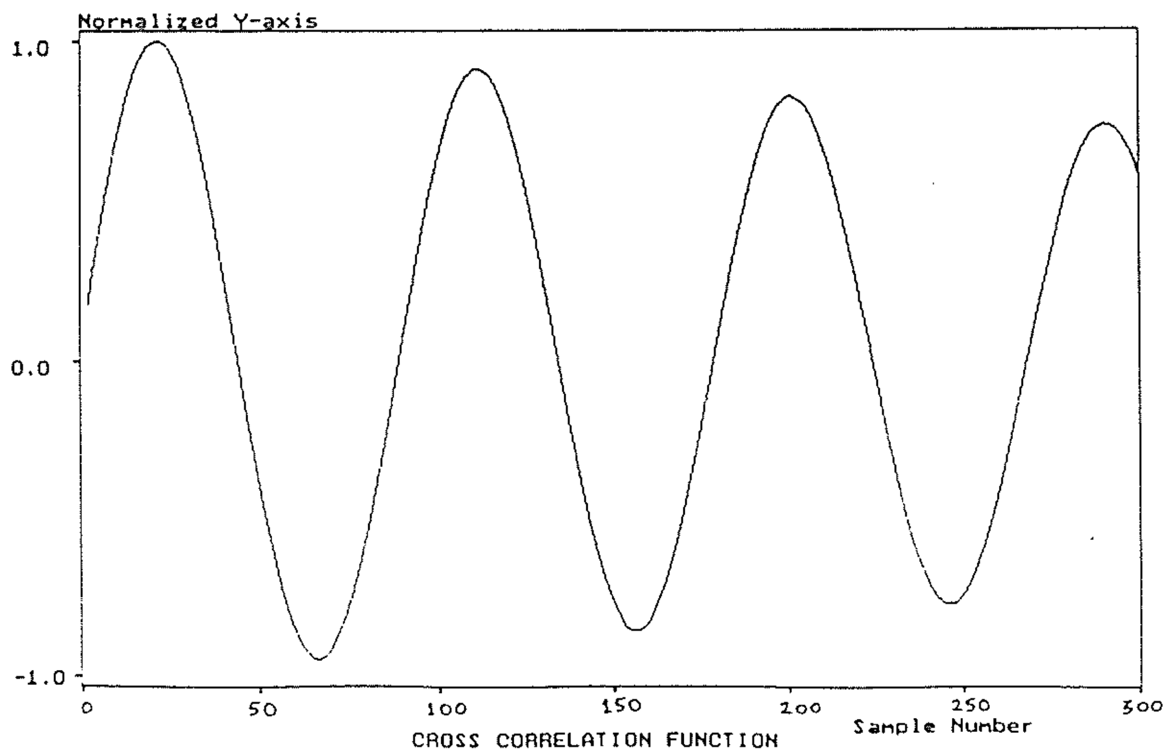
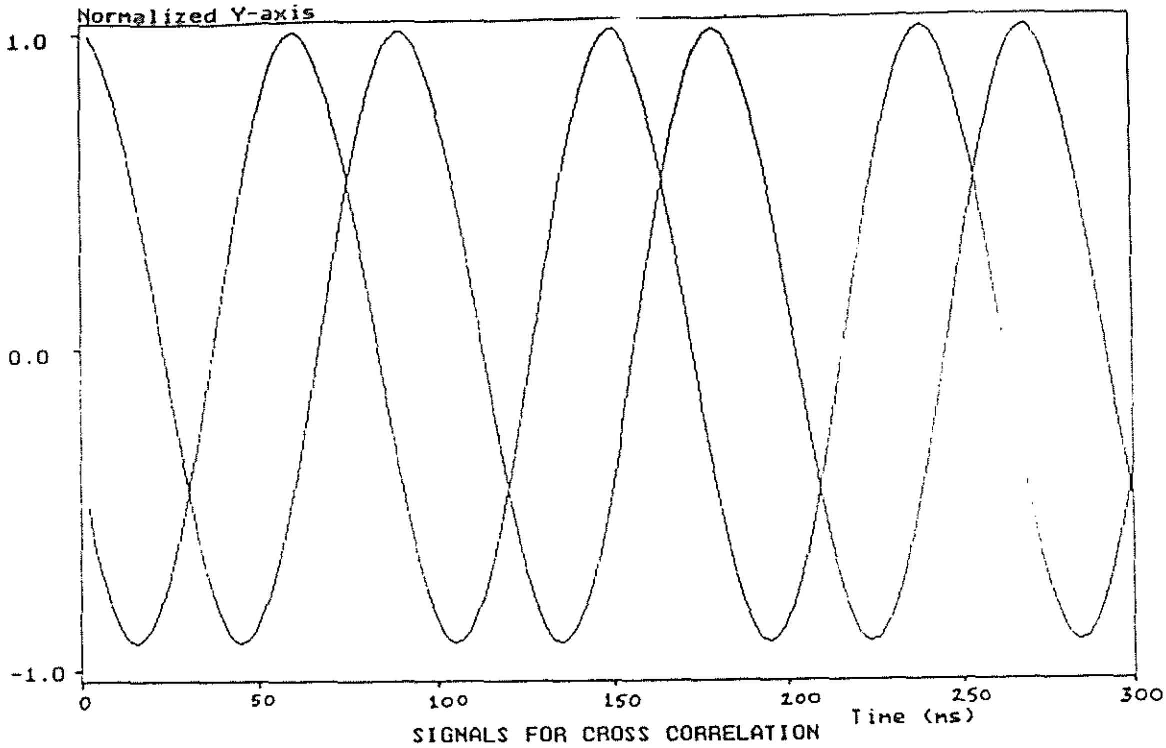


FIG. 4.2[b] Cross Correlation Function - With Phase Shift of 20 Samples between Two Inputs



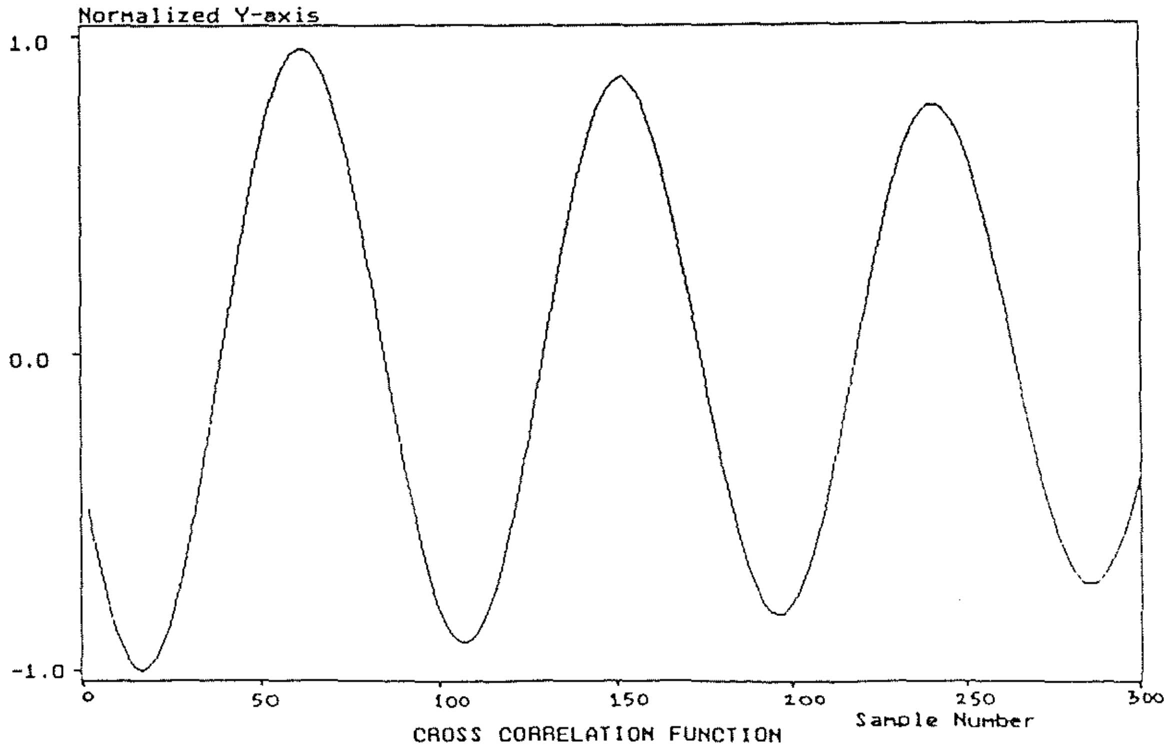
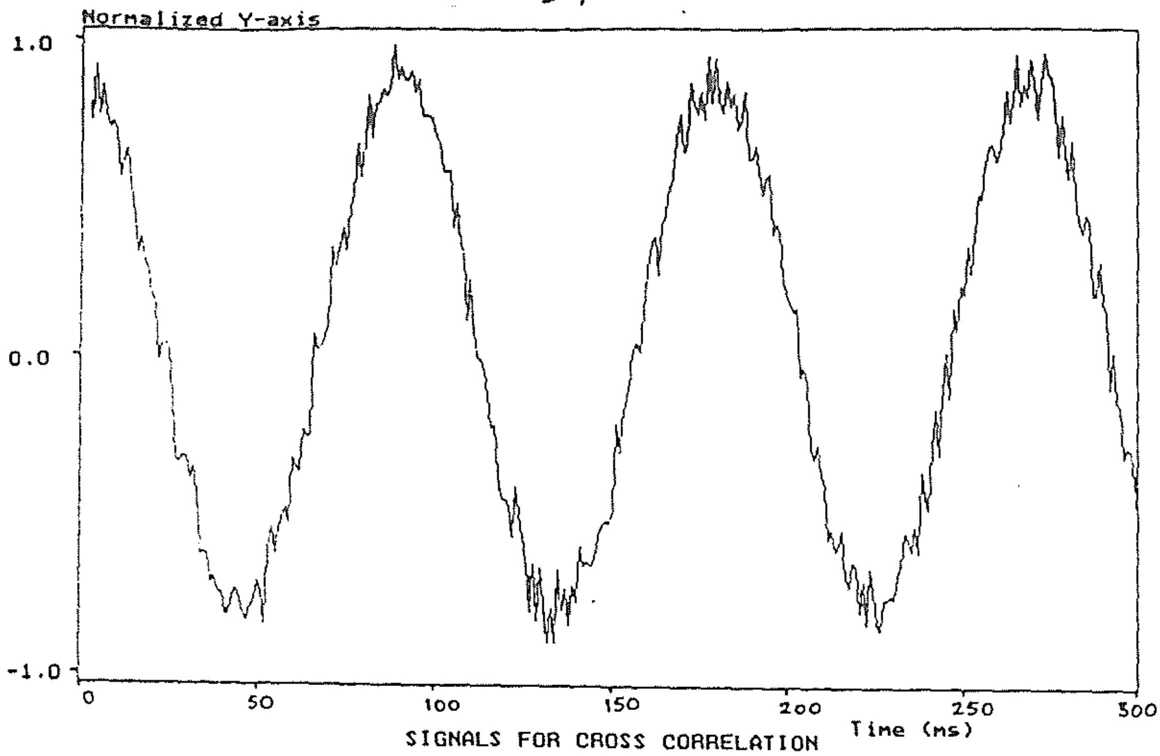


FIG. 4.2[c] Cross Correlation Function - With Phase Shift of 60 Samples between Two Inputs



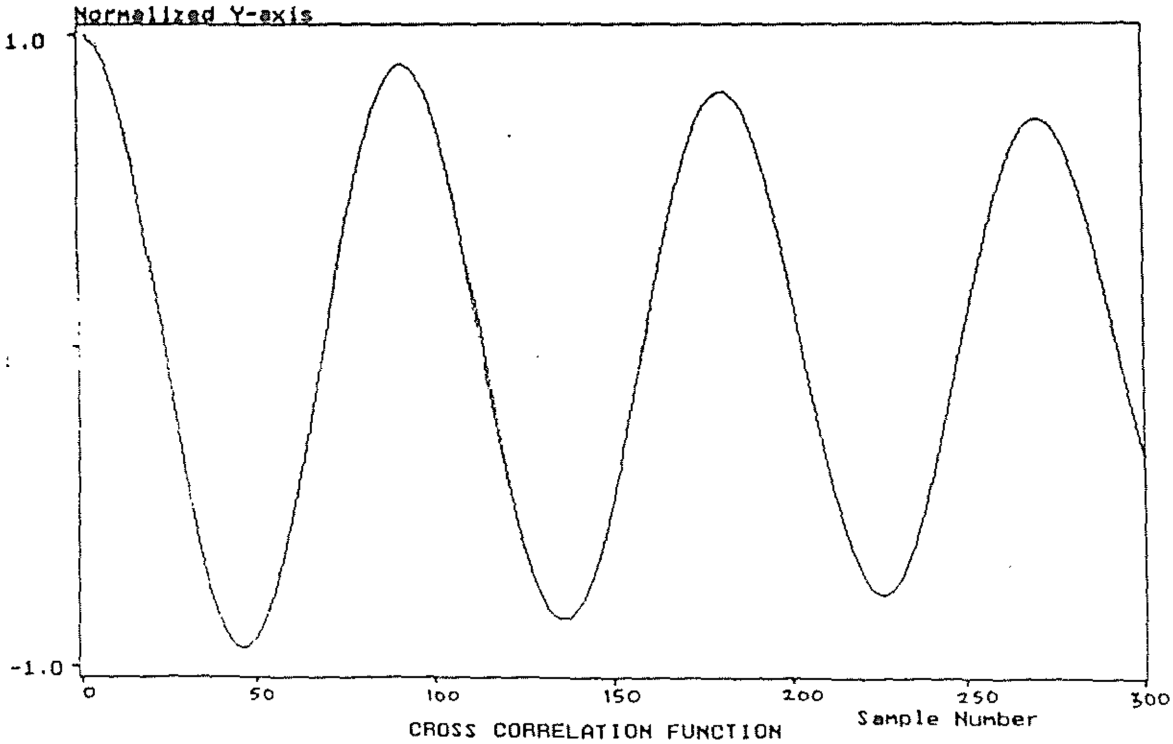
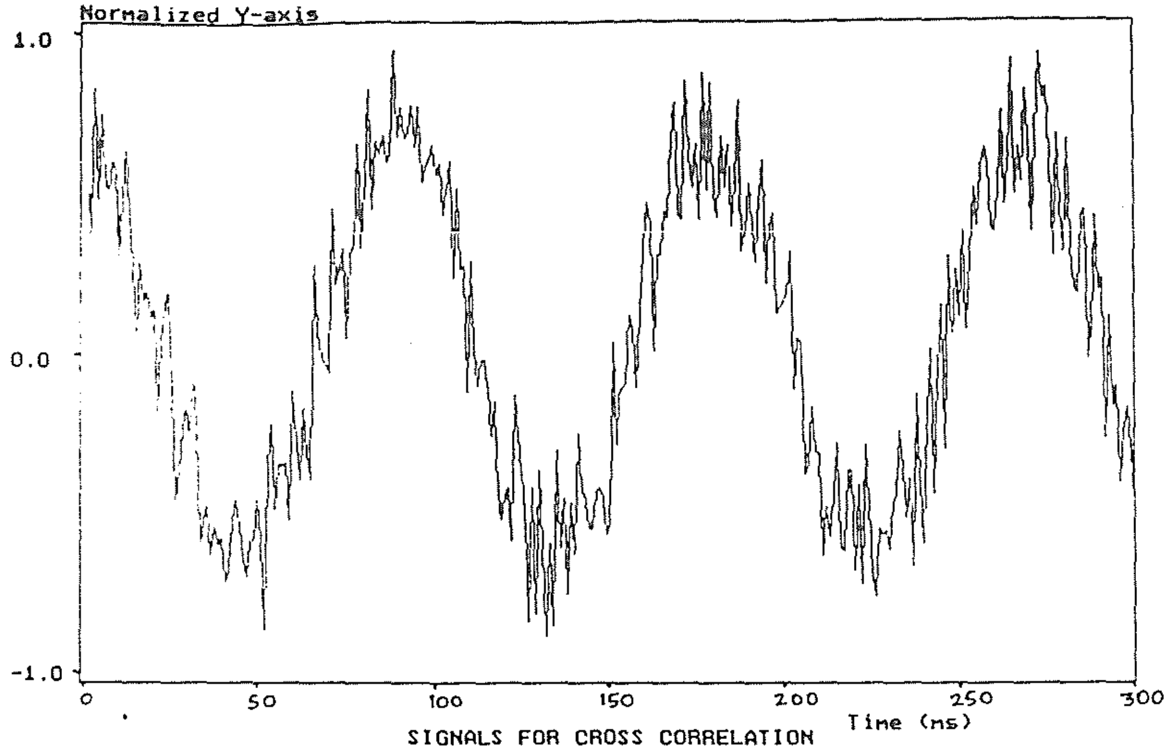


FIG. 4.3[a] Cross Correlation Function for SNR = 20 dB



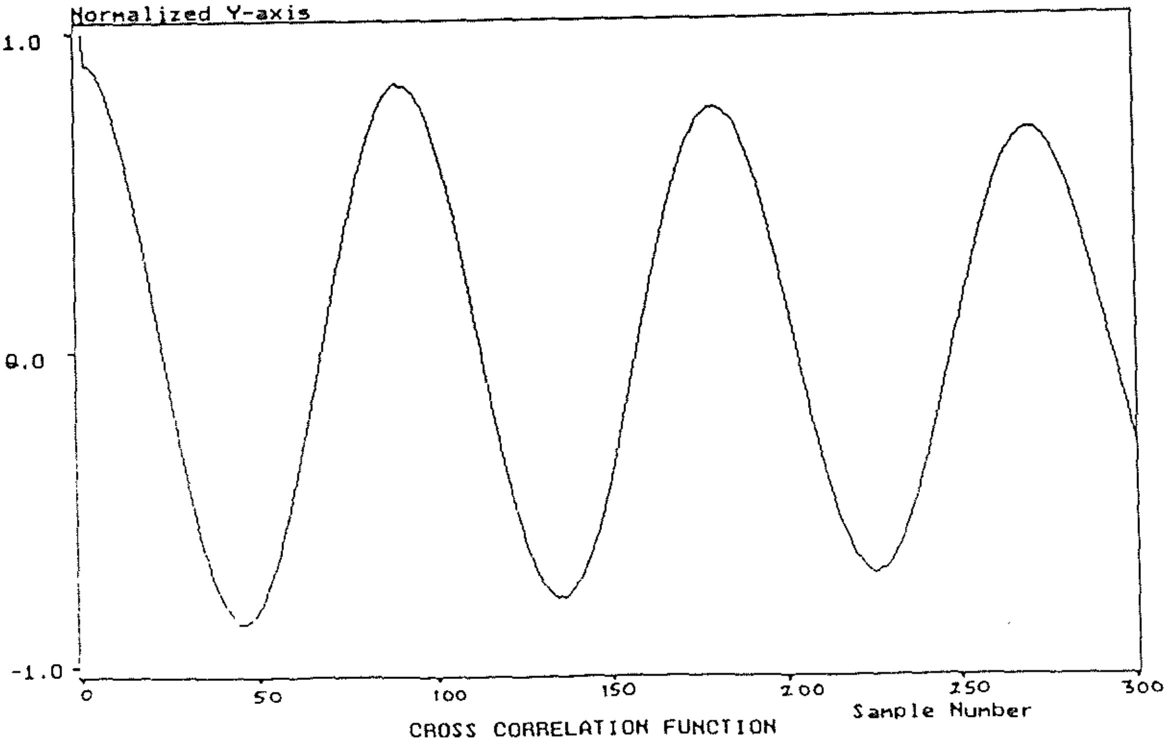
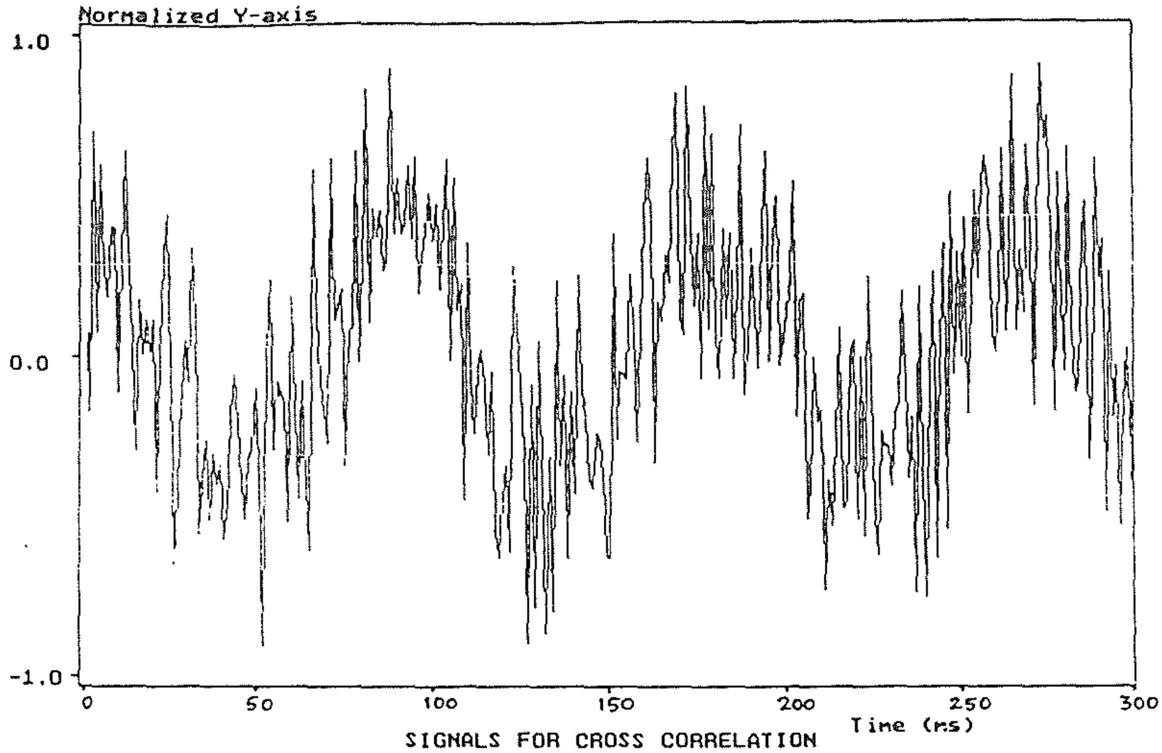


FIG. 4.3[b] Cross Correlation Function for SNR = 10 dB



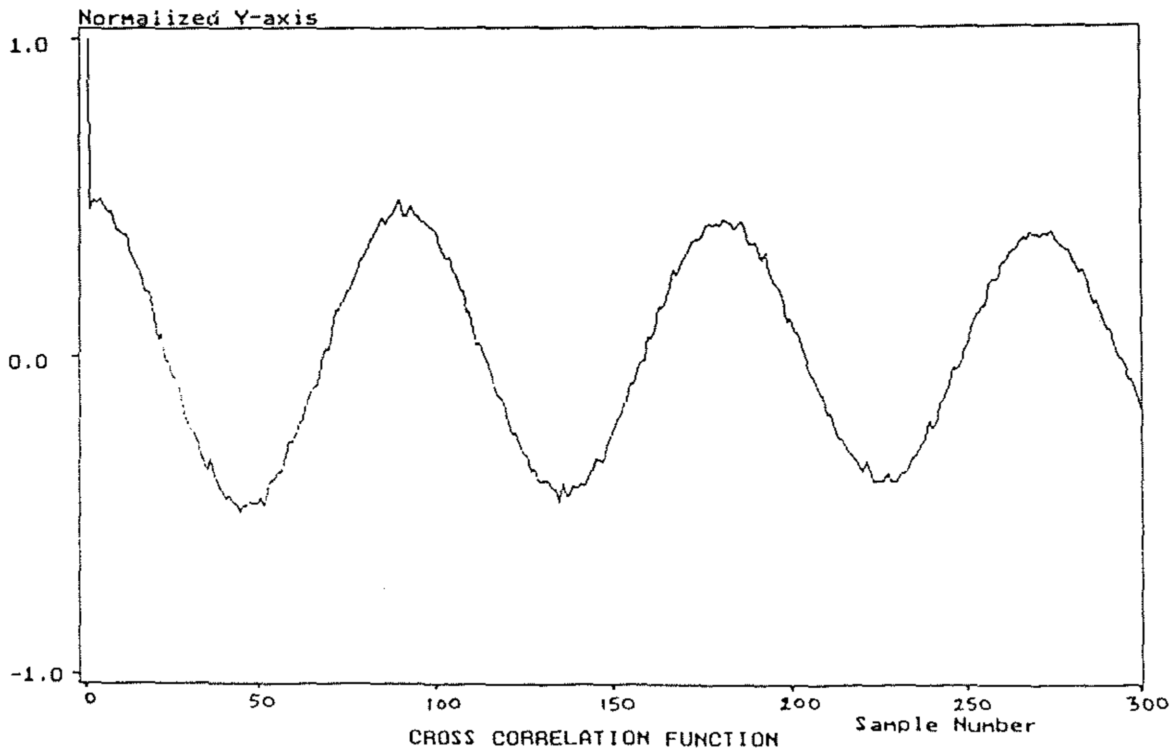
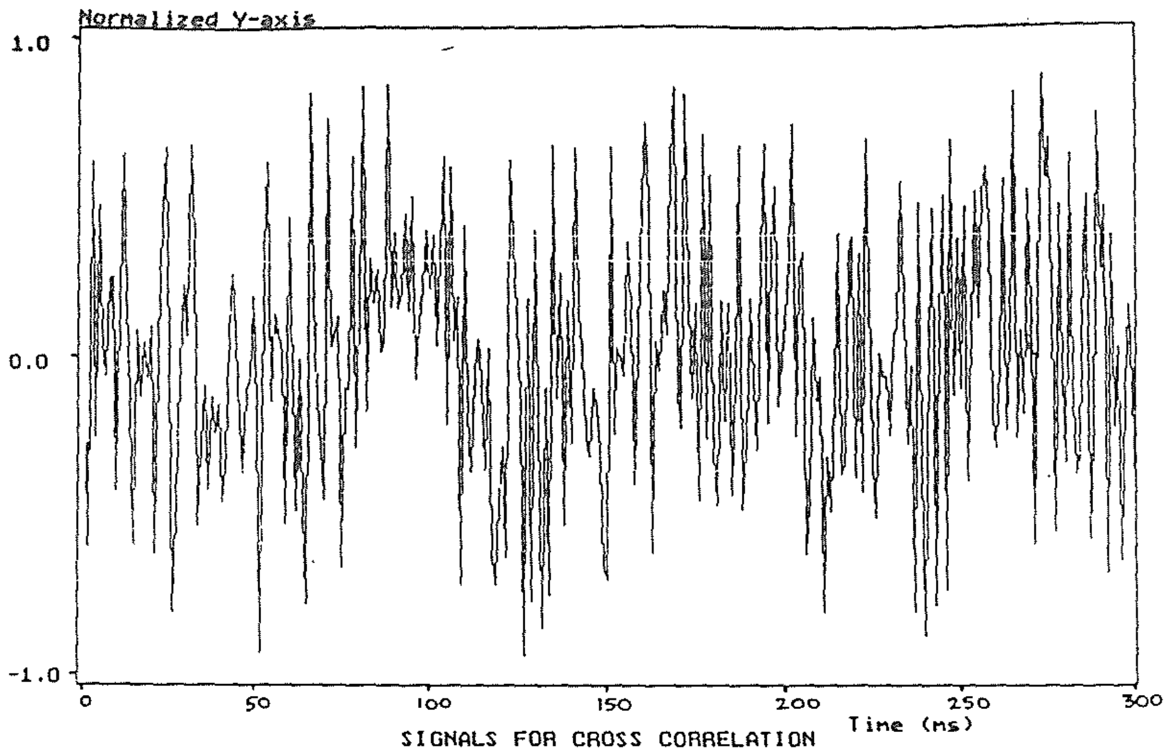


FIG. 4.3[c] Cross Correlation Function for SNR = Ø dB



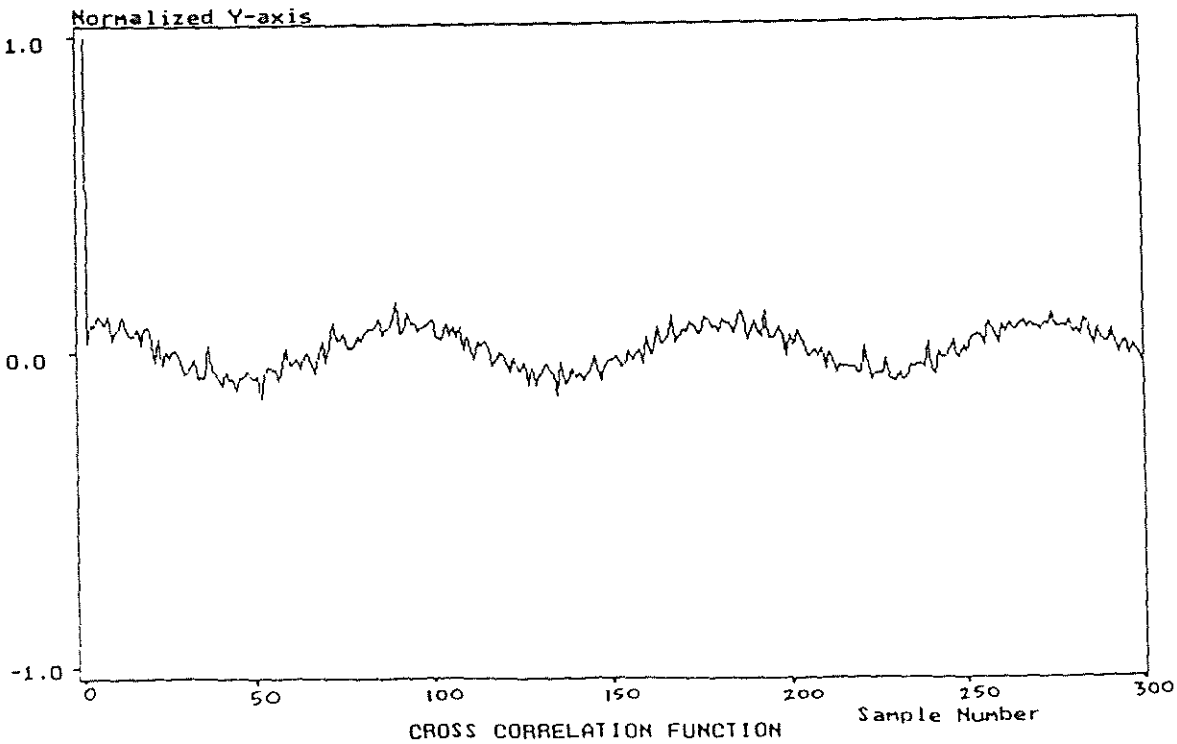
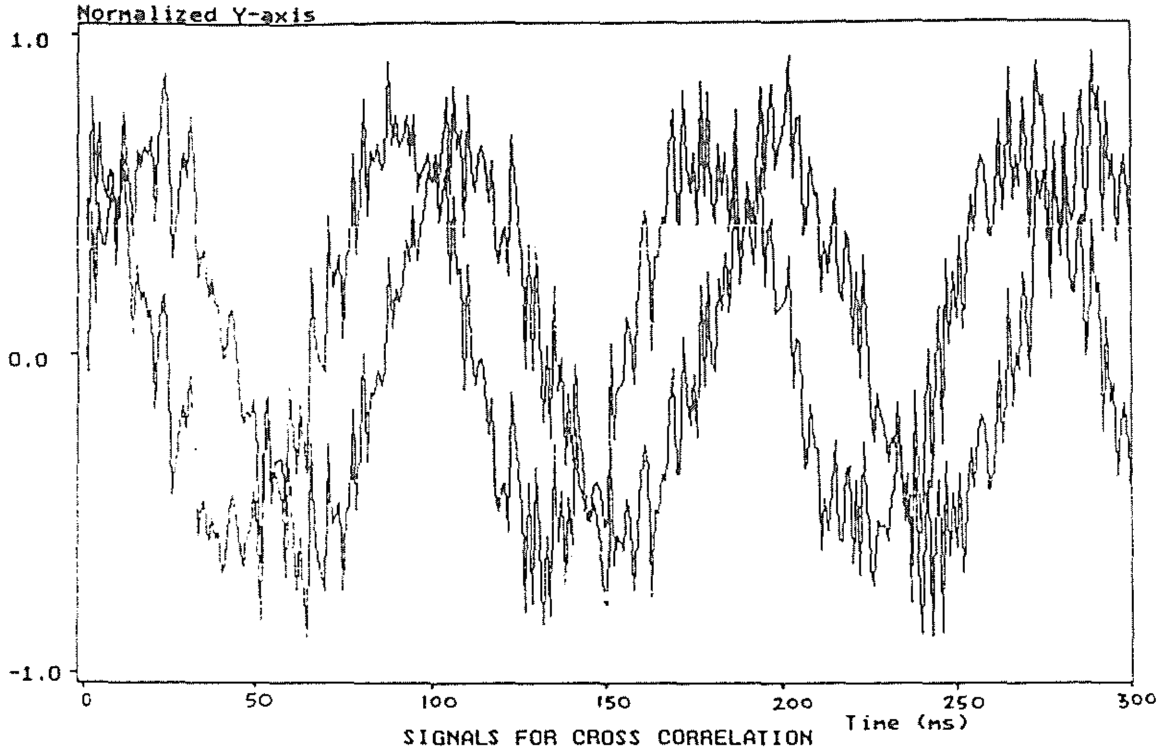


FIG. 4.3[d] Cross Correlation Function for SNR = -10 dB

peak of cross correlation function becomes so small as compared to the pulse that it could not be identified. This correlator can be used for SNR of 0 dB or above. In presence of noise, if there is a shift in data, the peak of the cross correlation function also shifts. For SNR of 10 dB and shift of 20 samples in the signal, the result is shown in Fig. 4.4.



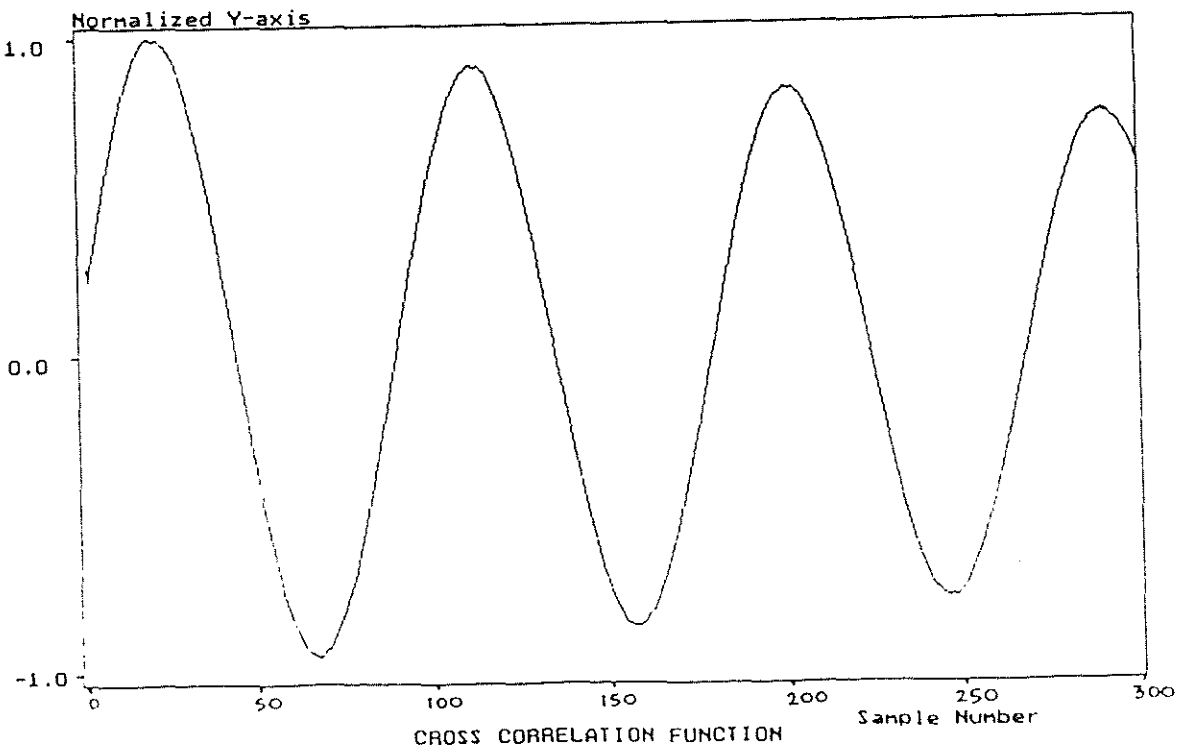


FIG. 4.4 Cross Correlation Function for SNR = 10 dB and Phase Difference of 20 Samples

CHAPTER 5

SUMMARY

The aim of this project was to develop sensor electronics and correlator for the cross correlation flow-meter with ultrasonic transducers. Sensor electronics which include RF amplifier, AM demodulator, band-pass filter and amplifier were assembled and tested. The desired performance was achieved and is given below.

RF amplifier	: 3-stage RC coupled transistor amplifier with bootstrapped input stage. Gain : 29 dB to 37 dB at 2 MHz Input impedance : 15 kΩ at 2 MHz
Demodulator	: AM envelope detector. Linear response for 0.5% to 14% modulation
Band-pass filter	: second order Butterworth filter. pass band : 5 Hz to 90 Hz for gain variation of 1.5 dB stop band : f < 1 Hz and f > 400 Hz for attenuation > 20 dB

Frequency domain correlator was implemented using data acquisition card and PC/AT. The correlator was tested with

sinusoidal input with phase difference between the channels. It was observed that the peak of the cross correlation function appears at the time corresponding to the phase difference. Random white noise was added to the signal and the correlator was tested for different signal to noise ratios. For SNRs below -10 dB, peak of cross correlation function could not be identified.

At the end of this project, some suggestions for further work on the project emerge. Three ICs used for filter and amplifier can be replaced by a single quad opamp IC. In the correlator program, data is stored in a file in ASCII format. Instead, binary files can be used which require less memory.

The set-up was tested with water circulating system. It was observed that received ultrasonic wave was getting modulated by line frequency. In presence of this interference, modulation due to turbulence of the flow could not be detected. This line frequency interference could be due to vibration of the pipe. More work has to be done regarding mounting of transducers on the pipe wall, rubber padding for the entire system to reduce the vibration effect. Further, 50 Hz notch filters should be incorporated in both demodulator channels, so that correlator inputs are free from line frequency interference.

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APPENDIX A

CROSS CORRELATION FUNCTION IN FREQUENCY DOMAIN

Cross correlation function for discrete signals is given by

$$r_{uv}[i] = \frac{1}{N} \sum_{n=0}^{N-1} u[n - i]\ v[n]$$

If $U(k)$ and $V(k)$ are discrete Fourier transforms of sequences $u[n]$ and $v[n]$, then

$$U(k) = \sum_{m=0}^{N-1} u[m]\ e^{-j \frac{2\pi}{N} km}$$

and
$$V(k) = \sum_{n=0}^{N-1} v[n]\ e^{-j \frac{2\pi}{N} kn}$$

The complex conjugate of $U(k)$ is

$$U^*(k) = \sum_{m=0}^{N-1} u^*[m]\ e^{j \frac{2\pi}{N} km}$$

For real signals, $u^*[m] = u[m]$

Therefore
$$U^*(k) = \sum_{m=0}^{N-1} u[m]\ e^{j \frac{2\pi}{N} km}$$

If $Y(k)$ is defined as

$$\begin{aligned} Y(k) &= \frac{1}{N} U^*(k)\ V(k) \\ &= \frac{1}{N} \sum_{m=0}^{N-1} u[m]\ e^{j \frac{2\pi}{N} km} \sum_{n=0}^{N-1} v[n]\ e^{-j \frac{2\pi}{N} kn} \\ &= \frac{1}{N} \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} u[m]\ v[n]\ e^{-j \frac{2\pi}{N} k(n-m)} \end{aligned}$$

Inverse DFT is defined as

$$y[i] = \frac{1}{N} \sum_{k=0}^{N-1} Y(k)\, e^{j \frac{2\pi}{N} ki}$$

$$\therefore \quad y[i] = \frac{1}{N^2} \sum_{k=0}^{N-1} \left[\sum_{m=0}^{N-1} \sum_{n=0}^{N-1} u[m]\; v[n]\; e^{-j\frac{2\pi}{N}k(n-m)} \right] e^{j\frac{2\pi}{N}ki}$$

$$\therefore \quad y[i] = \frac{1}{N} \sum_{m=0}^{N-1} u[m] \sum_{n=0}^{N-1} v[n] \left[\frac{1}{N} \sum_{k=0}^{N-1} e^{-j\frac{2\pi}{N}k(n-m-i)} \right]$$

Now,

$$\frac{1}{N} \sum_{k=0}^{N-1} e^{-j\frac{2\pi}{N}k(n-m-i)} = 1 \quad \text{for } m = n-i-lN$$

$$= 0 \quad \text{otherwise.}$$

$$\therefore \quad y[i] = \frac{1}{N} \sum_{n=0}^{N-1} u[n-i]\; v[n]$$

This is nothing but cross correlation function. Thus cross correlation function in frequency domain can be represented as

$$R_{uv}(k) = \frac{1}{N} U^{*}(k)\; V(k)$$

APPENDIX B

MECHANICAL SET-UP

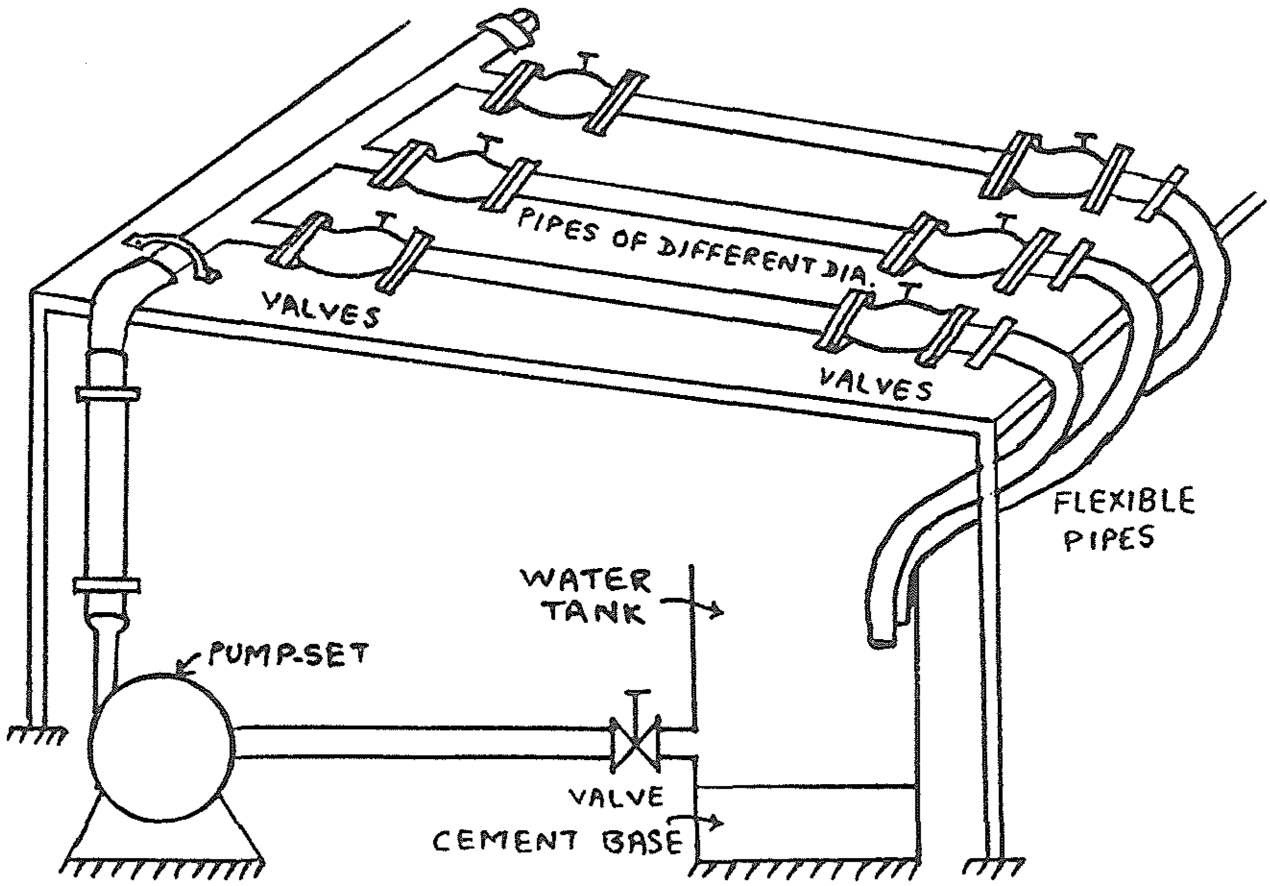


FIG. B.1 Water Circulating System

APPENDIX C

PCB LAYOUT

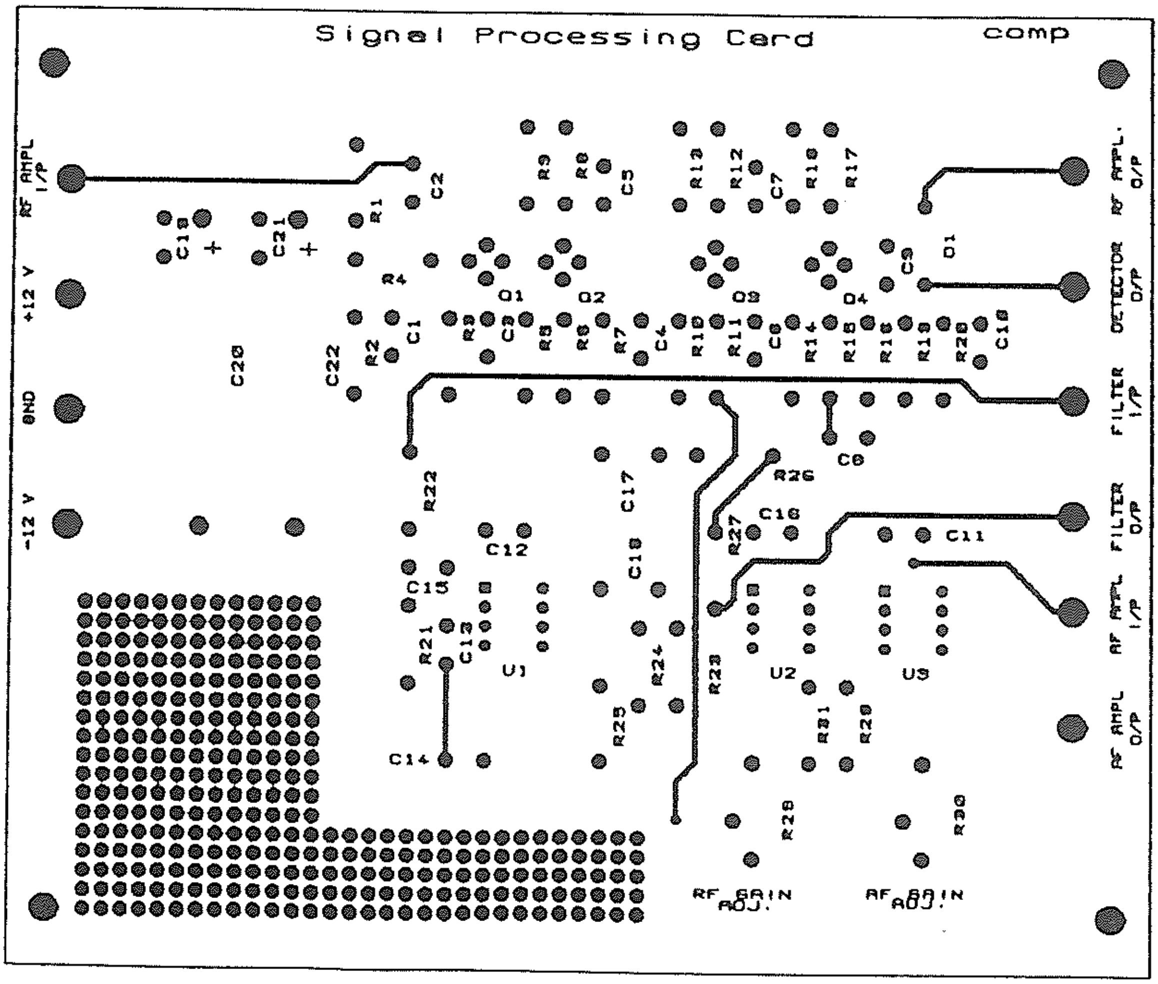


FIG. C.1 PCB Layout - Component Side

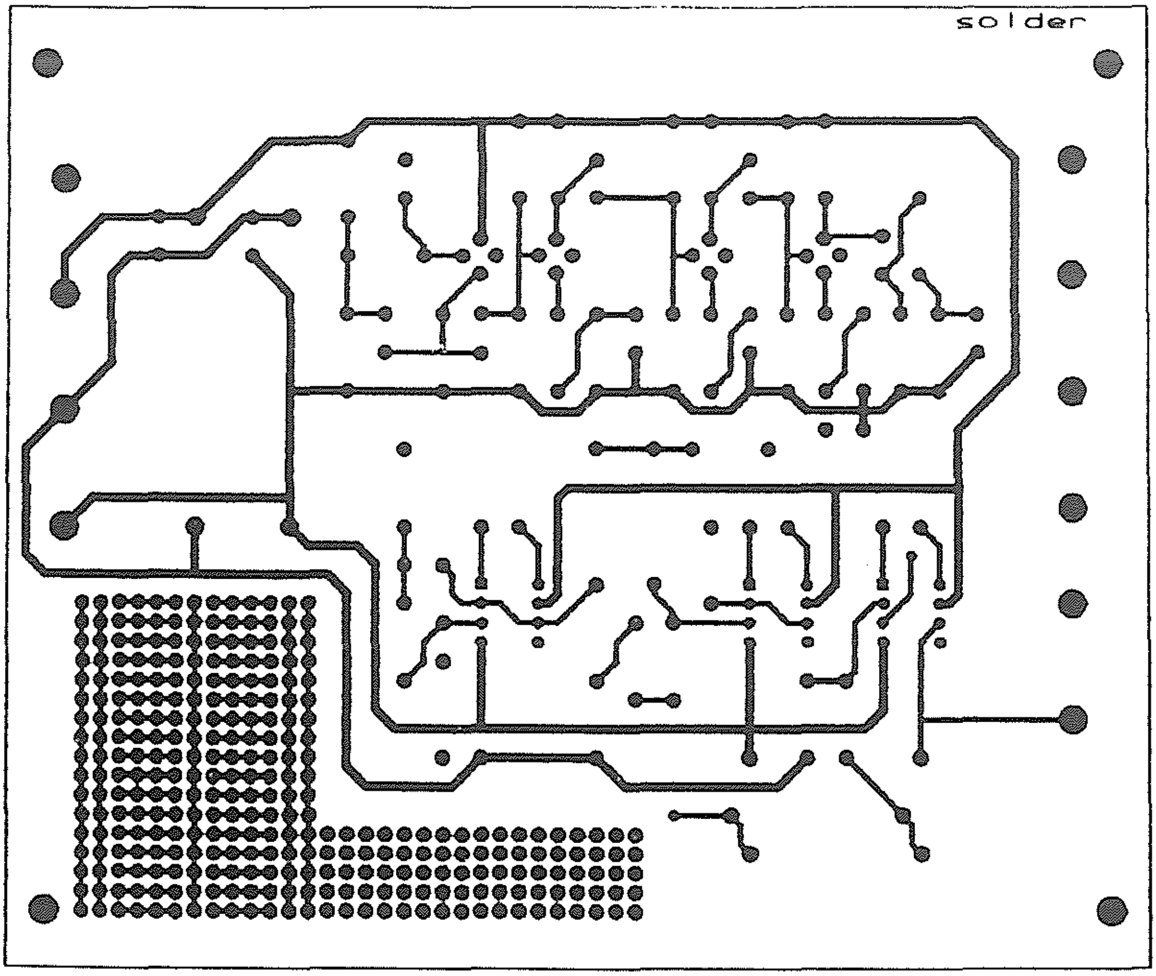
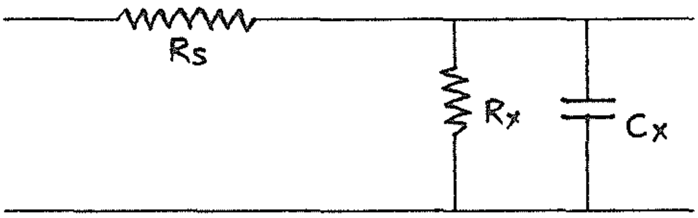


FIG. C.2 PCB Layout - Solder Side

APPENDIX D

<u>MEASUREMENT OF INPUT IMPEDANCE OF AN AMPLIFIER</u>

Input impedance of an amplifier can be measured by inserting a source resistance 'Rs' and measuring the change in gain and phase angle between input and output. Let R_x and C_x be input resistance and capacitance of the amplifier. Let A_1 and θ_1 be gain and phase without source resistance. If a source resistance R_s is introduced, new values of gain and phase are A_2 and θ_2. The source resistance R_s and input impedance of the amplifier will form a voltage divider network as shown below.



Gain of network $A = A_2 / A_1$ and phase $\theta = \theta_2 - \theta_1$

The transfer function of the network is given by

$$\frac{\dfrac{R_x}{1 + R_x C_x S}}{\dfrac{R_x}{1 + R_x C_x S} + R_s} = \frac{R_x}{R_x + R_s + R_s R_x C_x S}$$

$$= \frac{R_x}{R_x + R_s} \quad \frac{1}{1 + (R_s \,||\, R_x) C_x S}$$

The gain and phase of the network are

$$A = \frac{R_x}{R_x + R_s} \quad \frac{1}{\sqrt{1 + [(R_s \,||\, R_x) C_x w]^2}}$$

and $$\theta = -\tan^{-1} (R_s \,||\, R_x) C_x w$$

By substituting phase θ into gain equation,

$$A = \frac{R_x}{R_x + R_s} \frac{1}{\sqrt{1 + \tan^2\theta}} = \frac{R_x}{R_x + R_s} \cos\theta$$

Equations for input resistance R_x and capacitance C_x are obtained as

$$R_x = \frac{A\ R_s}{(R_s \parallel R_x)w} = \frac{R_s}{(\cos\theta\ /\ A) - 1}$$

and

$$C_x = \frac{-\tan\theta}{(R_s \parallel R_x)w}$$

APPENDIX E

BUTTERWORTH FILTER DESIGN

SPECIFICATIONS :

The specifications band-pass filter are

Pass band : 5 Hz < f < 100 Hz   Gain variation < 1.5 dB

Stop band : f < 1 Hz and f > 500 Hz Attenuation > 20 dB

DESIGN :

The filter can be realized by cascading high pass and low pass filters [18]. Specifications for these are

Low pass		High pass	
100 Hz	-1.5 dB	5 Hz	-1.5 dB
500 Hz	-20 dB	1 Hz	-20 dB

Low pass filter design :

Low pass steepness factor $A_s = 500/100 = 5$

The response curve indicates that 2^{nd} order Butterworth filter meets requirement of 1.5 dB attenuation at 0.8 rad/sec and 20 dB attenuation at 4 rad/sec. Let Normalized low pass filter is given in Fig. E.1[a].

Frequency scaling factor $FSF = 2\Pi f = 2\Pi(100)/0.8 = 785.4$

Let scaling factor $Z = 180.04 \times 10^3$

$C_1' = C_1 / (FSF \times Z) = 10$ nF

$C_2' = C_2 / (FSF \times Z) = 5$ nF

$R_1' = R_1 \times Z = 180$ KΩ

$R_2' = R_2 \times Z = 180$ KΩ

High pass filter design :

High pass steepness factor A_s = 5/1 = 5

The response curve indicates that 2^{nd} order Butterworth filter meets the requirement. With low pass to high pass transformation of $C_{hp} = 1 / R_{lp}$ and $R_{hp} = 1 / C_{lp}$, normalized high pass filter is obtained and is given is Fig. E.1[b].

Frequency scaling factor FSF = $2\Pi f = 2\Pi(5)\times 0.8 = 25.133$

Let scaling factor $Z = 180.86 \times 10^{3}$

$C_1' = C_2' = 1 / (FSF \times Z) = 0.22\ \mu F$

$R_1' = R_1 \times Z = 0.707 \times Z = 127.8\ K\Omega \simeq 100\ K\Omega + 27\ K\Omega$

$R_2' = R_2 \times Z = 1.41 \times Z = 255.7\ K\Omega \simeq 220\ K\Omega + 33\ K\Omega + 2.7\ K\Omega$

The complete circuit of band-pass realization is shown in figure E.1[c].

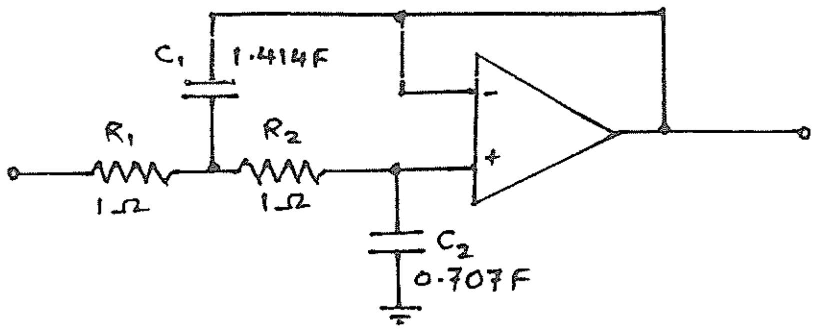


FIG. E.1[a] Low-pass Normalized Filter

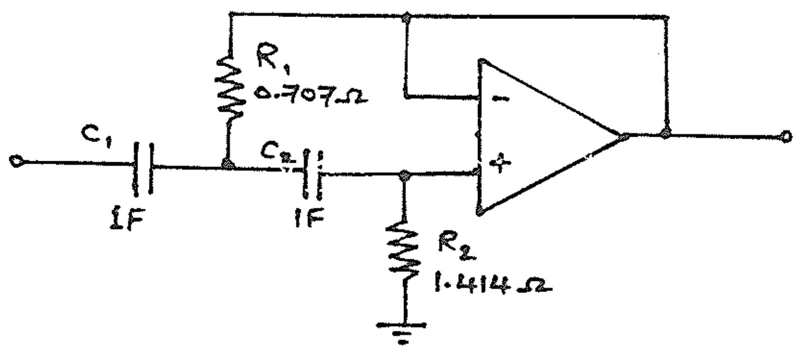


FIG. E.1[b] High-pass Normalized Filter

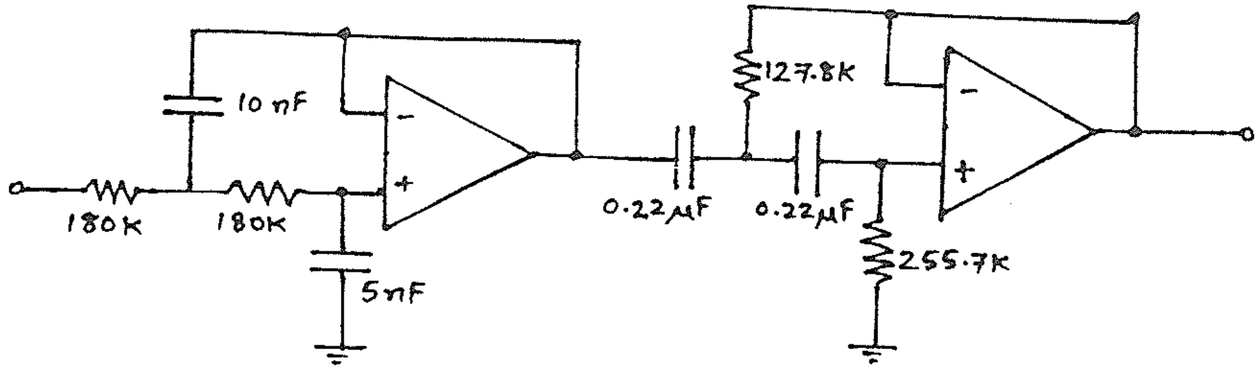


FIG. E.1[c] Band-pass Realization

FIG. E.1 Band-pass Filter Design

APPENDIX F

DATA ACQUISITION CARD PCL 208

PCL-208 (or equivalently, PCL-718) is data acquisition card manufactured by Dynalog Microsystems, Bombay [17]. It is a PC/XT/AT add-on card with 16 single-ended or 8 differential 12 bit A/D input channels.

FEATURES

A/D channels	:	16 single ended or 8 differential
Resolution	:	12 bits
Input range	:	Unipolar : +10, +5, +2, +1 V
		Bipolar : ±10, ±5, ±2.5, ±1, ±0.5 V
Conversion type	:	Successive approximation
Conversion speed	:	60 KHz
Accuracy	:	±0.01% of reading ± 1 bit
Trigger mode	:	Software trigger or Programmable pacer trigger or External trigger
Data transfer	:	Program control or Interrupt control or DMA

SETTINGS

The channel range and pacer rate selected by the software. Following hardware settings are of interest for A/D conversion.

SW1 : The card provides two clock input frequencies, 10 MHz and 1 MHZ to the 8254 programmable timer to generate pulses to trigger the A/D. The switch is set in 1 MHz position.

SW2 : It is a input selection slide switch. It is set in 'Bipolar' mode.

SW3 : With this channel configuration switch, the PCL-208 offers 16 single ended or 8 differential analog input channels. The configuration is done for 16 single ended channels.

SW4 : The PCL-208 provides DMA data transfer capability. The selection of DMA level 1 or 3 is controlled by this slide switch. As DMA is not used for data transfer, this switch setting is not required.

SW5 : The specific analog input range within the unipolar or bipolar group is selected by this DIP switch. The setting is done for ±5 V range.

SW6 : The I/O port base address is selectable via 8 position DIP switch. The switch is set for the hex address of 300.

APPENDIX G

RADIX-2 FFT ALGORITHM

Discrete Fourier transforms of sequences $u[n]$, is given as

$$U(k) = \sum_{n=0}^{N-1} u[n]\, e^{-j\frac{2\pi}{N}kn}$$

Total number of multiplications involved are N^2. These can be reduced if N is a power of two by using radix-2 FFT algorithm [10].

Let us represent $e^{j\frac{2\pi}{N}}$ by W_N

$$\therefore \qquad U(k) = \sum_{n=0}^{N-1} u[n]\, W_N^{-kn}$$

Consider odd and even terms of $u[n]$ separately as $g[n]$ and $h[n]$.

$$\therefore \quad U(k) = \sum_{n=0}^{\frac{N}{2}-1} \left[u[2n]\, W_N^{-2kn} + u[2n+1]\, W_N^{-(2n+1)k} \right]$$

$$\text{Now, } W_N^{-2kn} = \left[e^{j\frac{2\pi}{N}}\right]^{-2kn} = \left[e^{j\frac{2\pi}{N/2}}\right]^{-kn} = W_{N/2}^{-kn}$$

$$\therefore \quad U(k) = \sum_{n=0}^{\frac{N}{2}-1} g[n] W_{N/2}^{-kn} + W_N^{-k} \sum_{n=0}^{\frac{N}{2}-1} h[n] W_{N/2}^{-kn}$$

$$= G(k) + W_N^{-k}\, H(k) \qquad o \le n \le \frac{N}{2} - 1$$

$$= G(k-\frac{N}{2}) + W_N^{-k}\, H(k-\frac{N}{2}) \qquad \frac{N}{2} \le n \le N - 1$$

W_N^{-k} is called as a twiddle factor. The above equation shows that N point DFT can be computed as two N/2 point DFTs. Number of multiplications are reduced from N^2 to $2(\frac{N}{2})^2 + N$. Further two N/2 point DFTs can be obtained by four N/4 point DFTs. In that case, number of multiplications will reduce to $4(N/4)^2 + 2N$. In general, if $N = 2^{\nu}$ then after ν^{th} stage the number of multiplications will be νN i.e. $N\log_2 N$. The efficiency of algorithm is best judged by number of multiplications involved. As this algorithm of computing DFT reduces number of multiplications, the algorithm is efficient and called Fast Fourier Transform (FFT) algorithm.

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I.I.T., Bombay — **Sudheer P. Gokhale**

January 1994