CHAPTER 2

DESIGN AND DEVELOPMENT OF COMPUTER BASED INSTRUMENTATION SYSTEM FOR PHOTOACOUSTIC STUDIES:
HARDWARE DETAILS

2.1 BLOCK DIAGRAM OF COMPUTER BASED PHOTOACOUSTIC SPECTROMETER:

The Block Diagram of Computer based Photoacoustic Spectrometer is shown in Fig.2.1, it consists of the following functional blocks. Various modifications to this fundamental instrument have been incorporated by several workers\(^1\) and used them for a wide variety of PA measurements by.

i. Radiation Sources
ii. Modulators
iii. Photoacoustic Cell
iv. Acoustic signal detectors (microphone)
v. Preamplifier
vi. Filter

When the modulated laser beam falls on the sample which is kept in a closed cell absorbs photon energy. All or part of this absorbed energy is transferred into thermal energy through non-radiative process in the sample. Since the incident radiation onto the sample is intensity modulated, the internal heating of the sample is also modulated at the same frequency. The air at the sample-gas interface
Fig. 2.1 Block Diagram of Computer Based PAS

1. Pre-amplifier
2. Acoustic Signal Detector
3. Sample Holder
4. Modulator
5. Radiation Source
6. Narrow Band-Pass Filter
7. Lock-in Amplifier
8. Computer
9. Monitor
10. Temperature Controller
undergoes compression and rarefaction by this internal heating of the sample, which in turn produces acoustic signal at the same frequency as that of the modulating frequency.

These acoustic disturbances generated in the sample cell are detected by the electret microphone. This microphone converts acoustic signal into electrical signal. The output of the microphone is usually very small which is amplified by high gain pre-amplifier designed using LA3161 dual operational amplifier. The output of the pre-amplifier is passed through the narrow band-pass filter, which enhances signal-to-noise (S/N) ratio of the signal. Finally the output of the band-pass filter is given to the computer based lock-in amplifier, the later recovers the photoacoustic signal which is obscured by the noise. The temperature controller is used to control the temperature of the photoacoustic cell to the desired temperature, which enables to study the sample characteristics as a function of temperature.

2.2 RADIATION SOURCES:

Incandescent lamps or arc lamps are normally used as radiation sources for Photoacoustic (PA) studies. The lamp-monochromator combination can provide continuous tunability over a wide wavelength range from near-infrared to the vacuum ultraviolet. High pressure Xenon arc lamps, high pressure Hg lamps, tungston lamps, Nernst glowers etc., are commonly used as radiation sources. The major drawback with these sources is the relatively low bandwidth and low power output.

Lasers have found wide acceptance as convenient radiation sources in PA spectroscopic studies owing to their highly collimated beam of extremely high spectral brilliance. Different types of solid state, gas and dye lasers have been
employed in various kinds of PA studies. The high peak power available from pulsed lasers is especially attractive for measuring very weak absorptions. The solid state diode lasers have found applications in PAS because of their relatively high power and the narrow-band emission in Visible and Near Infrared regions, and the advantage that it can be easily modulated by just modulating the voltage applied to the diode. Further, the fact that they are compact, inexpensive and easy to handle make it an ideal choice for use in small, sample specific PA cells. With LED as source, modulation frequencies of ~40MHz are easily obtainable without loss of average power. The same is true for semiconductor diode lasers up to ~200MHz. With respect to laser sources, lead-salt diode lasers have the additional advantage because their wavelength can be rapidly tuned within a few wavenumbers directly by varying the current.

A switchable diode laser with the following specifications has been used for the present study.

<table>
<thead>
<tr>
<th>Type</th>
<th>Switchable Diode Laser</th>
</tr>
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<tbody>
<tr>
<td>Power</td>
<td>4.5 mW</td>
</tr>
<tr>
<td>Wavelength</td>
<td>640 nm</td>
</tr>
<tr>
<td>Switching voltage</td>
<td>TTL signal</td>
</tr>
</tbody>
</table>

A diode laser is widely used for PAS work, due to the following most important advantages viz. possibility of direct modulation, simplicity, low voltage operation, immunity from microphonics, robustness, low power consumption and low cost. The beam from the diode laser is modulated directly using a modulatable power supply driving it. The light output of the laser is proportional to the injected current over a large current range. Since the photon lifetime in the cavity is very short; amplitude modulation (AM) can only be accomplished at very high rates.
AM of light is obtained by adding small time varying signal $I(t)$ to the average pumping current.

2.3 LASER BEAM MODULATORS:

To generate the PA signal, it is necessary to modulate the laser beam. A variety of modulation techniques have been used viz. Q-switching, mode locking, pulsing the flash lamp, wavelength or frequency modulation, acousto-optic modulation, electro-optic modulation and also mechanical chopping modulation.

A modulating signal for laser source is derived from the lock-in amplifier, which also acts as a reference signal to lock-in amplifier. The detailed design and working of the lock-in amplifier developed by the author for the present study is discussed in detail in the foregoing sections.

2.4 PHOTOACOUSTIC CELLS:

The PA cell can be considered as the heart of the PA spectrometer and the literature contains several references to cell designs both for general use and for very limited but special applications. The ultimate aim in cell design is to maximize the signal to noise ratio. Therefore in order to achieve maximum sensitivity, certain criteria which govern the design of the PA cell are to be followed which are presented below.

a. The acoustic isolation of the cell from external vibrations.

To achieve this, one should as far as possible, use chopping frequencies different from those present in the acoustic and vibrational spectrum of the environment. In addition to this, the walls of the PA cell should be sufficiently
thick so that they prevent any acoustic disturbances from interfering with the signal. External acoustic isolation like vibration free tables also are to used for this purpose.

b. To minimize any spurious (noise) PA signal that may arise from the interaction of the light beam with the walls and windows of the PA cell.

To achieve this the windows must be selected such that they are as much optically transparent as possible for the wavelength region of interest. Also the body of the PA cell should be made out of polished aluminum or stainless steel. Although the aluminum or stainless steel walls absorb some of the incident and scattered light, the resultant spurious (noise) PA signal will be quite weak, as long as the thermal mass of these walls is large. A large thermal mass results in a very small temperature rise at the surface and thus reduces the magnitude of the background noise signal. In addition the cell should be designed in such a way that the scattered light must be a minimum inside the cell.

c. The PA signal generated by the sample in the cell should be as high as possible to detect it with a sensitive microphone placed in the PA cell.

The amplitude of the PA signal varies in an inverse manner with the cell volume and therefore it is necessary to keep the cell volume as small as possible to achieve an appreciable signal to noise ratio. The dimensions of the cell, however should not allow the acoustic signal produced from the sample surface to suffer appreciable dissipation at the cell window or cell walls. The distance between the sample surface and the cell window should always be greater than the thermal diffusion length in the gas medium adjacent to the sample. Therefore an optimum gas column length \( l_g \) should be provided for a maximum PA signal amplitude, and the PA signal decreases for both larger and smaller \( l_g \).
Experimentally the optimum value for $l_g$ is found to be governed by the relation shown in equation 2.1:

$$l_g = 1.8 \mu_g$$

where $\mu_g$ is the thermal diffusion length in the gas. From this it is obvious that the PA signal amplitude is directly related to the thermal diffusion length in the gas which in turn depends on the physical properties of the gas medium. Thus, a careful selection of the gas medium will enhance the signal to noise ratio. Some investigations revealed that helium gas improves the sensitivity of the PA cell by a factor of 3.2 compared with that for N2 gas at the same chopping frequency. This is because helium gas possesses large thermal conductivity which enhances the thermal diffusion processes through the gas medium. Considering the operation of the PA cells, they can be broadly classified into two groups. They are (i) resonant and (ii) non resonant PA cells.

**Design and Fabrication Details of Resonant cells:**

Resonant cells which utilize the longitudinal or radial resonances that occur in the cylindrical cavity of the PA cell when the PA signal frequency becomes equal to the inherent frequency of the PA cell. Therefore when these frequencies are exactly equal, maximum acoustic energy transfer occurs in the PA cell which essentially increases the PA signal amplitude. These types of PA cells are often used with a single modulation frequency which is the same as the resonant frequency of the cell, so as to increase the signal-to-noise ratio.

In the present study a Helmholtz resonance type of PA cell is designed and fabricated. This cell shows acoustic frequencies, which are well within the
frequency range used in the photoacoustic study. This type of PA cells are very useful for use in temperature variation studies.

The photoacoustic cell used in the present study is designed according to the Helmholtz resonance principle\textsuperscript{16}. It has been constructed with a view to achieve high sensitivity and to expand the operating ranges for the temperature (upto 500K) and frequency (upto 1KHz) specifically for the study of phase transitions in solids.

The whole PA cell is placed inside a main outer chamber. This chamber is sealed off by two MS flanges fixed at the top and bottom ends by using neoprene O-rings. Two stage rotary pump is used for evacuating the chamber. This evacuation of the chamber minimizes (by avoiding the external noise entering into the cell) the background noise level and to avoid the condensation of moisture on the window adjacent to the sample. The other window is used for letting-in the light beam for the optical excitation of the sample to enable the photoacoustic signal to be generated. The sample is kept in a cylindrical cavity of inner diameter 12mm and depth of 10mm made out of copper block which is chrome plated. The copper flange on the opposite side of the cavity is provided with highly polished circular glass plate which is fixed onto it using epoxy resin adhesive. The rear side of the sample cavity is press-fitted onto a cold-finger provided with a heater used for heating the sample. The cold-finger is permanently joined to an stainless steal (SS) tube through an L-joint (made of brass material) such that the sample cavity is pointed towards one of the window ports. The length of the SS tube is adjusted so that the centre of the sample cavity is on the axis of the window. The top end of the SS tube is permanently joined to an MS flange which is vacuum sealed to the top flange of the main chamber using neoprene O-ring.
The temperature of the sample is monitored by a temperature transducer Pt100 on the rear side of the sample cavity by drilling a 2mm bore in the sample holder assembly. The capillary tube which connects the sample compartment and the microphone compartment is made out of SS. It has a bore diameter of 1mm and a length of 10cm. The electret microphone BT-1759 is mounted in the microphone chamber and the assembly is attached to the top flange of the outer chamber. Electrical connections to the heaters, temperature sensor Pt100 and the microphone biasing are made through 3-pin feedthrough connectors fixed on the top plate of the outer chamber. The PA signal is taken out using a BNC connector fixed on the top plate. The complete schematic diagram of the PA cell is shown in Fig.2.2 and the dimensions of different parts of the cell are shown in Fig.2.3. The PA cell designed for the present study has the following advantages.

i. The major advantage of this cell is its simplicity of construction and good temperature stability.

ii. Since the outer chamber of the PA cell assembly is evacuated the system is virtually immune to ambient acoustic noise, apart from providing thermal insulation.

iii. The PA cell can be used for phase transition studies in the specified temperature range 77 to 500 K.

iv. The liquid nitrogen consumption, on cooling the sample, is found to be very small.

**Non-Resonant PA cells:**

In a Non-Resonant PA cell, the detector is located in close proximity of the sample. To reduce the spurious signals it is protected from direct illumination. These cells are operated at frequencies much below the resonant frequency of the
Fig. 2.2 Schematic Diagram of the PA Cell

1. M.S. OUTER CHAMBER
2. GLASS WINDOW
3. BNC
4. NEOPRENE O-RINGS
5. TO VACUUM PUMP
6. S S TUBE
7. COPPER BLOCK
8. \( \text{N}_2 \) CAVITY
9. MICA INSULATION
10. HEATER WINDINGS
11. Cu PA CELL
12. SAMPLE CHAMBER
13. S S PIPE
14. MICROPHONE ASSEMBLY
15. MICROPHONE
16. BRASS MICROPHONE HOLDER
Fig 2.3 Dimensions of Different parts of the PA Cell
cell cavity. Since a low or a high sample temperature can cause damage to the microphone, this type of cells are not useful for temperature variation studies.

2.5 ACOUSTIC SIGNAL DETECTORS:

Several devices are available for detecting the acoustic signal (disturbance) generated by the absorption of radiation. They can be broadly classified into three groups:

i. Pressure Sensors
ii. Refractive Index Sensors and
iii. Temperature Sensors.

Most of the photoacoustic experiments utilize pressure sensors, the majority of them are microphones. The following three types of microphones are normally used for PAS studies:

a. Condenser Microphone
c. Piezoelectric Microphone
b. Electret Microphone

a. Condenser Microphone:

The conventional condenser microphone basically works on the principle of capacitance variations caused due to pressure variations by the sound waves. It has two parallel plates, where one plate is rigidly fixed and the other acts like a diaphragm. The dielectric material between the plates is air. When acoustic waves are directed towards it, the diaphragm follows the vibrations of the sound, thereby altering the capacitance of the microphone, which leads to a voltage change that is
detected by a high input impedance amplifier. The microphone signal increases with the bias voltage applied across the microphone. These microphones have generally a flat frequency response up to ~ 15 KHz, which is ideal for PA studies, have low distortion and little response to mechanical vibrations. They respond well to pulsed pressure impulses, thus making them suitable for pulsed PA studies also. Bruel & Kjaer model 4145 is one of the widely used condenser microphones having a sensitivity of ~ 40mv/pascal in combination with a built-in MOSFET preamplifier.

b. Piezoelectric Detectors:

Since only one tenth part (1/10) of the acoustic pressure amplitude generated at the surface of a condensed matter sample is transmitted to the sample-gas interface and finally to the diaphragm, these microphones are not ideally suited for this application. To overcome this problem, a piezoelectric detector is attached directly to the solid or liquid sample. The pressure variations striking the piezoelectric element give rise to voltages which follow the PA pulses. Piezoelectric detectors such as lead zirconate titanate (PZT), lithium niobate, quartz crystal etc. are most popularly used. The different kinds of piezoelectric devices and their applications as acoustic transducers are reviewed by Mason et al and Juarez.

The sensitivity of a piezoelectric device and its frequency response is dependent on its dimensions. For a typical transducers element of diameter and thickness of the order of a few mm, the sensitivity is ~ 0.003mv/pascal as compared to 5-10 mV/Pascal for miniature condenser and electret microphones. The transducer is usually enclosed in a steel chamber to offer protection from electromagnetic radiation pickup, corrosion, absorption of stray light etc. The sample is then placed in contact with the transducer so that a better acoustic
impedance matching between the detector and the sample is possible and can thus detect high frequency signals associated with the sample\textsuperscript{22,23}. For corrosive environments, microphones protected with the sapphire or metallic films have been used. Here, the microphone senses the movements of the film which follow the pressure fluctuations in the cell. This technique compromises on the sensitivity since the sound waves do not fall directly on the microphone\textsuperscript{24}.

The new kind of piezoelectric transducers are film transducers. They are made of highly insulating polymeric films poled in a strong electric field at elevated temperatures or by electron bombardment so that they become electrically polarized and thus exhibit piezoelectric effect. Films like polyvinylidene fluoride (PVF2), Teflon, mylar etc. are the commonly used films. Due to their very small thickness, they are more sensitive and do not have the ringing effect. They have high rise times and their high flexibility helps in innovative transducer designs and better acoustic coupling with the sample\textsuperscript{24}.

c. Electret Microphone:

The electret microphone\textsuperscript{25-28} works in the same principle as the condenser microphone, but with the difference that the capacitance is provided by the electret, which is a thin foil of material with a permanent electrical polarization and high dielectric constant. One side of the electret foil is metalized and the insulating side is placed on a fixed back plate. The impinging sound waves on the metalized side cause a change in polarization characteristics of the electret material which in turn provide a small voltage between the metalized front electret and the fixed back plate. The large capacitance/unit area achieved in electrets enables them to be made into highly sensitive and miniature microphones. These microphones do not need the biasing voltage due to the permanent electrical polarization of the electret. Owing to the small capacitance of such microphones, the output
impedance is high (specially at low frequencies) and thus necessitates the use of high input impedance amplifiers. Some commercial miniature electret microphones (Knowles Electronics model BT1759 and BT1753) have built-in MOSFET pre-amplifiers and hence a bias voltage has to be supplied. These microphones have a sensitivity of ~ 10 mV/pascal and can be effectively matched to a low input impedance amplifier.

The microphonic detection is generally used for phase studies. Microphones do not couple very well to acoustic signals in condensed samples. To overcome this, a gas column is used to transfer the acoustic signal (disturbance) from the sample surface to the microphone.

An electret microphone is used in the present study is BT 1759 manufactured by the Knowles company. It can be operated with supply voltages ranging from 0.9 to 20 V. Its output impedance is about 3.5 K and has a nominal weight of 28 mg. Moreover it has an open circuit sensitivity of dB relative to 1.0 V/microbar. A comparative study of the characteristics of both electret and condenser microphones are presented in Table 2.1.
Table 2.1

Characteristics of Microphones

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Electret</th>
<th>Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BT 1759</td>
<td>B &amp; K 4145</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>10 mV/Pascal</th>
<th>40 mV/Pascal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear range</td>
<td>10 Hz - 10 KHz</td>
<td>~ 15 KHz</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>0.9 - 20 V DC</td>
<td>5 - 15 V DC</td>
</tr>
<tr>
<td>Responds to</td>
<td>Sinusoidal</td>
<td>Sinusoidal</td>
</tr>
<tr>
<td>input signals</td>
<td>and pulsed</td>
<td>and pulsed</td>
</tr>
</tbody>
</table>

2.6 LOCK-IN AMPLIFIER AND THE PRINCIPLE OF
PHASE SENSITIVE DETECTION:

For several applications it requires the measurement of very low level signal of about nano-volt (nV) amplitude obscured by noise. To achieve this task a lock-in amplifier is normally used. In fact, by means of phase sensitive detection, tremendous reduction in the noise level can be achieved by limiting the bandwidth of the detection to that just necessary to include just the single desired frequency of the signal only. This reduces greatly the noise power by about $10^6$ without affecting the signal power.

Fig.2.4 shows the block diagram of a lock-in amplifier. The lock-in amplifier is essentially a "very narrow band-pass filter-amplifier" that overcomes the Q-limitations of conventional circuits. Further, it is easy to achieve a noise bandwidth of less than 0.001 Hz and Q values of $10^8$ or greater with this. The lock-in amplifier can also provide an amplification of $10^9$ and greater easily. The
Fig. 2.4 Block Diagram of Lock-In Amplifier
Fig. 2.5 Principle of Lock-In Amplifier
term lock-in comes from the fact that the instrument locks-onto the frequency ($f_r$) of a reference signal. With an external reference signal, the lock-in amplifier acts as a "Tracking Band-pass Filter and Detector" with a centre frequency equal to that of the reference frequency $f_r$. Several investigators have designed computer/DSP based lock-in amplifiers\textsuperscript{29-41}.

The Fig.2.5 shows the principle involved in the design of a lock-in amplifier. A lock-in amplifier is equivalent to a combination of narrow-band filter and a phase discriminator. It basically consists of a phase sensitive detector followed by a low pass filter. The PSD multiplies the input signal ($V_i$) by reference signal ($R_i$). The output of the PSD is given to the low-pass filter, the filtered output is a dc voltage sensitive to each Fourier component common to $V_i$ and $R_i$ with a bandwidth equal to that of the low-pass filter\textsuperscript{29}.

As is evident from this figure, the functions of phase sensitive detection and the subsequent integration of the signal, which in an analogue lock-in amplifier, are normally performed by the multiplier and the low-pass filter, are digitally executed by the computer\textsuperscript{30} in the present experiment by the author. The detailed descriptions of the design of various blocks in Fig.2.5 are presented in the following sections of this chapter.

2.7 PRE-AMPLIFIER FOR PAS:

The photoacoustic effect is based on the absorption of light energy by the sample resulting in production of a very low amplitude signal. Hence, a high input impedance, high gain, low noise pre-amplifiers are required to amplify such signals. High gain pre-amplifiers are commercially available, and can also be built using discrete components like FETs/MOSFETs and low noise integrated circuits like LM308, OP07 etc. The typical noise level of the microphone is $\sim 4 \text{ nV/Hz}$ and
Fig. 2.6 Gain Selectable Microphone Pre-amplifier
since the noise in the PA signal is also amplified, a compromise between the signal-to-noise ratio (SNR) and the amplifier gain is necessary for optimum PA signal detection. It has to be noted that, even with the best available electronic circuitry, the amplifier noise exceeds the signal generated by transducer itself resulting in a detection sensitivity far below the theoretical limits determined by the displacement of the microphone diaphragm. Several circuits for microphone and piezoelectric transducer pre-amplifiers have been described by several investigators. The use of operational amplifiers with low temperature coefficient with large feedback substantially reduces the gain drift with temperature in comparison to pre-amplifiers with FET/MOSFETs in the input stage.

The electret microphones have built in MOSFET amplifiers which makes it easy to couple them to moderately high input impedance pre-amplifiers. It must be noted that the frequency response of the microphone and pre-amplifier system should be flat within the modulation frequency range being used. The electret microphone will have three terminals, one is connected to 100K resistor which acts as a biasing resistor, the middle pin produces an electrical output signal proportional to the acoustic input signal and the third pin is connected to the body of the microphone, which in turn should be connected to the ground. The bias voltage needed for the electret microphone is provided by the highly regulated power supply. The Fig.2.6 shows the circuit diagram of pre-amplifier designed for amplifying the photoacoustic (PA) signal developed by the electret microphone. The amplifier is built around a dual operational amplifier LA 3161. The gain of the pre-amplifier can be varied by varying the capacitor connected to the inverting input of the op. amp. as shown in figure. Here, the voltage across this capacitor acts as a negative feedback to the amplifier, the gain of the amplifier can be increased by selecting low value capacitor conversely the gain can be decreased by increasing the capacitance value. In this circuit eight capacitors of
different values (0.1, 0.47, 4.7, 10, 22, 33, 100 and 230μF) are used for selecting different gains of pre-amplifier. The second stage of the op. amp. is used as a voltage follower for achieving better isolation between the pre-amplifier and the filter network.

2.8 DESIGN OF NARROW BAND-PASS FILTER:

The signal to noise ratio is the most important parameter that needs to be considered, and hence the use of signal filters becomes a necessity when low level measurements or high resolution measurements are attempted47. Filters can be broadly classified into two types viz., Passive and Active filters. One of the serious constraints with the passive filters is the necessity to always use the specified source and termination impedances, besides compensating for the heavy attenuation suffered by the signal. Cascading of the filters is also not a straightforward solution inspite of designing the filters so that their source and termination impedances are equal. Additional isolation amplifiers are to be often interposed between cascaded filter sections. This presents severe distortion in the filter characteristics due to non-ideal matching between source-end and the input filter-end section and the output-end of the filter and the input amplifier section or the filter-end section terminating load. Another main drawback is the necessity to use bulky and often non-linear inductors for low and very low frequency filters.

The availability of operational amplifiers in the integrated circuit form has tremendously changed the concept of filter design, leading to the emergence of active filters. Today, a majority of low frequency filters are necessarily of this type, particularly for frequencies below 100 KHz. The special advantage of the active circuitry for use as low-frequency filters is the fact that inductors can be totally avoided. In addition, active capacitance multiplication technique also enables the use of capacitors of low practical values to be used even for cut-off
Fig. 2.7 Tunable Narrow Band-pass Filter
frequencies down to a fraction of one hertz. However, due to the limited gain bandwidth product of IC and their effect on the filter characteristics, these filters are limited to few hundred kilohertz. The recently introduced inexpensive general purpose FET input operational amplifiers are particularly useful in the design of active filters\textsuperscript{48-50}.

The Fig.2.7 shows the state-variable band-pass filter designed for the present study. The state-variable filter, in spite of large number of components, is a good choice for very high Q band-pass filters. It has low component sensitivities, do not make great demands on operational amplifier's bandwidth and it is easy to tune\textsuperscript{51} such filters. The important advantage of this circuit is that, its bandwidth (i.e., Q) can be adjusted without affecting the mid-band gain. In fact, Q and gain 'G' and the central frequency $f_0$ can be set with single components ($R_q$, $R_g$ and $R_f$ or $C$). They are completely independent of one another and are give by the following simple equations.

\begin{align}
    f_0 &= 1/(2\pi R_f C) \\
    Q &= R_1/R_q \\
    G &= R_1/R_g
\end{align}

The present circuit shown in Fig. 2.7 is designed for $Q = 50$ and $G = 10$. The centre frequency $f_0 \approx 70$ Hz. In this circuit a ganged potentiometer is used as $R_f$. So varying the ganged potentiometer, centre frequency can be adjusted to the desired value. As it is not possible to cover the entire range of frequencies interested with a single ganged potentiometer, three ganged potentiometers are used through a band switch for selection of a particular frequency band in the present design. With this arrangement the frequency range from $\sim 10$ Hz to 1 KHz can be covered which is well beyond the frequency range required for the present study. The output of the filter is applied to the inverting amplifier for further
amplification of the signal and finally is taken through a buffer amplifier to provide impedance matching of the filter circuit with following sections.

### 2.9 DESIGN AND DEVELOPMENT OF COMPUTER BASED PHASE SENSITIVE DETECTOR:

The block diagram of the computer based phase sensitive detector is presented in Fig.2.8. The entire system can be divided into three functional blocks viz.,

i. Reference Signal Generator  
ii. Window Pulse Generator and  
iii. Data Acquisition System

The detailed design description of each block is presented in the following sections.

**Development of Reference and Window pulse generation card:**

The reference signal and window pulse are generated from a common circuit shown in Fig.2.9. The details of their generation is described in section (i) and (ii).

**i. Generation of Reference Signal (Square Wave):**

The Fig.2.9 shows the schematic diagram of the reference and window signals generator. In this design a 9-bit counter is used to generate a reference signal. The Integrated Chips\textsuperscript{52} 74LS393 and 74LS76 are used for this purpose. IC 74LS393 is a dual 4-bit binary counter and IC 74LS76 is dual JK flip-flop used as divide by 2 counter. The two 4-bit binary counters in 74LS393 are cascaded to make an 8-bit
Fig. 2.8 Block Diagram of Computer Based PSD
counter. The 9th bit is provided by the flip-flop 74LS76. The input of this 9-bit counter is driven by the out-0 of programmable interval timer/counter (8254) which is operated at a frequency of 10 MHz (crystal clock) in square wave mode. Each time the count reaches 512 (11111111B), the counter gets reset automatically and starts counting again from zero. Thus counter acts as a reference frequency generator, which is used to modulate the laser diode.

Thus the output of the 9-bit counter is a square wave whose frequency depends on the frequency of the timer output. The frequency of the timer (8254) output $f_{\text{out}}$ can be varied to meet the frequency requirements by loading a suitable number 'N' in the 16 bit counter of 8254. The value of N is calculated with the help of relation (2.5) shown below.

$$f_{\text{out}} = \frac{f_{\text{cryst}}}{N} \quad \text{...... (2.5)}$$

where $f_{\text{cryst}}$ is the crystal clock frequency. Since this particular counter is operated as binary counter, N can be varied from 0004 to FFFFH. Thus $f_{\text{out}}$ can vary between 2.5 MHz to 152.59 Hz.

Since one clock pulse of $f_{\text{out}}$ is needed to increment the 9-bit counter by 1, for every 512 clock pulses one full square wave will be generated at the output of the 9 bit counter. The frequency of the reference signal is, therefore, is given by

$$f_{\text{out}} = \frac{f_{\text{cryst}}}{N} \quad \text{...... (2.6)}$$

$$f_r = \frac{f_{\text{out}}}{512} \quad \text{...... (2.7)}$$

$$f_r = \frac{f_{\text{cryst}}}{(512\times N)} \quad \text{...... (2.8)}$$

or

$$N = \frac{f_{\text{cryst}}}{(512\times f_r)} \quad \text{...... (2.9)}$$
Fig. 3.9 Schematic Diagram of the Reference and Window Signal Generator
Thus, in order to fix the required reference frequency, \( N \) is calculated from the aforesaid equation (2.9). Thus it is possible to obtain the reference frequencies \( f_r \) ranging from 4882.81 Hz to 0.2980 Hz. As the reference frequency \( f_r \) is derived from the crystal clock by division, the reference signal is highly stable.

ii. Window pulse generation:

The Fig.2.9 shows the schematic diagram of window and reference signal generator. The key point used in generating the window pulses which are differing in phase by 180° with each other is being done by using the output lines of 9-bit counter. Among the nine lines of the 9-bit counter eight are connected to eight of the sixteen input lines of digital comparator 74LS266. It consists of an array of 8 numbers of 2-input exclusive NOR gates. The other eight input lines of the X-NOR gates are driven by port-A of the programmable peripheral interface (PPI) from the data acquisition card. This card is also designed by the author for the present experiment the details of which are discussed in the next section. The output of the 9-bit counter varies from 000H to 1FFH. As only lower eight bits of this counter are used, each time the 8-bit data occurs twice in a full cycle there is a bit change in the 9th bit position. For example, consider the 8-bit number FFH. This occurs twice as follows.

\[
\begin{align*}
01111111B & \text{ i.e. } 0FFH \\
11111111B & \text{ i.e. } 1FFH
\end{align*}
\]

This 8-bit number is passed to the X-NOR gates for comparison through I/O port of PPI (8255). Whenever the count crosses the 8-bit number in 9-bit address a positive pulse occurs at the output of these X-NOR gates. The duration of these pulses is roughly 10 \( \mu \text{sec} \). These pulses are directly coupled to a monoshot multivibrator. The integrated chip 74LS121 is used as monoshot multivibrator,
which has a complete flexibility in controlling the pulse width. These window pulses act as a start conversion signals to the analog to digital converter to digitize the photoacoustic signal at $S_k$ and $S_{k+1/2}$ (i.e at a phase difference of 180°). The use of these monoshots (windows) are described in detail in the following sections.

**Development of Data Acquisition Card :**

A complete Data Acquisition Card has been designed and fabricated by the author indigenously for the present study. The Fig.2.10 shows the block diagram of Data Acquisition Card. The detailed schematic diagram of the data acquisition card and the interfacing the same with the computer is presented in Fig.2.11.

The card is designed as a multipurpose card. The card can be used not only for measurement but also for controlling the parameter being measured. The card mainly consists of a high speed Analog to Digital (A/D) converter AD 1674, Programmable Peripheral Interface (PPI) 8255 and Programmable Interval Timer (PIT) 8254. These three devices are interfaced to computer at different addresses through the I/O slot.

**i. Interfacing of Analog to Digital Converter AD1674 with Computer :**

The A/D converter AD1674 used for this application has the following specifications

* 12 bit Resolution
* 10 micro seconds conversion time
* Bi-polar operation + 5V and - 5V
* Conversion speed upto 100K samples per seconds
* Does not require external zero and full scale adjustments.
* On chip sample and hold facility
* On chip clock facility
* Ranges: bipolar +5V or +10V and Unipolar 0-10V or 0-20V

Interfacing of A/D converter AD1674 with the computer is presented in Fig.2.11. The A/D converter is interfaced to the computer through its I/O slot. In a computer all the address, data and control lines will be terminated in the I/O slot, these lines are essential to interface any peripheral device to the CPU of the computer. As shown in the circuit, the address lines (A0 - A9), control lines (AEN, RD, WR, RESET) and data lines (D0 - D7) are brought onto the card through two latches 74LS573 (IC1 & IC2) and one bi-directional buffer 74LS245 (IC3). The latches and buffer are used to protect the address, control and data lines of the CPU. If any short circuit or spark is generated in the external circuit these latches are destroyed and CPU is protected.

Since the I/O slot (ISA) of the computer has only 8-bit data lines, to interface 12 bit A/D converter needs two 8-bit latches 74LS573 (IC4 & IC5) as shown in the circuit. The data lines (D0 - D7) are connected to latch (IC4) and remaining data lines (D8-D11) are connected to another latch (IC5). The pins R/C and STATUS of analog-to-digital converter are connected to the PC0 and PC7 of programmable peripheral interface (PPI) 8255 respectively to start conversion and to see whether conversion is completed or not. The STATUS pin is also connected to the STROBE pins of two latches IC4 & IC5 which strobos the 12 bit digital data of A/D converter onto the outputs of these latches after converting analog voltage into digital.

A 3 to 8 decoder 74LS138 (IC6) is used to select these latches and other peripheral devices present in the card. A dip switch logic has been provided in card to change the base address of the card. This provision makes the user to use more
Fig. 2.11 Detailed Circuit Diagram of the Data Acquisition Card
than one card in same computer. This logic is designed with 8-bit digital comparator 74LS688. This comparator consists of a 8 two input NAND gates, one set of inputs the P0, P1, P2, P3, P4, P5, P6 & P7 of this gate are connected to the buffered lines A4, A5, A6, A7, A8, A9, AEN and +5V of the computer. Another set of inputs Q0, Q1, Q2, Q3, Q4, Q5, Q6 and Q7 are connected to the dip switches. When the data on the dip switches data matches the data on the address lines, the comparator output goes low. This signal is used to enable the bi-directional data bus buffer IC3 74LS245 and the decoder IC6 74LS138. This signal acts as a board selecting signal. Hence, the position of switches is very important to give particular address to any peripheral device. For example, the following dip switches status gives the base address of the board as 0300H.

<table>
<thead>
<tr>
<th>SW1</th>
<th>SW2</th>
<th>SW3</th>
<th>SW4</th>
<th>SW5</th>
<th>SW6</th>
<th>SW7</th>
<th>SW8</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>0300H To 030FH</td>
</tr>
</tbody>
</table>

When an analog voltage is applied to A/D converter input, the process of converting analog voltage into digital signal is started when pin R/C is made first high and then low, this is done by PC0 of 8255 which is available on the card. To see whether the conversion is completed or not, STATUS pin is continuously monitored through PC7 of 8255. When the STATUS pin goes low then conversion is completed and the digital data are available on 12 lines (D0-D11) of A/D converter.

Since the STATUS pin of A/D converter is connected to the STROBE pin of latches IC4 & IC5, when this signal goes low (i.e. after digitizing analog voltage) the 12 bit digital data are strobed into these latches and the same are placed on the outputs of these latches. The lower byte of digital data can be read by enabling latch IC4 by sending an address 0300H and high nibble of digital data can be read by enabling latch IC5 by sending an address 0304H. Finally by
substituting the digital data in the equation (2.10) gives the input amplitude directly in volts.

\[ V = \frac{V_{\text{ref}} \times \text{(Digital data)}}{4096} \text{ volts} \quad \text{..... (2.10)} \]

ii. Interfacing of PIT 8254 with computer:

Most microcomputers have counter devices such as the Intel 8253 or 8254, which can be programmed with instructions to divide an input frequency by any desired number. Besides acting as programmable frequency dividers, these devices play many important roles in microcomputer systems. Intel 8254 is used in the present design which contains three 16-bit counters which can be programmed to operate in several different modes. The maximum input clock frequency for 8254 is 10 MHz. The 8254 has a read-back feature which allows it to latch the counts in all the counters and the status of the counter at any point is indicated.

Interfacing of 8254 (IC8) programmable interval timer (PIT) with computer through I/O slot is also presented in Fig.2.11. The data lines D0 to D7 of I/O slot are connected to the data lines D0 to D7 of 8254 through the bi-directional buffers 74LS245 (IC3), and the control lines RD, WR, A0, and A1 are connected to the 8254 through the latch 74LS573 (IC2). To select the chip the output of the decoder (Y3) of 74LS138 (IC6) is connected to the chip select pin of 8254. By properly setting the position of dip switches on the card and giving the address 030CH to 030FH selects the counters and control register of 8254. The remaining decoding logic circuit is identical to that explained in the previous section. The address of the 8254 can be changed by changing the position of dip switches on
the card. The power supply and ground of 8254 are carefully connected to the +5V and ground pins of I/O slot through the de-coupling capacitor.

<table>
<thead>
<tr>
<th>counter</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>counter-0</td>
<td>030CH</td>
</tr>
<tr>
<td>counter-1</td>
<td>030DH</td>
</tr>
<tr>
<td>counter-2</td>
<td>030EH</td>
</tr>
<tr>
<td>control register</td>
<td>030FH</td>
</tr>
</tbody>
</table>

iii. Interfacing of PPI 8255 with the Computer:

The 8255 is a widely used, programmable, parallel I/O device. It can be programmed to transfer data under various conditions, from simple I/O to interrupt I/O. It is flexible, versatile, and economical (when multiple I/O ports are required), but somewhat complex in its operation. It is an important general-purpose I/O device and can be used with almost any microprocessor/microcomputer.

Interfacing of 8255 (IC9) Programmable Peripheral Interface to the computer through I/O slot is also presented in Fig.2.11. The interfacing of 8255 is achieved through I/O mapped I/O. Therefore, the pins required to interface 8255 is taken from the I/O slot. The data lines of I/O slot (D7 to D0) are connected to the data lines of 8255 (D7 to D0) through the bi-directional buffer 74LS245 (IC3) and the control lines of I/O slot i.e., A0, A1, RD, WR, RESET connected to the A0, A1, RD, WR, RESET pins of 8255 through the latch 74LS573 (IC2). The
power supply for 8255 is given from the I/O slot through de-coupling capacitor. The decoder 74LS138 (IC6) output (Y2) is connected to the chip select (CS) pin of 8255, by giving proper address, the chip is selected. The remaining circuitry i.e., comparator 74LS688 (IC7), DIP switch logic is identical to that explained in the previous sections.

Address for selection of different ports in 8255

<table>
<thead>
<tr>
<th>port</th>
<th>address</th>
</tr>
</thead>
<tbody>
<tr>
<td>port-A</td>
<td>0308H</td>
</tr>
<tr>
<td>port-B</td>
<td>0309H</td>
</tr>
<tr>
<td>port-C</td>
<td>030AH</td>
</tr>
<tr>
<td>control register</td>
<td>030BH</td>
</tr>
</tbody>
</table>

iv. The Technical Specifications of the Personal Computer used in the Present Experiment:

A personal computer with the following features is employed for interfacing the photoacoustic system in the present study.

* 80486DX 100 MHz Intel Microprocessor
* 8 MB RAM
* 570 MB Hard disk drive
* 1.2 MB and 1.44 MB Floppy disk drives
* Two Serial Ports
* One Parallel Port
* Six ISA slots to connect I/O, A/D, D/A converter cards etc.
Working of Computer Based Phase Sensitive Detector:

The working of phase sensitive detector can be explained with signals shown in Fig.2.12. When an 8-bit number is placed to the X-NOR gates through port-A of 8255 shown in Fig.2.9, whenever the count crosses the 8-bit number in 9-bit counter a positive pulse occurs at the output of this X-NOR gate. Thus for each reference cycle the window pulse generator produces two narrow output pulses differing by a phase of $\pi$ (180°). Since these pulses act as start conversion signals to the A/D converter, it samples the photoacoustic signals at two phases differing by $\pi$ (180°). The two values $S_k$ and $S_{k+1/2}$ have different sign as shown in Fig.2.12b, thus contributing to enhancement of the signal. The process of sampling signals at $S_k$ and $S_{k+1/2}$ is repeated for large number of consecutive cycles 'N' at the same points. Once these 'N' cycle of operations have been performed, these 'N' values are averaged to get signal value at a particular point. This procedure completely eliminates the random noise.

When the 8-bit number passed to the X-NOR gates through port-A of 8255 as shown in Fig.2.9 is incremented by 1. Then the window pulses generator generates window pulses which are slightly (~0.7°) moved towards right as shown in Fig.2.12b. Then the above procedure is repeated to obtain the signal amplitude at the next point with a phase difference of (~0.7°) from it's previous point. This procedure is repeated for 256 points to get a complete half cycle (180°) of the signal. The Fig.2.12c shows the output of the phase sensitive detector. This signal is smoothened by the software low-pass filter designed to get a smooth signal, free from noise. the Fig.2.12d show the output signal after subjecting it to digital filtering as specified above.
Fig. 2.12 (a) Reference and Photoacoustic Signal
(b) Window pulses
(c) PSD output
(d) Digital Filter output
2.10 MICROCONTROLLER BASED PID TEMPERATURE CONTROLLER:

i. Introduction:

Several investigators have designed and fabricated precise computer/microprocessor/microcontroller based temperature controllers\textsuperscript{56-63}. An attempt is made in the present investigation to achieve precise temperature regulation for studying the behaviour of the samples with temperature in photoacoustic spectroscopy with minimum hardware. As the need for improved, inexpensive, highly reliable and safer methods of control is being felt more and more, there is an increasing search going-on for achieving this objective. One of the avenues available for achieving this objective is the use of microcontroller. This has lead to the fabrication of a microcontroller based temperature regulator system, providing the much needed relief and flexibility to the main computer which is tied-up with other tasks assigned which are discussed in the earlier sections.

ii. Block diagram:

The block diagram of the microcontroller based temperature controller system is shown in Fig.2.13. Here the temperature of the photoacoustic cell (sample) is measured by a suitable sensor (Pt-100), and the measured analog signal is converted to a signal that is compatible with the microcontroller using A/D converter. The microcontroller is designed to sense the temperature signal, set the desired temperature (fix the set point), compute the error by comparing the measured signal with the reference signal (set point), solve the PID equation and output the necessary control signals to the actuator. The later controls the quantity of heat added-to or removed-from the heater connected to the
Fig. 2.13 Block Diagram of Temperature Controller
photoacoustic cell to maintain the desired temperature. The temperature of the photoacoustic cell is displayed on a 2 Line X 16 Character LCD display.

The following six basic control actions are very common among industrial analog controllers: Two position or ON/OFF, Proportional (P), Integral (I), Proportional+Integral (PI), Proportional+Derivative (PD), Proportional+Derivative+Integral (PID) control action. In the present experiment a PID controller is designed with the help of a microcontroller 8031.

i. Hardware features of the Microcontroller 8031:

The microcontroller is used for the present study has the following features:

* 8 bit microcontroller
* 256 bytes of on-chip RAM
* 4 I/O ports
* 2 sixteen bit counters
* 16 Address lines
* 8 data lines
* 1 full duplex serial port

Hardware Development of a Microcontroller Based Temperature Regulator:

A microcontroller based PID temperature regulator system is designed for controlling the temperature of the PA sample. It consists of the following elements:

i. Transducer for temperature measurement
ii. Signal Conditioning Circuit
iii. Analog to Digital Converter & Interfacing to Microcontroller
The conventional temperature transducers have some significant limitations. The Thermocouple outputs a very small signal that varies nonlinearly with temperature. It also must have some form of reference correction. The thermistors' output is very large, the distinguishing characteristics are a high temperature coefficient and the fact that their resistance is a function of absolute temperature. But disadvantage of thermisters is that their output is also quite nonlinear. For each of these transducers we must add electronics to compensate for these shortcomings. Also additional circuitry may be needed to produce a reasonably large output voltage or current. This resulted the development of IC sensors. But the disadvantage of IC sensors is it's low temperature range limitation64.

The Platinum Resistance Thermometer (Pt-100) is used for the present study to overcome the above difficulties. It operates on the principle of change (increase) in electrical resistance of platinum wire as a function of temperature. Of all the usable metals for temperature sensing, platinum best meets the stringent requirements of the thermometry. It can be highly refined to a purity of 99.99% and it resists contamination. It is mechanically and electrically stable. One of the important features of Pt-100 is that, the relationship between temperature and resistance is quite linear and is given in the relation (2.11). Drift and error with aging and usage are negligible. The platinum resistance thermometers are used for temperature measurements in the range -220 to 750°C and it has a temperature
coefficient $a = 0.0389$ ohms per degree centigrade. Hence, it is selected for the present study.

$$R_T = R_o (1 + AT + BT^2 + \ldots) \ldots (2.11)$$

$$\approx R_o (1 + AT)$$

since all the second and higher order terms are negligibly small

**ii. Signal Conditioning Circuit:**

The Fig.2.14 shows the signal conditioning circuit for converting changes in the resistance of Pt-100 sensor into changes in the voltage. A constant current source has been designed for this purpose. This will eliminate the lead-wire error of Pt-100. A simplest constant current source is constructed using operational amplifier (A1) OP07 as shown in Fig.2.14. The stability of the current source is dependent on the stability of the reference voltage. A stable voltage source is constructed using LM336 which gives a constant voltage of 2.450 volts. The constant voltage is divided through a potential divider network consisting of $R_A = 10$ K (1%) and LM 336 IC Zener source. This reference voltage is applied to the non-inverting input of A1. The operational amplifier is configured in non-inverting mode. The Pt-100 acts as a feedback resistance and the resistance $R_s$ determines the amount of constant current. For example, if it is required to construct a constant current source for 100 $\mu$A, the resistance $R_s$ can be calculated by the following equation

$$Rs = \frac{(2.450V)}{100 \mu A} = 2.450 \text{ K} \ldots (2.12)$$

A 5 K multi-turn potentiometer is used, and it is adjusted to the value 2.450 K. This gives the constant current source of 100 $\mu$A. As along as the resistance of $R_A$ and voltage source $V_{CC}$ remain constant, this circuit gives a constant current of 100
Fig. 2.14 Temperature Sensor and Signal Conditioner
μA. When this current passes through the temperature sensor Pt-100, produces a differential voltage equal to

\[ \Delta V = 100 \, \mu A \times (\text{Resistance of Pt-100}) \] ............ (2.13)

at 0°C the resistance of Pt-100 is 100 ohms, hence, the voltage across the Pt-100 at this temperature is

\[ 100 \, \mu A \times 100 = 10 \, \text{mV} \] ............ (2.14)

then this voltage is amplified by a factor of 10 with the help of an instrumentation amplifier designed using A2, A3, A4 to increase the sensitivity of the system ten-fold. This amplified voltage is measure of the resistance of the Pt-100 and is used for computing the temperature of the sample through software making use of the resistance to temperature conversion relation (2.11) and the computer displays the temperature directly in °C. An instrumentation amplifier designed using A2, A3, A4 is used to amplify the output of the Pt-100. The important features of instrumentation amplifiers are

* Selectable gain with high gain accuracy and gain linearity
* Differential input capacity with good CMRR
* High stability of gain with low temperature coefficient
* Low dc offset
* Very high input impedance
* Low output impedance

The operational amplifiers A2, A3, A4 forms an instrumentation amplifier. A high precision monolithic op. amps. OP07's are used, which have low-offset voltage and low-drift. A high input impedance is ensured due to the non-inverting configuration in which they are designed to operate. High common mode
rejection is achieved in the following state which is wired as a differential amplifier. The resistors R1, R2, R3, R4, R5, R6 are selected as 10 K (0.1%) to obtain a high/optimum CMRR. The gain of the instrumentation amplifier can be varied by varying \( R_G \) alone. In this circuit \( R_G \) (1K) is adjusted in such way that, the output of the instrumentation amplifier is 10 times to that of it's input. For example, in the present experiment the resistance of Pt-100 is 100.0 ohms at 0°C and the output of the instrumentation amplifier will be 100.0 mV. This voltage again is suitably processed by the microcontroller through the software to get the temperature directly in degrees of Kelvin.

iv Development of the Microcontroller (8031) Board :

The Fig.2.15 shows the schematic diagram of the microcontroller board designed by the author for a dedicated application of temperature control. It contains all the features required for it to function as stand alone system. The board contains the following features:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>8031 (12 MHz)</td>
</tr>
<tr>
<td>Program Memory</td>
<td>2732 (4K) 0000H - 0FFFH</td>
</tr>
<tr>
<td>Data Memory</td>
<td>6116 (2K) 2000H - 27FFH</td>
</tr>
<tr>
<td>Parallel I/O</td>
<td>8255 6000H - 6003H</td>
</tr>
<tr>
<td>Timer</td>
<td>8253 8000H - 8003H</td>
</tr>
<tr>
<td>Serial Port</td>
<td>one</td>
</tr>
</tbody>
</table>

The role assigned to the microcontroller in the present is to acquire the temperature data, evaluate the error by comparison with a reference (a set point),
solve the PID equations and finally apply the output of the PID equation to the counter which controls the power to the heater through a triac.

a. Interfacing of Memories with the Microcontroller:

The Intel 2732 is a 4 K byte UV erasable and Electrically Programmable Read Only Memory (EPROM). The 2732 operates from a single +5V power supply has a stand by mode and features an O/P enable control. An important feature of 2732 is that it has a separate Output Enable (OE) and the Chip Enable (CE) pins. The OE control eliminates bus contention in multiple bus microprocessor systems. Intel 6116 is a 2 K byte high speed static CMOS RAM. Its access time is 120 nsec.(typical).

The buffered data lines (D0-D7) of microcontroller are connected to the data lines of memory chips i.e. EPROM and RAM. Since EPROM requires 12 address lines and RAM requires 11 address lines, the address lines A0 to A11 and address lines A0 to A10 are connected to the address lines of EPROM and RAM respectively. The remaining address lines A12 to A15 are used for selecting the chips with the help of a 3 to 8 decoder 74LS138 IC.

The RD and PSEN of the microcontroller are combined with the help of an AND gate constructed using NAND gate 74LS00, the output of the AND gate is connected to the output enable (OE) of EPROM. This arrangement enables the data to be read from the EPROM. The contents of the memory at any location can be accessed by sending the address to EPROM.

Since, the read and write operations will take place in the RAM, the RD and WR signals are connected to the OE and WE pins of the chip respectively.
Read and write operations are low active. The following Tables 2.2 and 2.3 show the addresses of EPROM and RAM respectively.

### Table 2.2
**ADDRESS of EPROM**

<table>
<thead>
<tr>
<th>A15</th>
<th>A14</th>
<th>A13</th>
<th>A12</th>
<th>A11</th>
<th>A10</th>
<th>A9</th>
<th>A8</th>
<th>A7</th>
<th>A6</th>
<th>A5</th>
<th>A4</th>
<th>A3</th>
<th>A2</th>
<th>A1</th>
<th>A0</th>
<th>Hex</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0000H</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0001H</td>
</tr>
<tr>
<td></td>
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</tr>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0FFFH</td>
</tr>
</tbody>
</table>

### Table 2.3
**ADDRESS of RAM**

<table>
<thead>
<tr>
<th>A15</th>
<th>A14</th>
<th>A13</th>
<th>A12</th>
<th>A11</th>
<th>A10</th>
<th>A9</th>
<th>A8</th>
<th>A7</th>
<th>A6</th>
<th>A5</th>
<th>A4</th>
<th>A3</th>
<th>A2</th>
<th>A1</th>
<th>A0</th>
<th>Hex</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>2000H</td>
</tr>
<tr>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>2001H</td>
</tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>27FFH</td>
</tr>
</tbody>
</table>
b. Interfacing of 8255 Programmable Peripheral Interface with Microcontroller:

Intel 8255 is a general purpose programmable I/O device designed for simple input/output operations. It has 24 I/O pins which are divided into three ports of 8-bits each viz., Port-A (PA0-PA7), Port-B (PB0-PB7) and Port-C (PC0-PC7). Port-C can be divided into two four bit ports (PC0-PC3) and (PC4-PC7).

Port Address Generation:

Since there are three ports, two address lines are sufficient to select all the ports. The address lines A0, A1 of the microcontroller are connected to the A0, A1 of 8255 which provide port selection. The pins RD and WR are connected to RD and WR of 8255 to synchronise its read/write operations with the microcontroller. The data lines D0 to D7 of microcontroller are connected to 8 data lines of 8255 for transmitting or receiving the data from the microcontroller. The CS of the 8255 is connected to the Y4 of the decoder (74LS138). The remaining 16 address lines A0, A1 and A13, A14, A15 are used for determining the selection of a port or control register of 8255. In this system the 8255 is used with address as specified in Table 2.4.

Table 2.4
Address for port selection of 8255

<table>
<thead>
<tr>
<th>A1</th>
<th>A0</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Port-A</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Port-B</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Port-C</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Control Register</td>
</tr>
</tbody>
</table>
The port addresses are generated as specified in Table 2.5

Table 2.5
Port addresses assigned for 8255

<table>
<thead>
<tr>
<th>A15</th>
<th>A14</th>
<th>A13</th>
<th>A12</th>
<th>A11</th>
<th>A10</th>
<th>A9</th>
<th>A8</th>
<th>A7</th>
<th>A6</th>
<th>A5</th>
<th>A4</th>
<th>A3</th>
<th>A2</th>
<th>A1</th>
<th>A0</th>
<th>Hex</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6000H</td>
<td>Port-A</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>6001H</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>6002H</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>6003H</td>
</tr>
</tbody>
</table>

The contents of the Control Register is called 'control word', which specifies an I/O function for each port. This register can be accessed by writing a control word when both A0 and A1 are at logic 1. This register is not accessible for a read operation.

c. Interfacing of 8253 Programmable Interval Timer/Counter with Microcontroller:

The Intel 8253 is a programmable counter/timer IC chip. It generates accurate time delays and can be used for the applications such as a real-time clock, an event counter, a digital one-shot multivibrator, a square wave generator, and a complex waveform generator. The 8253 includes three identical 16-bit counters that can operate independently in anyone of the six modes.
Since there are three counters/timers, two address lines are sufficient to select all the ports. The address lines A0, A1 of microcontroller are connected to the A0, A1 of 8253 which enable the selection of the desired counter. The pins RD and WR are connected to RD and WR of 8253 to synchronise its read/write operations with the microcontroller. The data lines D0 to D7 of microcontroller are connected to 8 data pins of 8253 for transmitting or receiving the data from the microcontroller. The CS of the 8253 is connected to the Y5 of the decoder (74LS138). The 16 address lines A0 to A15 determine the selection of a counter or control register of 8253. In this system one 8253 is used with addresses as specified in Table 2.6

Table 2.6
Counter addresses assigned for 8253

<table>
<thead>
<tr>
<th>A15 A14 A13 A12 A11 A10 A9 A8 A7 A6 A5 A4 A3 A2 A1 A0</th>
<th>Hex Counter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 8000H</td>
<td>Counter-0</td>
</tr>
<tr>
<td>1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 8001H</td>
<td>Counter-1</td>
</tr>
<tr>
<td>1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 8002H</td>
<td>Counter-2</td>
</tr>
<tr>
<td>1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 8003H</td>
<td>C.R.</td>
</tr>
</tbody>
</table>

In the present study 8253 is operated in Mode-1. Each counter of 8253 is individually programmed by writing a control word into the control word register of 8253.

The IC 74LS138 is a 3 to 8 decoder, it facilitates the selection of any chip on the board. The inputs A, B, C of the decoder are connected to address lines A13, A14, A15 of microcontroller as shown in Fig.2.15. Depending on the binary
count appearing on these lines any one of the eight output pins which are normally high become low, thereby select the associated chip. Since at any time, one and only one output of the decoder goes low, only one chip gets selected, consequently, eliminating the possibility of data bus clash. The chip selection pattern is specified in the Table 2.7.

Table 2.7

<table>
<thead>
<tr>
<th>C</th>
<th>B</th>
<th>A</th>
<th>Decoder Chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A15</th>
<th>A14</th>
<th>A14</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Y0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Y1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Y3</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Y4</td>
</tr>
</tbody>
</table>

The two ICs 1488 and 1489 are also incorporated in the microcontroller board for serial communication with the host computer. This enables the computer to read the temperature data of the sample and store it in the specified file.

iii. Analog to Digital Converter ICL7135:

In the present study four and half digit A/D converter ICL7135 is used. The Intersil ICL7135 is a precision A/D converter with its multiplexed BCD output and digit drivers, combines dual slope conversion. The A/D converter has the following features.
* Accuracy guaranteed to ±1 count over entire or 20,000 counts
* Guaranteed zero reading for 0 volts input.
* 1pA typical input current.
* True differential input.
* True polarity at zero count for precise null detection.
* Single reference voltage required.
* Over-range and under-range signals available for auto-range capability.
* All outputs are TTL compatible.
* Blinking output gives visual indication of over range.
* Six auxiliary input/outputs are available for interfacing to UARTs
* Interfacing to microprocessors or other circuitry.
* Multiplexed BCD outputs.

**Interfacing of ICL7135 to the microcontroller through 8255:**

The output of the A/D converter ICL 7135 is in multiplexed BCD form or in seven segment form. The BCD data are output from the converter on lines B1, B2, B4, and B8. A logic high is output on one of the digit strobe lines D5, D4, D3, D2, and D1 to indicate when BCD code for corresponding digit is placed on BCD outputs. The A/D converter outputs the BCD code corresponding to the digit that is placed on BCD outputs. The A/D converter outputs the BCD code for most significant bit and then outputs a high on D5 pin. After a short period of time it outputs the BCD code for the next most significant digit and outputs a high on D4 pin. The process is repeated until the least significant bit is output. After outputting of all the 5 digits the cycle repeats.
Fig. 2.16 Interfacing of ADC ICL7135 with Microcontroller
Fig. 2.17 Crystal Clock Generator for A/D converter and 8253
The data from this A/D converter are read by polling the bit corresponding to a strobe line (until that bit goes high) and store the data in reserved memory locations for future reference. After reading the BCD code for one digit, the bit which corresponds to the strobe line for the next digit is polled until that bit goes high and stored in next memory location. The process is repeated until the data for all the 5-digits are acquired.

Fig.2.16 shows an interface between an A/D converter with microcontroller. The five STROBE pulses start the transmission of the five data words represented by eight bit words as shown in Table 2.8. The STROBE starts the transmit sequence to a quad 2-input multiplexer, which is used to superimpose polarity, over-range, and under-range onto D5 word. Since, in this instance it is known that B2 = B4 = B8 = 0. Hence, the multiplexer eliminates the use of one more port to read the polarity, over-range and under-range.

The clock for A/D converter is derived from the crystal clock generator shown in Fig.2.17

<table>
<thead>
<tr>
<th>Digit</th>
<th>Data Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>0000 XXXX</td>
</tr>
<tr>
<td>4th</td>
<td>1000 XXXX</td>
</tr>
<tr>
<td>3rd</td>
<td>0100 XXXX</td>
</tr>
<tr>
<td>2nd</td>
<td>0010 XXXX</td>
</tr>
<tr>
<td>1st</td>
<td>0001 XXXX</td>
</tr>
</tbody>
</table>

Table 2.8
e. Interfacing of Alphanumeric Display with Microcontroller:

The Oriole's Display Module ODM (2 line 16 characters) is used in the present study. It is a dot matrix liquid crystal display (LCD) that displays English alphanumeric; Kana(Japanese) characters and symbols. The circuit diagram shown in Fig.2.18 presents the interfacing of the display module with the microcontroller through programmable peripheral interface PPI 8255. The data bus D0-D7 of display module is connected to PB0-PB7 of port-B of PPI 8255 and the control pins RS and E are connected to the P1.2 and P1.3 pins of microcontroller respectively. The command word is sent to the command register by making RS HIGH through P1.3 and the data can be sent to the display RAM by making RS LOW through P1.3. A HIGH pulse of about 40 micro second duration is sent to the pin E of the microcontroller to fetch/send the data/command word to the display, which can be done through the pin P1.2 of the microcontroller. The controller pin R/W is connected to the ground. The second pin of the display is connected to the variable terminal of the potentiometer as shown in the Fig. 2.18 which varies the contrast of the display.

vii. Zero Crossing Detector:

The circuit diagram of zero crossing detector is presented in Fig.2.19. The 12V transformer followed by the resistor and diodes produces a square wave at the input of an inverter A, which is synchronized with the ac line voltage but restricted to legal TTL levels. The RC and diode networks around the outputs of inverters A and B form positive differentiators. These differentiators produce a positive spike at every zero crossing of the ac mains at the input of the inverter C which inverts this spike holding the Gate-0 of the 8253 low. Hence, at each zero crossing of ac mains the inverter C, pulls this pin of 8253 to ground for a few microseconds. The 7405 is an open collector hex inverter
Fig. 2.18 Interfacing of LCD Module with Microcontroller

Microcontroller Board

8255

+5V

2K

Temp. = 303.10 K
Sp.Temp. = 313.10 K

LCD Display Module
Fig. 2.19 Circuit Diagram of Zero Crossing Detector
provided to assure adequate drive current for the differentiator and the optoisolator MOC 3010. At each zero crossing of the line, inverter C pulses the gate input and the count is re-loaded into the counter-0 of the 8253. Then the counter decrements at every clock pulse until the count loaded in the counter becomes zero at the rate decided by clock generator (1MHz).

vi. Final Power Control Element & Controller Section:

The final control element is nothing but an actuator which controls the power or energy supplied to the system to bring the physical parameter to the desired level. In the present study a triac is used as final control element. A triac can conduct in both directions (it conducts during both half cycles of the ac mains) and is normally used in ac phase control. It can be considered as two SCRs connected in anti-parallel with a common gate connection. Since a triac is a bi-directional device, its terminals cannot be designated as anode and cathode and hence designated them as MT1 and MT2. If terminal MT2 is positive with respect to terminal MT1, the triac can be turned ON by applying a positive gate signal between gate G and terminal MT1. It is not necessary to have both polarities of gate signals and a triac can be turned ON with either a positive or negative gate signal. The Fig.2.20 shows the power control circuit.

Here the triac acts as a switch. When it is OFF, no power is allowed pass through it to the load. When it goes ON, the load receives full line voltage. This is quite adequate for simple ON or OFF operations. But to provide proportional control of power to the load "phase angle firing control technique" is employed in the present experiment.
Fig. 2.20 Power Control Circuit
Proportional+Integral+Derivative Controllers:

The simplest controller turns the actuator either hard ON or fully OFF. To prevent excessive cycling or chattering, a dead band (hysteresis) is usually introduced to provide finer and smoother control. Proportional band may replace the dead band. Over this proportional band, the output of the proportional controller varies linearly with error around zero. Although capable of providing tight control than the ON/OFF controller, the proportional controller cannot fully eliminate the error to cause perfect steady state tracking between the set-point and the process variable. An integrator must be added to the proportional controller. This proportional + integral controller will provide good steady-state control, but responds sluggishly to transients. This deficiency can be overcome by the addition of a derivative element which constitutes a complete Proportional+Integral+Derivative (PID) controller.

This gives good transient as well as steady-state control. It offers rapid proportional response to error, while having an automatic reset from the integral part to eliminate residual error. The derivative section stabilizes the controller and allows it to respond to the rapid changes or transients in error. To enable the microcontroller to implement the PID control, the continuous differential equation must be converted to a discrete difference equation as given below.

\[
V_o = K_p(e) + K_i \int e dt + K_d \frac{de}{dt} \quad \ldots \quad (2.11)
\]

differentiating both sides of the above equation with time 't', we get
\[
data_v/dt = K_p(de/dt) + K_i (e) + K_d(d(de/dt)/dt) \quad \ldots \text{(2.12)}
\]

Alternatively, the above equation can be written in difference form as

\[
\Delta V_o/T = K_p(\Delta e/T ) + K_i(e) + K_d \Delta (\Delta e/T)/T \quad \ldots \text{(2.13)}
\]

where \( T = dt \) the cycle time. Multiplying throughout by \( T \) gives

\[
\Delta V_o = K_p (\Delta e) + K_i(e)T + K_d \Delta (\Delta e/T) \quad \ldots \text{(2.14)}
\]

where \( \Delta V_o = V_n - V_{n-1} \), \( \Delta e = e_n - e_{n-1} \) rewriting equation (2.14) gives

\[
V_n - V_{n-1} = K_p(e_n - e_{n-1}) + K_i e_n T + K_d \Delta (e_n - e_{n-1})/T
\]

\[
V_n - V_{n-1} = K_p(e_n - e_{n-1}) + K_i e_n T + k_d (\Delta e_n - \Delta e_{n-1})/T
\]

\[
V_n - V_{n-1} = K_p(e_n - e_{n-1}) + K_i e_n T + K_d ((e_n - e_{n-1}) - (e_{n-1} - e_{n-2})]/T
\]

\[
V_n - V_{n-1} = K_p(e_n - e_{n-1}) + K_i e_n T + (e_n - 2e_{n-1} + e_{n-2})] \quad \ldots \text{(2.15)}
\]

Finally, the current value of the output is given by

\[
V_n = V_{n-1} + K_p(e_n - e_{n-1}) + K_i e_n T + K_d/T [(e_n - 2e_{n-1} + e_{n-2})] \quad \ldots \text{(2.16)}
\]

At any instant of time the current value of the PID output \( v_n \) is calculated based on the previous value of the PID output \( V_{n-1} \), current error \( e_n \), previous error \( e_{n-1} \), previous to the previous error \( e_{n-2} \), the cycle time \( T \) and weighing constants \( (K_p, K_i, K_d) \).
Working of Microcontroller Based PID Controller:

The system is interfaced to the microcontroller through the programmable peripheral interface (8255) and programmable interval timer (8253). 8255 has three 8-bit ports. The Port-A of 8255 is used for interfacing the data acquisition system, Port-B is used for interfacing of LCD display and 8253 timer in association with an opto-coupler (MOC3010) is used for controlling the phase-angle of the ac mains supply to the heater. The opto-coupler provides the isolation between the microcontroller card and the ac mains.

After sampling the temperature of the photoacoustic cell through A/D converter, the microcontroller compares this value with the desired temperature (set value). Any difference between these two values is applied to the PID algorithm and the solution of the algorithm is fed into counter-0 of programmable interval timer (8253) which is operated in the Mode-1. An external clock of 1MHz is connected to clock-0 of 8253. The output-0 of 8253 is connected to the opto-isolator MOC 3010 which controls the firing angle of the triac. The firing angle is decided by the count in the counter-0 of 8253 which is proportional to the solution of PID equation. The usual method of controlling an alternating voltage (ac mains) is to vary the firing angle of triac as shown in Fig.2.20.

At each zero crossing of the ac line voltage, inverter C of the zero cross detector pulses the gate input of 8253 and the count is loaded into the counter-0 of 8253. Then the counter starts decrementing at the rate of 1MHz until the count in the counter becomes zero. This clock frequency accommodates 10,000 steps during one half a cycle (10 msec.) of the 50Hz main supply. The 8253 counter decrements at every clock pulse until the count becomes zero. Presenting a small count in the counter-0 means that the counter will decrement only a few times before it becomes zero. The triac is fired early
in the cycle, this produces large conduction angle (and hence large ON time) and a large output power to the load. Conversely, a large count in the counter-0 will take more time before reaching zero causing a small conduction angle (small ON time). Hence, smaller power is applied to the load. This variation in duty cycle controls the firing angle of the triac and hence an amount of energy supplied to the heater. Thus the later maintains the temperature of the sample in the photoacoustic cell at the desired value. The PID temperature controller designed by the author found to regulate the temperature of the photoacoustic cell with in \(\pm 0.1^\circ\text{C}\).
REFERENCES

52. RCA High-Speed CMOS Logic ICs Data Book, USA (1986).


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