Chapter 2

Design and Development of an Intelligent Instrumentation System for the Measurement of Ultrasonic velocity in liquids
Section 2.1
Principle

Acoustic Interferometer\cite{11-12} is the most commonly used instrument for the measurement of ultrasonic velocity in liquids and gases. The interferometer normally consists of a reversible transducer on one side, which is connected to an oscillator and a plane, parallel metallic reflector on the other side. When the distance between the transducer and the reflector is an integral number of half wavelengths of the sound wave, a stationary wave pattern is set up in the medium. The reflector, controlled in position by some kind of a micrometer device, can be moved until a state of resonance is obtained. This type is called single-crystal variable path interferometer. Alternatively, the stationary waves can also be set-up by varying the frequency of signal given to the transducer keeping the distance between the reflector and transducer constant. This type is called fixed path interferometer. When stationary waves are formed, the impedance of the transducer is minimum in liquids. As the distance between transducer and reflector is varied, the current flowing through the crystal also varied between maximum and minimum. The current through the crystal is usually measured with the technique developed by Hubbard.\cite{4}

In the present study, a single crystal variable path interferometer working at 3 MHz is interfaced with a personal computer. It consists of an electronically driven X-cut quartz crystal transducer coupled to the liquid column whose length can be varied by moving the reflector parallel to the quartz transducer. The liquid column vibrates in resonance whenever the distance between the transducer and the reflector
corresponds to ‘\(n\lambda/2\)’ where ‘\(n\)’ is an integer and ‘\(\lambda\)’ is the wavelength. The vigorous vibration of the liquid column increases the motional impedance of the quartz transducer resulting in a sharp dip in the voltage across it. The voltage measured across the transducer as a function of reflector distance exhibits a series of maxima and minima separated by \(\lambda/2\). The wavelength of the ultrasonic beam was determined by counting the number of minima or the dips when the reflector is moved through a distance of 4 cm approximately towards the transducer 6-8 times and the mean value of \(\lambda\) is used to evaluate the velocity using the relation

\[ u = f \lambda \]  

... (2.1.1)

Where \(f\) is the frequency of the ultrasonic waves generated by the quartz transducer. The distance through which the reflector is moved is almost the same in all measurements so as to keep the diffraction effects constant.

An RF oscillator was used to excite the quartz transducer at 3 MHz. The frequency stability of the oscillator is \(\pm 1\) Hz. The frequency is measured using a digital frequency counter with an accuracy of \(1 \times 10^6\). The voltage variations across the quartz transducer are observed using a differential amplifier followed by an analog to digital converter which is interfaced with the personal computer.

In conventional interferometer technique, the reflector is moved manually and human skill is involved in determining the position of the reflector corresponding to the minima. In the present technique the distance between the transmitter and the reflector is varied with the help of a computer controlled stepper motor. The voltage variations due to the
changes in the radiation impedance of the transducer as a result of change in the radiator-to-reflector distance are sensed. These voltage changes in the signal are conditioned and digitised for further processing with the computer. Finally the system is designed to display the velocity of ultrasonic waves in the medium.
Section 2.2
Instrumentation Features

The functional block diagram of the system is given in Figure 2.2.1. The system essentially consists of the following functional elements.

i) Mechanical Assembly
ii) Ultrasonic Oscillator
iii) Balanced Differential Amplifier-Detector
iv) Signal Conditioning Amplifier
v) Data Acquisition System (A/D Converter)
vi) Personal Computer
vii) I/O Card
viii) Stepper Motor and its Driver Unit
ix) Regulated Power Supply
x) Temperature Measurement and Control

The design features of each of the functional element is discussed below:

i) Mechanical Assembly of The Ultrasonic Interferometer

The schematic diagram of the mechanical assembly of a single crystal variable path interferometer is given in Figure 2.2.2. The experimental cell of the interferometer ‘A’ is made up of a nickel plated brass tube of inner diameter 3.8 cm. The bottom portion of the tube is partially closed leaving an opening of 1.95 cm in diameter in which a
Fig. 2.2.1 Block diagram for computer based ultrasonic interferometer.
Fig. 2.2.2: Mechanical Assembly of the Ultrasonic Interferometer
gold-plated X-cut quartz crystal 'Q' of natural frequency 3 MHz and of approximately 2.3 cm diameter is held firmly with a teflon O-ring. The crystal is kept pressed by a teflon ring 'D' held in position by three screws and tightened with optimum pressure by three nuts 'N'. The inner surface of the crystal touching the bottom of the cell forms the grounded terminal. A phosphor bronze strip H fixed to the teflon ring presses against the outer face of the crystal and forms the second lead for electrical connections. The experimental cell is rigidly fixed to a nickel plated brass cup 'U' with a neoprene O-ring seal to prevent the outer surface of the crystal from contacting with water when the interferometer is immersed in a thermostatic water bath. The crystal is in direct contact with the medium under investigation. The bottom of the crystal is air-backed which is a basic requirement to obtain large variation in the impedance of the crystal resulting in sharp dips. The stainless steel reflector R is 2.5 cm in diameter. This is coupled to a micrometer whose pitch is 1 mm and has a geared mechanism having a gear ratio of 2.5 is connected to the stepper motor, via the reflector rod. The micrometer screw actuates the reflector rod which is spring loaded to take care of any back-lash. The steel ball 'B' located between the reflector rod and micrometer screw prevents non axiality, if any. It also prevents rotation of the reflector assembly with the help of pin 'P' (free to move only along the vertical slot contained within Head 'C').

The micrometer assembly along with the reflector is mounted on the cell 'A' by three screws with a neoprene O-ring seal to prevent leakage of the thermostatic water into the cell. The parallelism between the surfaces
of the crystal and reflector is checked by studying the nature of the
dips (minima). When aligned exactly parallel, all the satellite dips are
eliminated. The total assembly is then filled with the liquid under
investigation and immersed in a constant temperature water bath.

ii) **Ultrasonic Oscillator**:

For ultrasonic studies highly precise and highly stable RF
frequency signals are required. Hence, crystal controlled oscillator is
necessary for generating stable high frequency ultrasonic oscillations/
waves.

The circuit diagram of the oscillator is shown in Figure 2.2.3. A
high frequency and high power transistor BD 115 is used. An At-cut quartz
crystal is connected in the feedback path. The oscillator is operated at the
series resonance frequency of the crystal. The collector-emitter capacitance
‘C_{ce}’ and the base-emitter capacitance ‘C_{be}’ constitute the phase
shifting network and produce the required positive feedback for the
maintenance of oscillations.

If the tank circuit is tuned exactly to the fundamental frequency
of the crystal, the oscillator cannot efficiently transfers maximum
power to the transducer crystal in the Interferometer cell. Hence, the
collector tank circuit is very slightly de-tuned to allow power transfer.
This introduces harmonic distortion in the output which affects the
velocity values. In order to reject these harmonics in the output, the
FIG. 2.2.3 SCHEMATIC DIAGRAM OF THE ULTRASONIC OSCILLATOR

FIG. 2.2.3 SCHEMATIC DIAGRAM OF THE ULTRASONIC OSCILLATOR
bandwidth of the collector tank circuit is adjusted to be very narrow which allows only the fundamental frequency component. The frequency stability of the oscillator is very high of the order of ± few Hertz in $10^6$.

The output from the oscillator is coupled to the transducer crystal in the ultrasonic interferometer cell through a tuned circuit. The transducer crystal is an X-cut quartz crystal which offers a very high impedance at resonance. If the path length between the transducer and the reflector is an integral multiple of $\lambda/2$, a standing wave pattern is formed between them. If the path length is varied, the voltage impressed across the transducer varies between a minimum and maximum. These variations in the voltage developed across the transducer crystal are detected with the balanced-differential amplifier detector.

iii) **Balanced Differential Amplifier - Detector:**

The differential amplifier is designed as a collector-coupled balanced differential emitter-follower. This circuit diagram is also presented in Figure 2.2.4. Transistors $T_1$ and $T_2$ connected in darlington configuration constitute first branch and the transistors $T_3$ and $T_4$ also connected in darlington configuration constitute the second branch of the differential amplifier. The Transistors $T_1$ and $T_3$ are matched pair of BC 507 and the $T_2$ and $T_4$ are matched pair of BD 115. The combination of darlington emitter-follower configuration enhances the input impedance to about few mega ohms while the output impedance is reduced to few hundred ohms. This arrangement greatly reduces the
FIG. 2.2.4 BALANCED DIFFERENTIAL AMPLIFIER - DETECTOR
loading on the transducer crystal and also it provides a very high current gain of the order of $10^3$.

When the input terminals of both the branches are grounded or maintained at the same potential, the currents flowing through the two branches of the difference amplifier are identical and produce identical voltage drops across the emitter load resistors. Hence, the differential voltage across the two emitter loads will be zero.

The total current supplied to the two branches through the current source $R_7$ in series with the supply voltage $+V_{cc}$ is constant. Hence, any increase in the current flow through one branch results in an identical decrease in the current flow through the other branch. These current changes will produce equal and opposite variations in the voltage drops across the two emitter loads given by the following formulae respectively.

\[ + \Delta V_{E1} = + \Delta I_{E1} \cdot R_{E1} = + \Delta I_E \cdot R_E \quad \ldots (2.2.1) \]
\[ - \Delta V_{E2} = - \Delta I_{E2} \cdot R_{E2} = - \Delta I_E \cdot R_E \quad \ldots (2.2.2) \]

\[ \therefore \text{The differential voltage between the two emitters is given by} \]
\[ \Delta V_o = + \Delta V_E - (-\Delta V_E) = 2\Delta V_E \quad \ldots (2.2.3) \]

Hence, the differential output voltage between the two emitters is equal to twice the voltage drop across each emitter load. This is another advantage of employing collector-coupled differential
configuration, in which the voltage gain achieved will be double that of a single stage amplifier.

The difference amplifier serves the dual purposes of a detector and an amplifier. The voltages developed across the transducer are applied to the branch consisting of transistors T1 and T2. No external forward bias is applied to the base of T1 of this branch. However, these transistors are forward biased and conduct during the positive half cycles of the input signal. Hence, a voltage drop is produced across the load resistance in the emitter.

The negative half cycles of the input signal are bypassed to ground through a reverse biased point contact diode D1. The point contact diode OA 85 has no barrier potential and hence eliminates the entire negative half cycle of the input signal. This diode has a very large peak-inverse voltage of about 100 V which enables it to withstand large amplitude signals.

The second branch of the differential amplifier consisting of T3, T4 is provided with a forward bias through R8, R9 and R10. The forward bias is adjusted to produce null differential output voltage at any input signal level (either a maximum or a minimum of the standing wave pattern). The maxima of the standing wave pattern are very broad and the minima are very sharp. Hence, it is always preferred to detect the minima.
As the position of the reflector is varied with respect to the transducer, different points of the standing wave pattern are made to be incident on the transducer, which change its radiation impedance. Hence, varying voltages are developed across it. These signals when coupled to the differential amplifier produce variable differential voltage outputs. The differential output voltage is integrated using a low-pass filter ($R_0-C_0$) having a time constant of $0.4-0.5 \times 10^3$ s which is very large compared to the time period of the input (ultrasonic) signal of $0.33\mu$s. These differential output signals are further amplified by a signal conditioner.

iv) **Signal Conditioning Unit**:

The output voltage from the differential amplifier is very small of the order of a few milli-volts. It is not sufficient to be applied to the analog to digital converter. Hence, an Instrumentation amplifier is designed with the help of LM 308 IC operational amplifier. The schematic circuit diagram of the signal conditioning amplifier is shown in Figure 2.2.5 This is a three stage amplifier.

The input stage is a differential stage with both input terminals being non-inverting thereby offering very high input impedance of the order of $10^8-10^{10}$ ohms. The gain ‘$a$’ of this stage is adjusted to be low ($\leq10$) and is given by the relation (2.2.4).

\[ V_o = (1 + 2/a) (E_1-E_2) \quad \cdots (2.2.4) \]
Where $V_o$ is the output voltage, $E_1$ and $E_2$ are the input voltages and $a = (R_g/R)$.

The second stage is a simple differential amplifier which has a gain of about 10. The third stage is an inverting amplifier with a gain of about 10. The overall gain of the signal conditioner is about $10^3$. All the operational amplifiers are provided with external frequency compensation by connecting 56 pf capacitors between the terminals 1 and 8 of each IC. The output of the signal conditioner is sufficiently large in amplitude (about few volts) which can be applied to the analog to digital converter. The fourth stage is a voltage follower employed as a buffer amplifier which provides direct analog output.

The most important feature of the signal conditioner is its ability to convert the balanced differential output signal into a single-ended output signal for further processing.

v) **Data Acquisition System**:

The voltage variation due to the change in the radiation impedance of the transducer has to be further converted into a digital form so that the microprocessor can understand and process. That Data Acquisition System (DAS) does this task. The DAS is basically an analog to digital converter with a multiplexer on its inputs. The analog to digital converter is the core of any data-acquisition system designed to transform data in the form of
continuous analog variable signal into a discrete binary coded signal suitable for digital processing. The analog to digital converter used in the present study is ICL 7109. It is a monolithic CMOS device with a 12 bit A/D Converter designed for easy interface with microprocessors and UARTs. The 12-bit binary plus polarity and over range outputs can be directly interfaced to a microprocessor bus. In this mode the ICL 7109 is controlled by the microprocessor through the chip select and two byte enable inputs. For remote data logging applications the ICL 7109 outputs are easily converted to a UART handshake mode, working with industry standard UARTs to provide serial data transmission.

This device offers high accuracy by lowering roll over error less than 1 count and zero reading drift to less than 1 μV/°C. In many data acquisition systems the ICL 7109 is an attractive, low cost, one-per-channel alternative to analog multiplexing due to its low power consumption and input bias current. Figure 2.2.6 shows the required external connections. The pins and support components of this analog to digital converter may be arranged into seven groups namely, power, input, reference, oscillator, integrator, data and control.

The power group consists of V’, V, common and ground. The ICL 7109 has been designed to use a + 5V positive supply voltage. However, in order to accept negative as well as positive inputs, a negative supply voltage is also required. Performance is tested and specified by the manufacturer with balanced ± 5V supplies. Pin 1, is digital ground. Common, pin 33 is
FIG. 2.2.6 PIN CONFIGURATION AND TEST CIRCUIT
analog ground. The equation for data conversion is given by the following relation.

\[
\text{Data out} = 4096 \times \frac{V_{\text{in}}}{2 \times V_{\text{ref}}} \quad \quad \ldots (2.2.5)
\]

An input of +1 V will generate the same 12-bit data output as an input of -1 V. However, the POL pin will be at a logic high for positive input signals and at a logic low for negative input signals.

The input pins IN, HI and IN LO provide a true differential input with negligible input bias currents and very high input impedance. The differential input voltages anywhere within the common-mode range of the input amplifier can be accepted as it specifically has a CMRR of 86 dB typical in this range. For achieving optimum performance the input voltage of IN-LO and IN-HI should not come within 1V of either the positive or negative supply. That is, for ±5 V dc supplies, you must limit each input to ± 4 V or less. In Figure 2.2.7 the 100 k resistor and 0.001MF capacitor at the input pins are used to prevent any noise picked up on the input leads from entering the IC. All these components should be placed as close to the IC as practically possible.

The ICL 7109 has 14 three-state outputs namely, 12 data bits, 1 polarity bit and 1 over range bit. These bits are enabled either by the CE/LOAD, LBEN, and HBEN control signals or by entering the handshake mode. The control group consists of the remaining eight pins. They initiate
FIG. 2.2.7 DATA ACQUISITION SYSTEM
a conversion, the end of the conversion, and control the way in which the two bytes of data are transferred to the processor.

When the RUN/HOLD input is tied to \( V^\text{high} \), the ICL 7109 continuously performs A/D conversions with a fixed length of 8192 clock cycles per conversion. When RUN/HOLD is made low, the ICL 7109 will complete the conversion in progress, then wait in the auto zero phase. After the minimum auto zero time has been completed, a high going pulse on RUN/HOLD of at least 200 ns is required to start a new conversion; but any pulse during a conversion or up to 2048 clock cycles after STATUS goes low will be ignored. If the ICL 7109 is holding at the end of the auto zero phase, a new conversion will start and STATUS will go high within seven clock cycles after RUN/HOLD goes high.

The ICL 7109 can be controlled through I/O peripheral ports as shown in Figure 2.2.7. These schematics are some practical circuits utilising the parallel three-state output capabilities of ICL 7109. Although a read performed while the data latches are undergoing updates will lead to scrambled data, this interface can be used in a read-anytime mode.

In Figure 2.2.7 the 100 kΩ resistor and 0.01 µF capacitor at the input pins are used to prevent any noise picked up on the input leads from entering the IC. So these components are placed as close as possible to the IC. As recommended by the manufacturer’s data sheet, a pre-set of 25 kΩ is connected between pin 29 (REF out) and +5 V, whose tap is given to pin
36 (REF In). This pre-set is adjusted to get +4V full scale, which means that the inputs between -4V to +4V can be converted.

vi) **Personal Computer**

The decade of 1980's has witnessed a phenomenal growth in information processing power and automation. The personal computer, hereafter called the PC, has proven to be very popular and versatile system that can be used in many applications at home, at work, in the class room, or in the laboratory in the industry. It is relatively inexpensive and available in a compact form.

The pentium processor 166 M Hz based system, supplied by Wipro Computers Limited consists of the system unit, the 105 key - full function key board, Super VGA color monitor and a graphics printer. The heart of the system unit is the processor board which fits horizontally in the base of the system unit. It contains, 8MB RAM, 1 GB Hard Disk, 1.2MB and 1.44MB Floppy Disk Drives. The system has 2 serial and 1 parallel ports. The power supply provides +5 Volts and +12 Volts. The motherboard consists of 3 ISA slots and 3 PCI slots to interface I/O cards.

The PC supports the MS-DOS operating system versions 3.0/4.1/6.22 etc. and also Windows. The operating system is a kind of system software closely associated with the hardware. It serves as a link between the user and the computer.
vii) **I/O Card:**

The I/O card developed by Electrosystems Associates Pvt. Ltd., which is compatible for PC/XT/AT is used in the present study. It has two programmable peripheral interface devices (INTEL 8255A) and one programmable interval timer (INTEL 8253). The card can be plugged into any one of the free extension slots of the system.

The programmable peripheral interface used with I/O card is an INTEL 8255A. It is a general purpose Programmable Peripheral Interface device. It is compatible with any microprocessor. It can be programmed to transfer data under various conditions, from simple I/O to interrupt I/O. It is a silicon gate MOS chip available in a 40 pin, dual in-line package. The block diagram of the DIOT card is shown in Figure 2.2.8. The 8255 has 24 I/O lines which can be grouped primarily into two 8-bit parallel ports- A&B, with remaining 8-bits as port-C. The eight bits of Port-C can be used as individual bits or can be grouped into two 4-bit ports as $C_{upper}$ and $C_{lower}$. The functions of these ports are defined by writing a control word in the control register.

The 8255A has three major modes of operation. In mode 0, each group is programmable as either input or output. Basically, mode 0 gives three 8-bit I/O ports A, B and C. Mode 1 has two 8-bit ports that can be defined as either a handshake input or output port. Each of the two ports has associated with a 4 bit control port. In mode 2, an 8-bit bi-directional data bus is provided with an associated 5-bit control port. The additional
Fig. 2.2.8 (a) DIOT Card (Interface logic)
Fig. 2.2.8 (b) DIOT Card (8255)
Fig. 2.2.8 (c) DIOT Card (8253)
control line is borrowed from one of the other groups. It has bit set/reset capability that gives the system a high degree of flexibility. The 8255A can be interfaced with any microprocessor for parallel transfer of data under program control.

In the present study, the device is used in simple I/O mode to interface the A/D converter (Data Acquisition System) and the stepper motor (Micrometer Drive) with an appropriate software. The card is mapped to different addresses by setting the DIP switches SW1 - SW4 suitably. Table 2.2.1 gives the I/O address mapping for different switch positions. In the present study, the following ports of 8255A of I/O card are selected by means of setting switch positions.

Table 2.2.1

<table>
<thead>
<tr>
<th>SW4</th>
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<td>OFF</td>
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<td>ON</td>
<td>01C0 H</td>
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<tr>
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<td>OFF</td>
<td>01D0 H</td>
</tr>
<tr>
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</tr>
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<td>ON</td>
<td>OFF</td>
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</tr>
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<td>OFF</td>
<td>02D0 H</td>
</tr>
</tbody>
</table>
viii) **Stepper Motor and its Driver Unit**

The function of the stepper motor in the present study is to move the reflector normal to the transmitter by rotating the micrometer screw. The stepper motor is interfaced with the PC, through I/O card and Darlington drive circuitry.

All rotating motors have essentially a stator and a rotor and some windings. Whenever a conventional motor is switched ON, the rotor rotates continuously until it is switched OFF again. The stepping motors action differs from that of the conventional motors. Even when the stepping motor is switched ON, its shaft remains stationary until a coded step pulses are applied to the stator coils ABCD of the stepper motor. When the drive circuit receives a step pulse, the shaft rotates by a precise angle or step and then stops until the next pulse code is received. Consequently the angular displacement of the shaft is equal to the step angle and the number of pulses supplied to the drive circuit provided that the maximum power load is not exceeded. Saying that the angular displacement is equal to the number of pulses, since the step angle for any particular motor is fixed further modifies this relation.

The majority of the stepper motors have step angles in the range of $0.45^\circ$ to $90^\circ$ with the most configuration. The stepper motor that is used to move the micrometer screw of the Ultrasonic Interferometer being $0.9^\circ$ for step (400 Steps/Rev). The positional error at each step is typically $\pm 5\%$, but this factor obviously depends upon the motor.
For accurate linear displacement rather than rotational positioning, the shaft of the stepper motor is coupled to micrometer. The relationship between displacement and number of step pulses is given by

\[
\text{Linear displacement} = \frac{\text{No. of Steps}}{\text{Steps per revolution}} \times \frac{\text{Pitch of the micrometer}}{\text{Pitch of the screw}}
\]

The stepper motors are classified into three types. These are (a) permanent magnet stepper motors, b) variable reluctance stepper motors and c) hybrid stepper motors. In the present study, to move the reflector of ultrasonic interferometer, a hybrid stepper motor is used. The hybrid stepper motor has combinational features and characteristics of both permanent magnet and variable reluctance stepper motors. It is generally called as permanent magnet stepper motor because its rotor is an axially magnetised cylindrical permanent magnet.

The stepper motor used in the present study (STM 601) is manufactured by Srijan Control Drives, Pune, and it has the following specifications:

- **The typical rating current**: 400 mA
- **The step size**: 1.8°
  (With the help of software step size can be reduced to 0.9°)
- **Torque**: 2 kg-cm.
To rotate the micrometer screw through a precise angle the shaft of the stepper motor is coupled to the head of the micrometer. The pitch of the micrometer screw is 0.5 mm and the number of steps for one revolution is 400. So the linear displacement of the micrometer screw for 1 step is $0.5/400$ mm = 1.25 $\mu$m. So the accuracy in measuring the distance between two minima is 1.25 $\mu$m. If 50 minima are scanned and the distance between these 50 minima are used to compute the wavelength, then the accuracy is decreased to $1.25/50$ $\mu$m = 0.025 $\mu$m. In this way if the number of waves scanned are increased, the error will be decreased. In the present study about 100 minima are used for the measurement of the wavelength.

Stepper Motor Driver Circuit and interfacing with a P.C.

To interface the high power stepper motor with the low power Personal Computer, a driver circuit is needed which is presented Figure 2.2.9. The computer can be programmed to send the desired sequence of control pulses to the four windings A, B, C, D of the Stepper motor. The logic levels and the control signal sequences for 200 and 400 steps per revolution are presented in Table 2.2.2 which can be applied through a software. But the stepper motor is a high power device, so, it cannot be directly connected to the low power output of the computer. 

The electrical incompatibility in this interfacing is overcome by using four power amplifiers (TIP 122's for driving A, B, C, D windings). Typical value of the current amplification factor for each of this Darlington pair TIP 122 is about 1000. Since, the rated current of each of the stepper motor windings is 400 mA, a base current of 0.4 mA (400 mA/1000) is required to drive the stepper motor.
FIG. 2.2.9 STEPPER MOTOR DRIVER CIRCUIT
This 0.4 mA drive current can be easily supplied by the 8255A of I/O card. Diodes IN4007 are connected across the four coils in reverse biased condition (also shown in Fig. 2.6) to protect the Darlington pair from the back emf when the transistors are switched to OFF state from ON state.

To interface the stepper motor with the computer an I/O card and a drive circuit is needed. In the present study four lower bits PC0-PC3 of Port C are used for applying the desired sequence of pulses to bases of the Darlington pairs in series with resistors of 1 k Ohm. Computer can send desired sequence of pulses (which are presented in Table 2.2.2 and Table 2.2.3) through I/O card with the help of software.

Table 2.2.2

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<th>A</th>
<th>B</th>
<th>C</th>
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Table 2.2.3
Half Step Mode

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<th>D</th>
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<tbody>
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ix) **Regulated Power Supplies**:

The regulated power supplies required for different circuits of the Ultrasonic Interferometer namely (a) 30 V/1 A required for the ultrasonic oscillator, and balanced differential amplifier detector; (b) 24 V/1 A required for Stepper motor driver; (c) 15-0-15 V/0.5 A required for the signal conditioner and (d) 5 V-0-5 V/0.5 A required for the ADC are designed and fabricated.

The circuit diagrams of all these power supplies are presented in Figures 2.2.10(a,b,c,d).
Fig. 2.2.10  SCHEMATIC DIAGRAMS OF REGULATED POWER SUPPLIES
Temperature Measurement and Control:

In the present work a discontinuous type automatic temperature control system using analog ICs, power transistors, On-Off relay and a thermistor as a temperature sensing transducer is developed. The important functional unit in the control circuit is a wheatstone bridge network with a thermistor in one arm and a variable resistor in another arm. Variable resistor is used to balance the bridge for a given set temperature. Once the bridge is balanced, for a set temperature the change of temperature alters the resistance of the thermistor and the bridge balance gets disturbed. This imbalance is detected by the comparator which drives an ON/OFF relay through a voltage follower and a driver. If the temperature of the bath is less than the set temperature, the heater is switched ON through the relay otherwise it is switched OFF. Thus the circuit maintains the temperature of the bath at a set point. The variable resistor can also be used to measure the temperature, when it is provided with a calibrated dial. The temperature calibration is done at three points viz., ice point, transition temperature of sodium sulphate, and steam point of triple distilled water at room temperature and pressure.

The circuit diagram of the temperature control is shown in Fig.2.2.11. The bridge rectifier in combination with 7805 gives a 5V DC regulated output. It is used to actuate the Wheatstone bridge network employing a BGX 2.2 K Bead Type Thermistor in one arm and a 10 turn 4.7 K potentiometer having a calibrated dial in another arm. One of the
FIG. 2.11 CIRCUIT DIAGRAM FOR TEMPERATURE CONTROL
op. amps in Quad (1/4 LM 324) acts as precision voltage comparator and detects the bridge balance.

The output can be either zero or five volts based on whether the bridge is balanced or not. Output of comparator is applied to second op. amp. (another 1/4 of LM 324) which is configured as voltage follower. Its output voltage is used to actuate a relay 6V, 50 ohms through a pre-amplifier (BC 147) and a darlington pair of power transistors (SL 100, 2N3055). The relay in turn will switch On/Off a bulb or a heater. Consequent temperature changes in the bath (which is kept under good stirring) are being sensed by the thermistor and the output of the bridge suitably controls the On/Off time of the heaters. Hence, the temperature is controlled. The temperature controller bath is made up of a double glass box for perfect insulation. Remi motor having stirrer with variable speed control is used to keep the thermostat liquid under constant stirring. An accuracy of ±0.01°C in temperature control was easily obtained with the above arrangement.
Section 2.3

Software Development

The role of the software in the present study is to control the following activities.

1. To move the Ultrasonic Interferometer reflector precisely by means of a stepper motor by sending the appropriate signals in sequence.
2. To make the data acquisition system to convert the analog information into digital information.
3. To fix the position of the reflector corresponding to the minimum.
4. To scan the number of waves prescribed.
5. To make different functional units of the system to work in a systematic and sequential manner.
6. To compute and display the ultrasonic velocity

The necessary software package is developed in the present study to implement all the above tasks for the effective functioning of the system. The high level language ‘BASIC’ is chosen for this purpose. The flow chart of the algorithm is presented in Figure 2.3.1. The salient features that are taken into consideration while developing the software are presented in the following sub-sections.
Fig. 2.3.1 Flow Chart for the Measurement of Ultrasonic Velocity
Fig. 2.3.1(a) Flow Chart for Minima Detection
a) **Ideal case of a non-absorbing liquid medium:**

It is essential to know the shape of the actual signal from the interferometer in order to develop the software. The variation of voltage from the differential amplifier of the ultrasonic interferometer as a function of the relative position of the reflector with respect to the transmitter in a non-absorbing liquid for an ideal is shown in the Figure 2.3.2. For absorbing liquids the maxima will be decreasing gradually as the reflector moves away from the transmitter.

As shown in the Figure 2.3.2, the half wavelength is the distance between two successive maxima or minima. But here it is convenient to detect minima than maxima because a sharp change is found at minima. In this minimum can be defined as the junction point of decrease and increase of voltage of differential amplifier for a particular direction of motion of the reflector.

b) **Real case of a non-absorbing liquid medium:**

However, in reality the voltage variation as a function of the relative position of the reflector with respect to the transmitter differs from that shown in the Figure 2.3.2, because the reflector and the transmitter are not exactly parallel to each other. And also the oscillator is slightly detuned for avoiding instability. So some satellite peaks are observed in the signal. In the Figure 2.3.2., A,B and C are the minima. Here ‘A’ and ‘C’ are satellite peaks, which have no significance in finding the wavelength and ‘B’ is the
FIG 2.3.2 STANDING WAVE PATTERNS IN IDEAL AND REAL LIQUID MEDIA

Distance Between Reflector and Transmitter
actual minimum. The distance between two such successive points ‘B’ is the half wavelength. This behaviour is borne in mind while developing the software for identifying the real minimum. The flowchart indicates the position of the reflector corresponding to the minimum of minima is considered for wavelength determination. Following the procedure mentioned below the required software is developed.

In most of the cases it is observed that the minima (points A, B and C) fall in a span of 125 steps of the stepper motor which is driving the reflector starting from the first minimum. This span is named as ‘Active Band’. The actual minimum can be found within this band. The flow chart describes the method of finding the minimum of minima (point B in figure 2.3.2) in the ‘Active Band’.

c) Computation of Wavelength and Velocity of Ultrasonic Wave:

The next task is to compute the wavelength and velocity of the ultrasonic wave in the medium. To compute the wavelength, the position of the reflector corresponding to the first minimum and the nth minimum is needed. Here the computer stores these positions of the reflector in terms of the number of stepper motor steps. The step size is converted into the actual linear movement of the reflector. The stepper motor used in the present study is programmed for 200 steps for each revolution. The pitch of the micrometer screw of the ultrasonic interferometer is 1 mm. The gear connected stepper motor to screw has 2.5 reduction. So each step has a movement of 1/500 mm which is equal to 2.0 μm. Multiplication of this
constant factor with the number of steps gives the actual distance advanced by the reflector. The distance advanced by the reflector between two successive minima becomes the half wavelength. Normally a large number of minima are considered and the average value of these is taken to reduce the error.

The mean of ‘\( \lambda \)’ is used to evaluate the velocity with the help of the following relation.

\[
\text{Velocity (u)} = f \times \lambda
\]

Where ‘\( f \)’ is the frequency of the ultrasonic wave generated by the transducer. For accurate measurement of velocity, the diffraction errors are to be taken into account.

d) **Correction for the Diffraction Error**

Diffraction of the ultrasonic beam very often leads to appreciable errors in the velocity and absorption measurements\(^{[7,16]}\). These errors are predominant near the radiator and decreases for a differential distance farther from it. In addition, the velocities measured near the source are higher than the plane wave velocities. These errors are systematic in nature and amenable to theoretical and experimental studies. Attempts were made to evaluate these errors theoretically for interferometric measurements\(^{[7,16-25]}\). Ilgunas and co-workers\(^{[26]}\) and McSkimin\(^{[27,28]}\) evaluated diffraction errors experimentally. Bass and Williams as cited
by McSkimin have shown theoretically that the excess velocity due to diffraction over the plane wave velocity \( u \) is equal to

\[
\frac{\Delta u}{u} = \frac{\lambda^{3/2}}{2 \pi d D^{1/2}} \quad \ldots \quad 2.3.1
\]

where \( \lambda \) is the wavelength of the ultrasonic wave, \( d \) is the beam diameter and \( D \) is the distance from the source at which measurements are made. Measurements carried out by McSkimin on solids confirm the theoretical results of Bass and Williams. Subrahmanyam et al\textsuperscript{[29]} have studied the diffraction errors in liquids with a view to test the applicability of theoretical expression given by Bass and Williams and found that the diffraction errors are 3.2 times the value envisaged in the theory. Hence, they have modified the relation as shown below.

\[
\frac{\Delta u}{u} = \frac{3.2 \lambda^{3/2}}{2 \pi d D^{1/2}} \quad \ldots \quad 2.3.2
\]

In the present study, the method of evaluation of diffraction errors developed by Subrahmanyam et al\textsuperscript{[29]} as explained above is adopted for correcting the diffraction errors in the measurement of ultrasonic velocity.

The detailed program written in BASIC language follows.
**INTELLIGENT INSTRUMENTATION SYSTEM FOR**
**THE MEASUREMENT OF ULTRASONIC VELOCITY**
**IN LIQUIDS**

*********************************************************

**** INITIALISATION OF VARIABLES *****

A = &H120 'Port - A
B = &H121 'Port - B
C = &H122 'Port - C
CR = &H123 'Control Register
CW = &H92 'Control Word -Port A,B are
     In & C as Out

STEPS= 0
XI = 100
X2 = 101
Y1 = 200
DIM SL(400), DAT1(400)
K = 0
INCFL= 0 'INCREMENT FLAG
TD = 400 'NO OF SAMPLE FOR NORMALISATION
DIM SMN(100), SMX(100), MN(100), MX(100)
DIM V(15000), M(4), STE(200)
M(1) = &HC: M(2) = &H6: M(3) = &H3: M(4) = &H9
ST = 1
S = 0 'NUMBER OF STEPS
VEL = 0

**MAIN PROGRAM**

MAIN: CLS
    CLOSE
    GOSUB INIT 'INITIALISATION
AGAIN: GOSUB INIT
    IF OPT = 1 THEN
        GOSUB MEASURE
    ELSEIF OPT = 2 THEN
        GOSUB CALIBRATE
    ELSEIF OPT = 3 THEN
        GOTO ENDP
    GOTO ENDP
    ELSE GOTO AGAIN
END IF

GOTO AGAIN
ENDP:
SCREEN 0
END
MENU: REM *** PROGRAM FOR MAIN MENU ***
SCREEN 0: CLS
CLOSE
LOCATE 2, 15: PRINT "INTELLIGENT INSTRUMENTATION SYSTEM FOR THE MEASUREMENT OF ULTRASONIC VELOCITY"
LOCATE 7, 25: PRINT "1. MEASUREMENT OF VELOCITY"
LOCATE 9, 25: PRINT "2. CALIBRATION OF INTERFEROMETER"
LOCATE 11, 25: PRINT "3. QUIT"
LOCATE 16, 30: INPUT "SELECT = OPT RETURN"

MEASURE: REM *** PROGRAM FOR MEASUREMENT OF VELOCITY ***
CLS
X1 = 100: X2 = 101 ' Initialise line
INPUT "ENTER NAME OF THE LIQUID = "; LIQ$
INPUT "TEMPERATURE = "; TEMP
OPEN "VEL.CAL" FOR INPUT AS #1
INPUT #1, RTEMP, GVEL
CLOSE #1
IF RTEMP <> TEMP THEN
  PRINT "CALIBRATE THE INTERFEROMETER AT THIS TEMPERATURE"
  INPUT "Press ENTER to continue...", xx
  RETURN
ELSE
  INPUT "NAME OF THE FILE = "; F$
RIN: INPUT "NUMBER OF MINIMAS TO BE SCAN = "; NOMIN
IF NOMIN < 20 THEN GOTO RIN
GOSUB NORMAL 'Normalisation
GOSUB MEMIN 'Detection of Max and Min
VEL = VEL * GVEL 'Multiply with gain
LOCATE 5, 50: PRINT "VELOCITY = "; VEL
GOSUB STORE
LOCATE 6, 50: INPUT "Press ENTER to continue..", xx
GOSUB STEPUP
END IF
RETURN

CALIBRATE: REM *** PROGRAM FOR CALIBRATION ***
CLS
X1 = 100: X2 = 101 ' Initialise line
PRINT "FILL THE INTERFEROMETER WITH STANDARD LIQUID"
INPUT "ENTER VELOCITY OF THE LIQUID = "; SVEL
INPUT "ENTER THE TEMPERATURE = "; TEMP
RIN1: INPUT "NUMBER OF MINIMAS TO BE SCANNED = "; NOMIN
IF NOMIN < 20 THEN GOTO RIN1
GOSUB NORMAL 'Normalisation
GOSUB MEMIN 'Detection of Max and Min
GVEL = SVEL / VEL
OPEN "VEL.CAL" FOR OUTPUT AS #1
PRINT #1, USING "###,##.#"; TEMP; GVEL
CLOSE #1
LOCATE 5, 50: PRINT "VELOCITY = "; VEL
LOCATE 6, 50: INPUT "Press ENTER to continue..",xx
GOSUB STEPUP
RETURN

INIT: REM *** PROGRAM FOR INITIALIZATION OF PORTS ***
OUT CR, CW
RETURN

REM ** PROGRAM FOR DETECTION OF MIN AND MAX AND VELOCITY **

MEMIN: LL = TD
GOSUB STEPUP1
STEPS = 0
GOSUB SCRN
VHEIGHT = MAX - MIN
BAND = OFSET1 - OFSET2
FOR NM = 1 TO NOMIN + 1
  GOSUB DMAX
  SMX(NM) = DS
  MX(NM) = MAX
  REM LOCATE 20, 50: PRINT "MAX = "; MAX, S
  GOSUB DMIN
  SMN(NM) = DS
  MN(NM) = MIN
  VHEIGHT = MAX - MIN
  REM LOCATE 21, 50: PRINT "MIN = "; MIN, S
NEXT NM
FOR I = 1 TO NOMIN
  REM PRINT SMX(I), MX(I), SMN(I), MN(I)
NEXT I
VEL = 0
FOR I = 1 TO 10
  DVEL = SMN(NOMIN - 10 + I) - SMN(I)
  VEL = VEL + DVEL
NEXT I
VEL = ((VEL / 10) / (NOMIN - 10)) * 4
for 3 mhz
RETURN
DMAX:
MAX = VIN
GOSUB ADC
VIN = DV3
GOSUB FMOT
GOSUB DLIN
IF VIN >= MAX THEN
   MAX = VIN
   DS = STEPS
END IF
IF VIN <= (MIN + VHIGHT / 3) THEN
   RETURN
ELSE
   GOTO DMN1
END IF

DMN1:
GOSUB ADC
VIN = DV3
GOSUB FMOT
GOSUB DLIN
IF VIN >= MAX THEN
   MAX = VIN
   DS = STEPS
END IF
IF VIN <= (MIN + VHIGHT / 3) THEN
   RETURN
ELSE
   GOTO DMN1
END IF

DMIN:
MIN = VIN
GOSUB ADC
VIN = DV3
GOSUB FMOT
GOSUB DLIN
IF VIN <= MIN THEN
   MIN = VIN
   DS = STEPS
END IF
IF VIN >= (MAX - VHIGHT / 3) THEN
   RETURN
ELSE
   GOTO DMX1
END IF

DMX1:
MIN = VIN
GOSUB ADC
VIN = DV3
GOSUB FMOT
GOSUB DLIN
IF VIN <= MIN THEN
   MIN = VIN
   DS = STEPS
END IF
IF VIN >= (MAX - VHIGHT / 3) THEN
   RETURN
ELSE
   GOTO DMX1
END IF

INITM: RETURN
NORMAL: REM *** PROGRAM FOR NORMALISATION ****
CLS
LOCATE 12, 20: PRINT "*** NORMALISING... PLEASE WAIT ***"
NOR1:
GOSUB ADC
GOSUB FMOT
GOSUB DINCR
FOR I = 1 TO TD
   GOSUB ADC
   GOSUB FMOT
   SL(I) = I
   DAT1(I) = DV3
LOCATE 1, 1
PRINT SL(I), DAT1(I)
NEXT I
GOSUB MINIMA
CLS
LOCATE 5, 10
PRINT "MINIMUM VALUE = "; MIN
REM PRINT "OFSET1 = "; OFSET1
GOSUB MAXIMA
LOCATE 6, 10
PRINT "MAXIMUM VALUE = "; MAX
REM PRINT "OFSET2 = "; OFSET2
LOCATE 7, 10
PRINT "VHIGHT = "; MAX - MIN
STEPS = 0
BEEP
LOCATE 9, 10
PRINT "Press ENTER to continuee...", xx
RETURN

DINCR: REM *** PROGRAM FOR FINDING INCRIMENTING THE WAVE ***
GOSUB ADC
D1 = DV3
GOSUB FMOT

DIN1:
GOSUB ADC
D2 = DV3
GOSUB FMOT
LOCATE 1, 1: PRINT STEPS, D2, K
IF D2 >= D1 THEN
  K = K + 1
  IF K = 20 THEN
    SN = STEPS
    INCFL = 1
    RETURN
END IF
ELSE
  K = 0
END IF
D1 = D2
GOTO DIN1

MINIMA: MIN = DAT1(1)
FOR I = 1 TO TD
  IF DAT1(I) <= MIN THEN
    MIN = DAT1(I)
    OFSET1 = SL(I)
  END IF
NEXT I
RETURN
MAXIMA:

MAX = DAT1(1)
FOR I = 1 TO TD
IF DAT1(I) >= MAX THEN
MAX = DAT1(I)
OFFSET2 = SL(I)
END IF
NEXT I
RETURN

ADC:

REM *** PROGRAM FOR ADC ***
REM STATUS = INP(B) AND &H40 'End of Conversion'
REM IF STATUS = &H40 THEN GOTO ADC
AD1:

STATUS = INP(B) AND &H40
IF STATUS = &H40 THEN GOTO AD1
DV1 = INP(A)
DV2 = INP(B)
OVR = DV2 AND &H10 ' OVER RANGE
POL = DV2 AND &H20
DV3 = ((&HF AND DV2) * 256) + DV1
IF POL <> &H20 THEN DV3 = -DV3
DV3 = 4096 - DV3
RETURN

STORE:

REM *** PROGRAM FOR FILE WRITE ***
OPEN F$ FOR OUTPUT AS #1
PRINT #1, "NAME OF THE LIQUID ="; LIQ$
PRINT #1, "VELOCITY= "; VEL
FOR j = 1 TO STEPS
WRITE #1, j, V(j)
NEXT j
CLOSE #1
RETURN

SCRN:

REM *** PROGRAM MEASUREMENT SCREEN ***
CLS : BEEP: SCREEN 12: PSET (100, 30)
DRAW "D280 R500"
FOR j = 100 TO 600 STEP 50
LINE (j, 309)-(j, 305)
NEXT j
FOR j = 30 TO 300 STEP 56
LINE (100, j)-(105, j)
NEXT j
REM * X SCALE *
RR1 = STEPS
FOR jj = 12 TO 72 STEP 12
LOCATE 21, jj: PRINT RR1
RR1 = RR1 + 100
NEXT jj
REM * Y SCALE *
LOCATE 4, 10: PRINT "4.0"
LOCATE 7, 10: PRINT "3.2"
LOCATE 10, 10: PRINT "2.4"
LOCATE 13, 10: PRINT "1.6"
LOCATE 16, 10: PRINT "0.8"
LOCATE 19, 10: PRINT "0.0"
LOCATE 1, 28: PRINT "MEASUREMENT OF VELOCITY"
LOCATE 4, 65: PRINT "'S' TO STOP"
REM * X LABEL *
LOCATE 7, 7: PRINT "V"
LOCATE 8, 7: PRINT "0"
LOCATE 9, 7: PRINT "L"
LOCATE 10, 7: PRINT "T"
LOCATE 11, 7: PRINT "A"
LOCATE 12, 7: PRINT "G"
LOCATE 13, 7: PRINT " 
LOCATE 14, 7: PRINT " 
LOCATE 15, 7: PRINT "V"
RETURN

FMOT: REM *** MOTOR ROTATE IN FORWARD ***
OUT C, M(ST)
STEPS = STEPS + 1
FOR Z = 1 TO 100: NEXT Z ' delay of motor
ST = ST + 1: IF ST = 5 THEN ST = 1
RETURN

RMOT: REM *** MOTOR ROTATE IN REVERSE ***
OUT C, M(ST)
FOR Z = 1 TO 75: NEXT Z ' delay of motor
ST = ST - 1: IF ST = 0 THEN ST = 4
RETURN

DLIN: REM *** PROGRAM FOR DRAWING OF LINE ***
GOSUB PRES 'PRINT RESULTS
Y2 = (310 - (VIN) / (100 / 7))
LINE (X1, Y1)-(X2, Y2)
X1 = X2: Y1 = Y2
X2 = X2 + 1
IF X2 = 601 THEN
X2 = 101
X1 = 100
GOSUB SCRN
END IF
FOR DD = 1 TO 100: NEXT DD
RETURN
PRES:

LOCATE 25, 1: PRINT "V ="; PRINT USING "+#.###"; VIN / 1000
LOCATE 25, 15: PRINT "STEPS ="; PRINT USING "+#####"; STEPS
LOCATE 25, 35: PRINT "NO_WS ="; PRINT USING "+#####"; (NM - 1)
LOCATE 25, 50: PRINT "MAX AT="; PRINT USING "+#####"; SMX(NM - 1)
LOCATE 25, 65: PRINT "MIN AT="; PRINT USING "+#####"; SMN(NM - 1)

V(STEPS) = VIN
SK$ = INKEY$
IF SK$ = "s" OR SK$ = "S" THEN
  GOSUB STEPUP
LOCATE 1, 5: INPUT "PRESS ANY KEY....", xx
GOTO AGAIN
END IF
RETURN

STEPUP:

REM *** STEP UP ***

LL = STEPS
STEPUP1: FOR L = 1 TO LL
  GOSUB RMOT
NEXT L
RETURN
Section 2.4
Standardisation of the System

a) Purification of Organic Liquids

In the present study analytical reagent grade samples are used after necessary purification and distillation following the procedure cited by Weissberger.\cite{30,31}

The purity of the samples are checked by determining their densities at different temperatures and comparing them with the standard density data available in literature. These data are presented in the next chapter in Table 3.4.1. There is a good agreement between the data of the present work and that of the literature values.

The molecular weights of the pure liquids are taken to be formula weights. The atomic weights of the elements are taken from the carbon-12 isotope scale. The atomic weight table wherein the carbon-12 isotope to which is assigned an exact atomic weight of 12 as cited in "Lange's Hand Book of Chemistry" (Revised Tenth Edition, McGraw Hill 1967) is followed.

b) Cleaning and Filling of Interferometer:

The interferometer is carefully cleaned to remove the oils or other organic materials that are in contact with the interior. For this purpose a suitable solvent is first added to remove them as completely as possible and
then the solvent is washed or dried out. The residual contamination is usually removed by filling the instrument with acetone and allowing it to stand overnight.

The introduction of the liquid under study into the interferometer is done by means of a 20 ml syringe. A mark is made on the interferometer so that same volume of the liquid is used in all the measurements for better reproducibility of results. After filling the liquid, the interferometer is carefully inserted into the constant temperature bath which is controlled at the desired temperature and allowed for atleast half an hour to attain the set temperature.

c) *Calibration of the Interferometer*:

To start with, the triple distilled water is taken into the interferometer and the interferometer is immersed in a temperature bath which is maintained with a precision of \( \pm 0.01^\circ\text{C} \) for about half an hour. The thermostat and electronic circuitry are housed in an air conditioned room, the temperature of which is maintained at \( 20 \pm 1^\circ\text{C} \). This results in an improved stability of the oscillator and the efficiency of the temperature control. The wavelength is computed for 100 minima. The experiment is repeated for about 10 times and the average velocity is calculated.

The working of the system developed in the present study is tested and standardised by measuring ultrasonic velocity in triple distilled water and in some standard organic liquids. The measured velocities are
corrected for diffraction errors adopting the procedure described in section 2.3. The plane wave velocity of 1496.60 ms$^{-1}$ obtained in the present study for distilled water at 25°C offer diffraction correction and is in good agreement with the data reported in literature. The ultrasonic velocities obtained with the instrument are presented in Table 2.4.1 and are compared with the literature. An accuracy of $\pm 0.01$ ms$^{-1}$ could be achieved in the measurement. Thus the instrument is assumed to be standardised for all practical conditions.
Table 2.4.1
Ultrasonic velocities of some standard organic liquids at 25°C

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Velocity m·s⁻¹</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Pure Water</td>
<td>1496.60</td>
<td>Present Study</td>
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<td></td>
<td>1496.59</td>
<td>Ilgunas et al. [26]</td>
</tr>
<tr>
<td></td>
<td>1496.40</td>
<td>Yesunaga et al. [32]</td>
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<td>1497.00</td>
<td>Greenspan et al. [33]</td>
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<td></td>
<td>1496.80</td>
<td>Hirata et al. [34]</td>
</tr>
<tr>
<td></td>
<td>1496.69</td>
<td>Del Grosso [35]</td>
</tr>
<tr>
<td></td>
<td>1496.65</td>
<td>McSkimin [36]</td>
</tr>
<tr>
<td>Benzene</td>
<td>1297.68</td>
<td>Present Study</td>
</tr>
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<td>Handbook of Chemistry and Physics [15]</td>
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<td></td>
<td>1298.90</td>
<td>Kiyohara and Benson [37]</td>
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<td></td>
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<td>Schaaffs [38]</td>
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<tr>
<td></td>
<td>1301.00</td>
<td>Freyer et al. [39]</td>
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<tr>
<td>Carbon Tetrachloride</td>
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<td>Tabhane et al. [40]</td>
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<tr>
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<td>921.30</td>
<td>Rajagopal and Subrahmanyam [41]</td>
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Table 2.4.1 (Contd.)

<table>
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<th>Liquid</th>
<th>Velocity $\text{m-s}^{-1}$</th>
<th>Reference</th>
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<td>Cyclohexane</td>
<td>1252.90</td>
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<td>Kiyohara and Benson$^{[37]}$</td>
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<td>1254.80</td>
<td>Rajagopal and Subrahmanyam$^{[41]}$</td>
</tr>
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<td>1252.70</td>
<td>Moelwyn-Hughes and Thorpe$^{[42]}$</td>
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<td>Toluene</td>
<td>1303.60</td>
<td>Present Study</td>
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References


