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Improved ultrasonic interferometer technique for propagation velocity and attenuation measurement in liquids

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ABSTRACT

Propagation velocity and attenuation are the two basic parameters used for the ultrasonic investigations of liquids. An ultrasonic interferometer is a widely used tool as a cost effective solution for propagation velocity measurement. The ultrasonic attenuation measurements are not possible using the existing interferometers commercially available in the market. Ultrasonic attenuation can be measured using the pulse echo method, which is relatively complex and expensive. Generally, in interferometers, a radio frequency voltage of more than 100 V is used to excite the piezoelectric transducer. In this article, an improved design of the ultrasonic interferometer with low (5 V) rf voltage excitation is discussed. The proposed design has several advantages over existing systems. The low voltage excitation reduces heating of the sample under study. Detection of the received signal is done directly at the transducer. The critical effects of a coaxial cable in rf detection are minimized by dc detection at the transducer node. The impedance response of the transducer is used for the detection of nodes and antinodes for attenuation and velocity measurements. The use of an instrumentation amplifier enables one to amplify the extremely small voltage changes across the transducer due to interference. The developed method has the capability to measure attenuation due to high receiver sensitivity. The technique has been validated for the propagation velocity and attenuation measurement in standard samples of water and other liquids. The results thus obtained have been compared with the literature and the conventional pulse echo technique which shows close agreement.

I. INTRODUCTION

An ultrasonic interferometer is an extensively used instrument by researchers, by engineers, in industry, and by metrologists as a cost effective tool for the measurement of ultrasonic propagation velocity in liquids. Using ultrasonic velocity, one can obtain the thermo-acoustic, physical, and chemical properties of liquids.[1,2] Ultrasonic propagation velocity is usually measured using either of the two methods, one by continuous wave and another by pulse echo. In an ultrasonic interferometer, continuous rf voltage is applied to excite the piezoelectric transducer. The wave travels through the liquid medium from one end and is reflected by the reflector placed at the opposite end. Due to the interference of reflected and transmitted waves, the standing waves are generated.[3] Generally, the reflector is kept movable. When the reflector moves to and fro parallel to the piezoelectric transducer face, maxima or minima are formed which are detected along the ultrasonic beam propagation, $\lambda/2$ steps. The excitation frequency and the distance between the successive maxima and the minima are used for the velocity measurement. Elaborated interferometric methods developed by the researchers to measure the ultrasonic velocity with improved accuracy and resolution are available in the literature.[4,5]

For ultrasonic attenuation, a small change in the amplitude detection plays a vital role in the measurement.[6] A literature survey revealed that the use of an ultrasonic interferometer is limited only for velocity measurement.[7–9] The present ultrasonic interferometers are not suitable for attenuation due their low sensitivity to amplitude variations. The ultrasonic attenuation is measured preferably by the pulse echo technique.[10,11] In the pulse echo method, the ratio of amplitudes of two successive echoes is used for estimation of attenuation.[10,12] Various pulse-based techniques that are developed for velocity and attenuation measurement are available in the literature.[13–17]

In this article, the effect caused by an rf cable for detection of maxima or minima in the ultrasonic interferometer is discussed. A technique is developed for the precise measurement of amplitudes with small changes in the impedance of the transducer. The rf excitation source of 5 V and a dc voltage detection module have been designed in our laboratory. The impedance variation response of the transducer as a result of interference of ultrasound is measured directly at the piezoelectric transducer by using a fixed resistor at the output of the piezoelectric transducer. The rf voltage signal at the transducer is converted into dc voltage. As the developed module detects the dc voltage change due to a small change in impedance, this minimizes the effect of the coaxial cable. The dc voltage detection module developed has extremely high sensitivity, so it provides capability to measure ultrasonic attenuation.

II. EFFECT OF HIGH VOLTAGE EXCITATION AND RF DETECTION WITH COAXIAL CABLE

Generally, a voltage of about 100 V or more is used to excite the piezoelectric disc using a coaxial cable to connect the rf output. Dubey *et al.* explained the effect of the coaxial cable in the rf voltage measurement.[18] Figure 1 shows an rf equivalent circuit for the excitation and detection system used in the ultrasonic interferometer. Here, in this figure, Mason's 1-D model equivalent circuit of a piezoelectric disc in thickness mode vibration[19] with a coaxial cable equivalent circuit has a major role in detection. Rs is the output impedance of the rf voltage source and Cc is the capacitance offered by the BNC connector used. The total impedance with the transducer as the source (receiving mode) is the sum of the impedance of the coaxial cable (Z_{cable}), piezoelectric disc (Z_{tx}), and liquid medium (Z_{liq}) given as[19]

$$Z_{total} = Z_{cable} + Z_{tx} + Z_{liq}, \tag{1}$$

where Z_{cable} is the impedance offered by the combination of series inductance L1 and shunt capacitance C1 of the coaxial cable. The practical impedance of RG59 cable[20] may be considered as $75 \pm 3\ \Omega$. The electrical equivalent circuit of the piezoelectric disc in thickness mode vibration is available in the literature.[19] The transducer disc impedance ($Z_{tx} = X_{Co} + Z_m$) parameter, which plays a major role in the rf detection of the node/antinode with coaxial cable, is the resultant of static capacitance, Co, and intrinsic capacitance, Cs. By using the value of the above parameter from the datasheet of a piezoelectric disc[21] (PZT-5J) of 2.05 MHz frequency (thickness 19 × 1 mm), Z_m, impedance due to mechanical elasticity, is very small in comparison with static impedance. Therefore, the practical impedance offered in the detection is as follows:

$$Z_{total} = 75\,\Omega + Z_{tx} + Z_{liq}, \tag{2}$$

where Z_{liq} depends on the characteristic acoustic impedance of the liquid medium used. The change in impedance is very small in the order of a fraction of ohm with detection of node/antinode. The high series impedance (75 Ω) of the cable forces to reduce the small change in the output of rf detection. This signal is suitable for the velocity measurement because it detects the change in wavelength or the path distance in terms of maxima to maxima. The effect of small change impedance is enhanced by measuring the change in the impedance directly at the transducer by dc voltage detection.

III. EXPERIMENT

A. Direct digital synthesis based rf excitation source

In the recently developed interferometer, a direct digital synthesis (DDS) software based on an excitation source is used. Figure 2 shows the block diagram of the DDS based source for the excitation of the piezoelectric transducer. It generates an rf excitation signal of a particular specified frequency and displays it on LCD. The frequency selection and control is provided to change the frequency of the signal with the step size of 10 Hz. The generation of the rf frequency is done with the help of an AD9850 module[22] and microcontroller[23] Atmega16A. High-resolution frequency selection is provided in order to select the precise frequency of the transducer and to achieve best response. This signal is further amplified to the desired level (5 V). The high bandwidth (200 MHz) operation amplifier[24] (IC, LM7171) is used with a gain of 5 to excite the piezoelectric transducer at a particular frequency. The software for the frequency generation was written in C using Code Vision AVR.

B. Modified and improved node/antinode detection module

The block diagram of the developed system with a measuring cell is shown in Fig. 3. The impedance response of the piezoelectric transducer was measured directly at the transducer node without cable. The rf voltage signal at the transducer is converted into dc

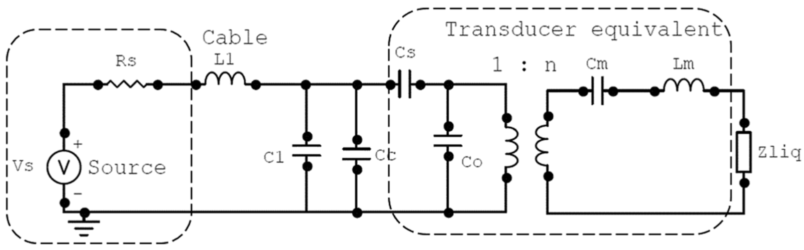

FIG. 1. Equivalent circuit showing the different components that influence the generation and detection of maxima or minima in the ultrasonic interferometer.

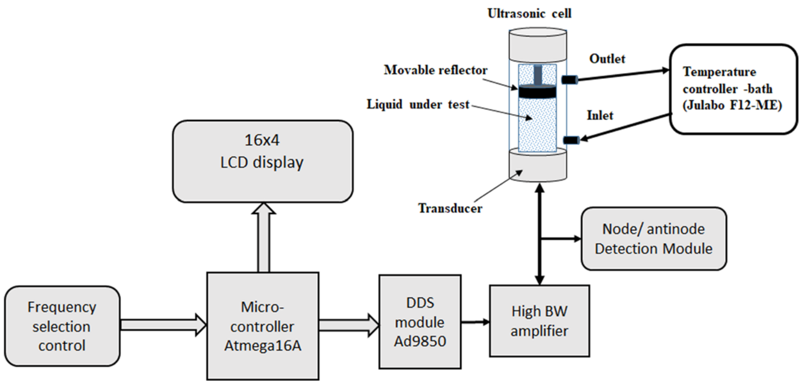

FIG. 2. Block diagram of the developed ultrasonic interferometer with a DDS based excitation source and dc detection system.

voltage. Figure 4 shows the detailed circuit diagram of the developed measurement system. The signal received at the piezoelectric transducer is directly converted to dc voltage by using a fixed series resistor R_5 and a peak detector. The value of the fixed resistor R_5 is chosen based on the transducer impedance. When the ultrasonic path is changed by the micrometer screw gauge, there is a change in the voltage drop across the resistor due to the change in transducer impedance. The signal after the resistor is used and converted

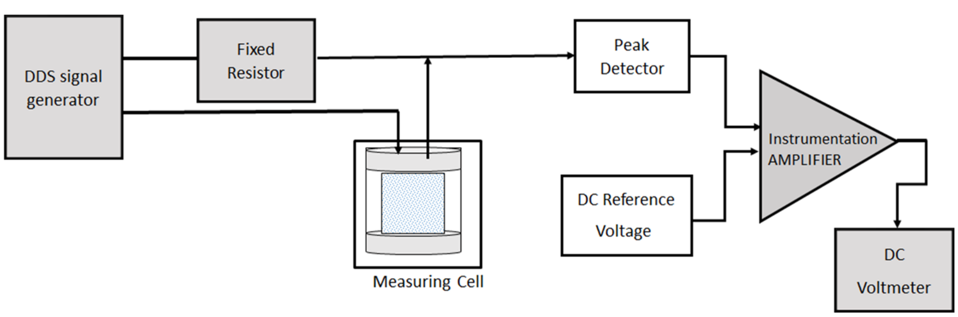

FIG. 3. Block diagram of the developed system with a measuring liquid cell.

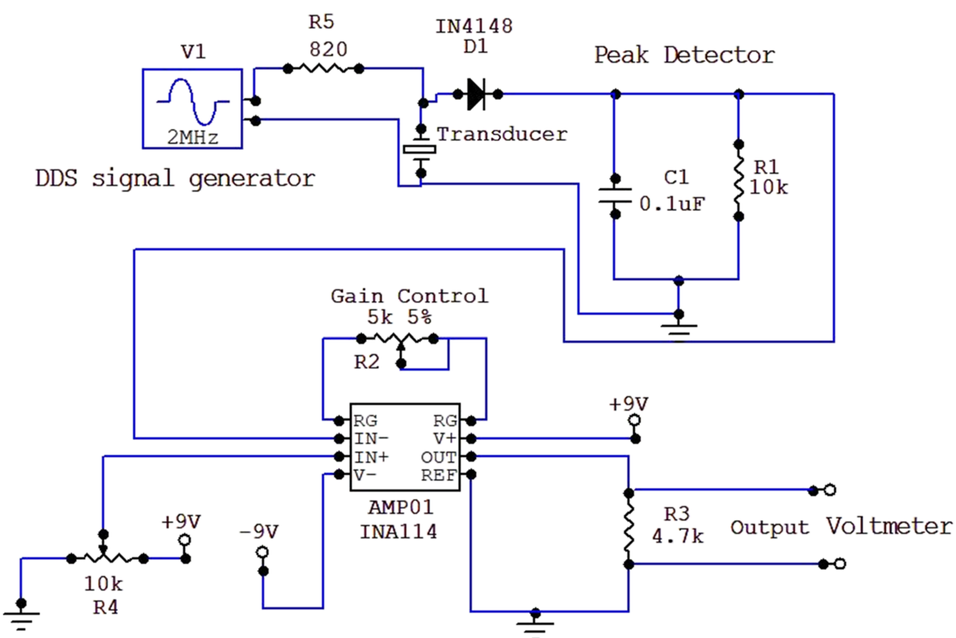

FIG. 4. The circuit diagram of the node/antinode detection module for attenuation and velocity measurement.

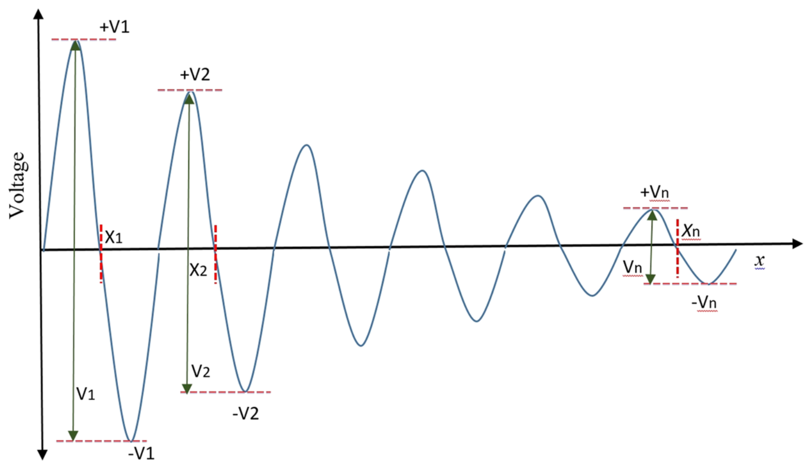

FIG. 5. The schematic representation of wave propagation in liquids with a number of maxima and minima.

to dc voltage by using the peak detector. A diode IN4148 with R_1C_1 time constant is chosen such that it holds the signal for 100 ms. Whenever the voltage is changed, it tracks the next value of the voltage. The detected signal has a small change in the voltage in the order of few mV as the path is changed. A differential high gain instrumentation amplifier (IC: INA114) is used to amplify the small change in the signal.[25] The reference voltage is applied at the input of the instrumentation amplifier, which has the gain variation from 10 to 10 000. The potentiometer R_2 is used to control the gain and corresponding amplified change in volts. The reference is used to amplify only the small variation that is caused by the node or antinodes.

For the sake of the convenience and visual identification of maxima and minima, the analog voltmeter is used with a range of 0-10 V and a resolution of 200 mV. The advantages of using the developed attenuation and velocity module[26] are as follows:

- It uses a low continuous wave excitation voltage of 5 V. The low excitation produces negligible heat in the sample, and accordingly, liquid properties are less affected by such temperature fluctuation.[6]
- The detection part includes dc voltage which is less affected by rf noise.
- The DDS software based frequency excitation is more precise with precision better than 50 ppm.[22]

C. Ultrasonic attenuation measurement

An improved ultrasonic interferometer detection device has been developed in our laboratory. The unique feature of the developed system is that it has the capability to measure both ultrasonic velocity and attenuation of the liquid samples. This developed detection and generation system is applicable for ultrasonic liquid cells of a suitable frequency within the excitation range of DDS. The ultrasonic cell consists of a piezoelectric disc, a reflector, micrometer reflector movement, and a double walled steel cylindrical structure. The ultrasonic signal inside the liquid sample is generated and received by the same piezoelectric transducer, when excited by the rf signal. The reflector reflects the signal back toward the transducer. By moving the reflector position by using a micrometer screw gauge, the separation between the transducer and the reflector is changed. For velocity, half wavelength is measured by the path difference at which maxima or minima occur.[26]

D. Estimation of attenuation

For attenuation measurement, the difference between the amplitude of maxima and minima at a different distance is considered. The schematic of a wave-propagated amplitude signal in liquids with maxima and minima detection is shown in Fig. 5. The liquid medium is considered as dispersion free. So, the dispersion component β of wave vector ($k = \beta + i\alpha$) is neglected. The amplitude

TABLE I. Ultrasonic propagation velocity measured at 25 °C temperature in distilled water, ethyl alcohol, cyclohexane, carbon tetrachloride, and glycerol by the developed technique.

S. no.	Liquid sample (purity %)	Average experimental velocity (m/s)	Literature[29] velocity (m/s)	Standard deviation (m/s)
1	Distilled water	1497.387	1496.72 (25 °C)	0.803
2	Ethyl alcohol (99.9%)	1146.145	1145.00 (25 °C)	0.635
3	Carbon tetrachloride (99.8%)	921.547	921.00 (25 °C)	0.688
4	Cyclohexane (99.5%)	1249.778 1282.267 (20 °C)	1280 (20 °C)	0.644 0.688
5	Glycerol (99.5%)	1908.619	1920.00 (25 °C)	0.702

of ultrasonic attenuated wave propagation[27] in the liquid medium is given as

$$v(x,t) = V_o e^{i(kx-\omega t)} = V_o e^{i[(\beta+i\alpha)x-\omega t]} = V(x)e^{i(\beta+i\alpha)}, \tag{3}$$

where V_o is the excitation voltage applied to the transducer, f ($\omega = 2\pi f$) is the excitation frequency, and x_n is the distance of the nth order of wave maxima-minima.

From Fig. 5, the detected dc amplitude $V(x_1)$, $V(x_2)$, and $V(x_n)$, at the distances x_1, x_2, and x_n are related by the equation

$$V(x) = V_o e^{(-\alpha x)}. \tag{4}$$

Similarly,

$$V(x_n) = 2V_o[\exp(-\alpha x_n)\cosh\left(\frac{\Delta xn}{2}\right), \tag{5}$$

where $V(x_n)$ corresponds to the maxima to minima (peak to peak) amplitude of the nth superimposed wave. The amplitude of both the maxima and minima is considered almost equal. Hence, from Eq. (5) divided by (4) and after solving the equation, the ratio of amplitude differences for the nth and first pairs of extrema will be

$$\frac{V(xn)}{V(x1)} = \exp\left[-\alpha(xn - x1)\frac{\cosh\left(\frac{\Delta xn}{2}\right)}{\cosh\left(\frac{\Delta x1}{2}\right)}\right] \tag{6}$$

with equal spacing (a half wavelength) of maxima to minima within the nth and first pairs of maxima and minima (i.e., $\Delta x1 = \Delta xn$) and allowance for the two-way attenuation propagation obtained as

$$\alpha = -\ln\left[\frac{V(x_n)}{V(x_1)}\right]/2(xn - x1). \tag{7}$$

The same transducer is used to detect the attenuated amplitude. Therefore, the ultrasonic path $(xn - x1)$ is considered as double in Eq. (7) of the path length in the liquid sample holder. The α obtained from Eq. (7) is in Np/m.

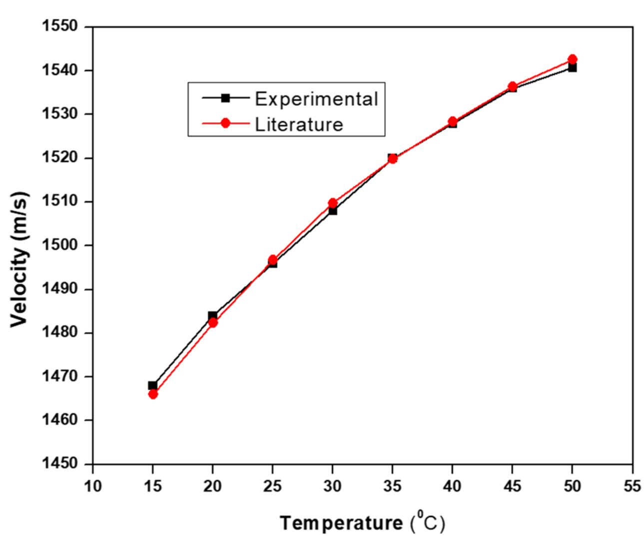

FIG. 6. Propagation velocity measured at different temperatures using the developed technique in distilled water.

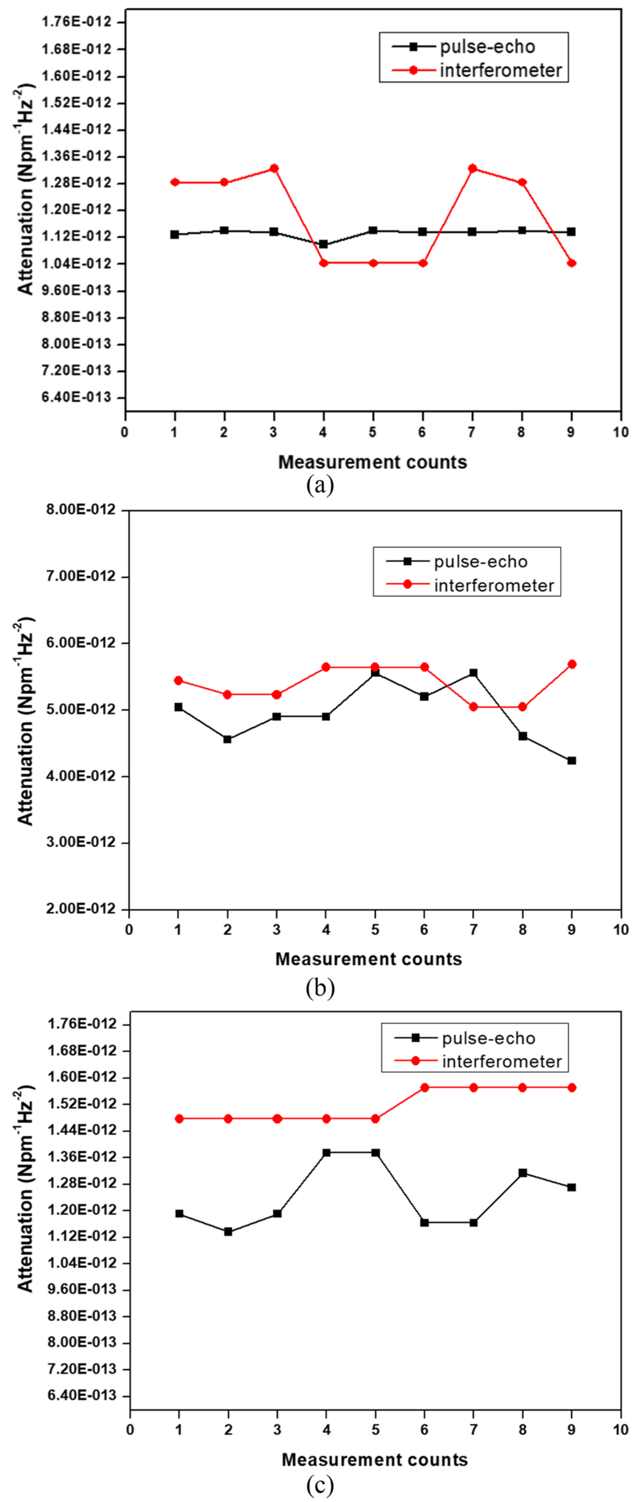

FIG. 7. (a) Relative attenuation measured by the developed technique in distilled water at 25 °C. (b) Relative attenuation measured by the developed technique in cyclohexane at 25 °C. (c) Relative attenuation measured by the developed technique in glycerol at 25 °C.

Then, ultrasonic attenuation in dB m^{-1} is computed by the above equation (8) or by simply multiplying Np/m by 8.686. As ultrasonic attenuation increases with the square of the frequency and therefore generally represented in terms of $^{\alpha}/_{f^2}$,

$$A = \frac{20}{2(xn - x1)} \mathrm{Log}_{10}\left[\frac{V(x_1)}{V(x_n)}\right]. \quad (8)$$

IV. RESULT AND DISCUSSION

Ultrasonic attenuation and propagation velocity were measured using the developed improved ultrasonic interferometer. The experiment was repeated 10 times for standard liquids to check the functionality of the developed technique and for estimation of attenuation and velocity in liquids. The sample temperature was maintained with the help of Julabo make (model: F12-ME) temperature controller.[28] The ultrasonic path measurement was carried out with micrometer scale having a range of 25 mm and a least count of 0.01 mm.

Ultrasonic propagation velocity measurements were carried out in the distilled water, ethyl alcohol, cyclohexane, carbon tetrachloride, and glycerol by the developed technique at an excitation frequency of 2 MHz. The experiment was repeated 10 times to know the precision in the velocity measurements. The temperature was maintained at (25 ± 0.01) °C. Table I shows the experimentally measured values in standard liquids for n = 30 (number of maxima to minima counts). The measured propagation velocity values found are in close agreement with the literature values. The standard deviation of the repeated measurements in liquids was calculated in each case and is shown in Table I.

The developed technique has also been tested and verified for its functionality at different temperatures in distilled water.

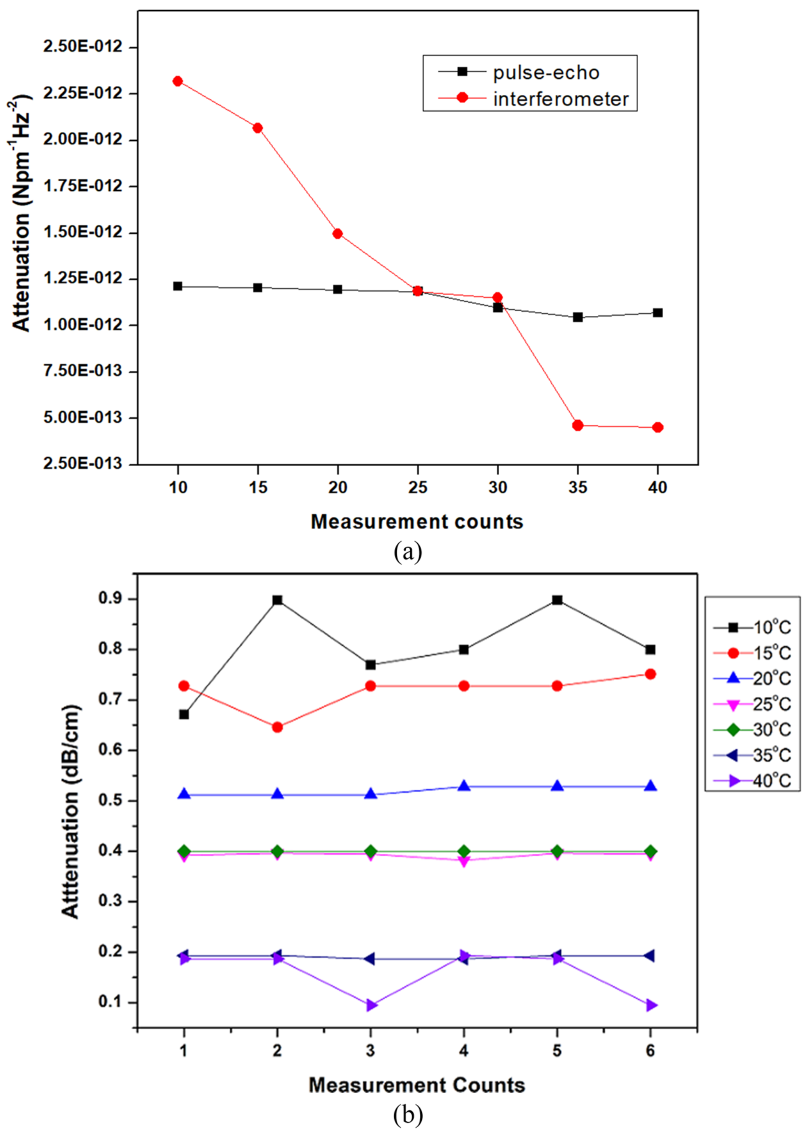

FIG. 8. (a) Change in attenuation measured by the developed technique and pulse echo technique with a change in temperature from 10 °C to 40 °C in distilled water. (b) Ultrasonic attenuation (dB/cm) with a change in temperature from 10 to 40 °C by the developed technique.

The ultrasonic propagation velocity was measured for n = 10 with an excitation frequency of 2 MHz. Figure 6 shows the propagation velocity measured at different temperatures in distilled water. The measured values are closely matching with those in the literature.[29]

Ultrasonic attenuation was measured in distilled water, cyclohexane, and glycerol. The experiment was repeated 9 times for attenuation measurement in liquids by both the developed technique and pulse echo technique. Figures 7(a)–7(c) show attenuation values measured at a temperature of 25 °C and an excitation frequency of 2 MHz in distilled water, cyclohexane, and glycerol, respectively. Our measured attenuation values by the developed technique in distilled water (low attenuating), cyclohexane, and glycerol (highly attenuating) are in good agreement with the values measured using the conventional pulse echo technique. For the ease of comparison, the measured attenuation values were normalized with square of the excitation frequency and attenuation was calculated in nepers per meter. The functionality of the developed technique has been verified for a change in attenuation values with a change in the sample temperature. Figure 8(a) shows the change in ultrasonic attenuation measured by the developed technique and pulse echo technique with temperature variation from 10 °C to 40 °C in distilled water. Each measurement points were repeated 6 times for long time, and average values were considered. Pal *et al.* explained the parameters, which affect the attenuation by the pulse echo technique.[30,31] The article emphasizes that the measurement of ultrasonic attenuation is difficult by the pulse echo method. The values reported in the literature are quite higher at a lower excitation frequency. The attenuation in distilled water at a lower frequency less than 3 MHz is observed as not proportional to square of the excitation frequency.[29] Figure 8(b) shows the change in attenuation (dB/cm) with a change in temperature from 15 to 40 °C by the developed technique. The value of attenuation (16.93×10^{-15} Np cm^{-1} f^{-2}) reported by Pal and Kundu at 2 MHz and 25 °C was little higher than 10 MHz excitation frequency.[30] The attenuation value in our case at 25 °C by 2 MHz excitation was 11.54×10^{-15} Np cm^{-1} f^{-2}. The measured attenuation values seem deviated from the literature[29] which may be due to the scattering of ultrasound, divergence of beam, liquid sample holder structure, and transducer parameter.[32] Martinez *et al.* explained the comparison of attenuation measurement by continuous wave and pulse echo methods at near field and far field, which is quite different. They observed that the attenuation value measured by the pulse echo method was lower than that by the continuous wave techniques. Pulse echo, the conventional experimental technique, is suitable for the measurement of ultrasonic velocity and attenuation in liquids, but attenuation varies due to the effect of near field and far field.[31]

V. CONCLUSIONS

An improved ultrasonic interferometer with a low voltage rf excitation, dc voltage detection system has been successfully designed and developed, and its functionality has been tested for attenuation and velocity measurements in several standard liquid samples. It has been observed that the measurement of the amplitude directly at the transducer with a fixed resistor and a peak detector is more precise than the rf measurement. It was concluded that the developed technique uses low excitation so that the liquid properties may not alter during measurements. The measurement technique has high receiver sensitivity than the existing other interferometric techniques. It is suitable for a wide range of attenuation measurements from lower to higher attenuating liquids.

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