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Ultrasonic interferometric sensor for rheological changes of fluids

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An ultrasonic interferometric sensor has been introduced for the measurement of subtle changes in the physical properties of fluids such as density, viscosity, and bulk modulus. Tone burst ultrasonic waves are generated using a single peizocrystal bonded in between two solid delay line media of slightly different lengths. One side is in contact with a reference fluid (with known properties) and the other with a fluid whose properties are to be measured. The ultrasonic waves reflect from the two solid-fluid boundaries and are received back by the peizocrystal where the interference effects are measured. The longitudinal waves were used to measure the longitudinal impedance, while shear waves were used to measure the shear impedance. Glycerin-water mixtures were used as the test material. A simple plane wave model was shown to provide satisfactory comparison with experiments. Various parameters that influence the measurement were studied. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2336771]

INTRODUCTION

Fluids that are undergoing rheological changes are important for process control. Density, adiabatic bulk modulus, and viscosity form a set of important mechanical properties of liquids. Their quantification provides information regarding the progress of many industrial processes, and hence this method serves as a useful tool for on-line process control. Extensive work in this area has been documented in the literature.[1–4] In the present work, the reflection at the solid-liquid interface was used for the determination of rheological properties of liquid.

As the waves are incident at the interface between the solid and the liquid, they sense a change in acoustic impedance and hence some part of the wave reflects back. In both solids and fluids, the longitudinal wave acoustic impedance can be defined as the product of the wave velocity in the medium multiplied by its density. In solids, the shear wave acoustic impedance is the product of the density and the shear wave velocity. For Newtonian fluids, it has been shown to be related to the product of viscosity and density.[4] Hence, if the solid media properties are well known, the densit $\times$ wave velocity product can then be found from the reflection factor measurements of the longitudinal wave reflection factor while the density $\times$ viscosity product, from the shear wave reflection factor.

It has been demonstrated by Sheen *et al.*[5,6] that the viscosity and density of fluids can be quantitatively measured using a combination of longitudinal and shear wave reflection coefficients and wave velocities. It has also been demonstrated[7–9] that a shear wave delay line technique can be used for temperature and viscosity measurements at high temperatures such as molten glass. The relationship between the magnitude and the phase of the reflection coefficient at a solid-viscous fluid interface has been discussed elsewhere,[4] and the use of the phase of the reflected ultrasonic shear wave for the measurement of the shear impedance of fluids has been demonstrated.[10] The measurement of physical properties of slurry has also been demonstrated using ultrasonic measurements.[11,12] It has been shown by Greenwood and Bamberger[11] that for fluids with high viscosity, the shear modulus can be directly measured and, using the density of the fluid, the shear wave velocity in the fluid can be derived. A noncontact laser ultrasonic method for molten fluid properties has also been reported.[13,14] Guided wave techniques using thin rods/wires have been demonstrated for the simultaneous measurement of both the density and the viscosity of fluids by several research groups.[15,16]

The ultrasonic measurement techniques for fluid properties have certain shortcomings, particularly related to the viscosity measurements:

- poor sensitivity to low viscosity fluids (<10 ps) and subtle changes in rheological properties;
- nonmonotonous behavior of shear wave reflection factor as a function of viscosity that limits measurements at the high viscosity range; and
- the coupled measurement of viscosity $\times$ density product, which then requires additional techniques to measure density, before viscosity can be obtained.

A double reflection ultrasonic interferometric technique based on the null method is proposed here for the measurement of rheological properties of fluids that addresses the first two issues stated above. Here, two tone burst (gated near-monochromatic wave) signals obtained from solid reflecting surfaces, one in contact with the liquid whose properties are being evaluated while the other in contact with a reference fluid, are allowed to interfere. The length of travel of the ultrasonic waves in the two solid delay lines was adjusted such that the interference causes a null minimum.

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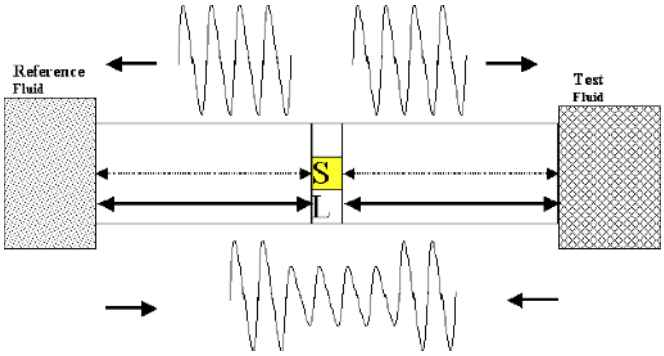

FIG. 1. (Color online) The schematic representation of the double delay-line ultrasonic interferometry sensor with typical transmitted and received signals.

Hence, any change in the conditions, either in the solid or the fluid media will cause phase difference between the two signals and the interfered signal will not satisfy the null condition. Hence, the interfered signal provides an extremely sensitive method for measuring small changes in the rheological properties of the liquids. This technique has potential for the on-line monitoring of the viscosity and/or density of liquids.

Potential advantages of the double delay line interferometric technique include the following:

- By appropriate choice of the reference fluid, this technique can measure subtle changes in fluid properties and viscosity in the low viscosity (cP) range.
- For low temperature applications (less than 200 °C), it may be possible to autocompensate for temperature variations by allowing the delay lines to be thin and made of material with low coefficient of expansion.

INTERFEROMETER SENSOR DESCRIPTION

The sensor consists of two delay lines of slightly different lengths (of the order of a few ultrasonic wavelengths) that sandwiches a piezoelectric crystal based sensor as illustrated in Fig. 1. Based on the type of measurement (viscosity × density or velocity × density), the piezoelectric crystal may either be a shear wave generator (S) or a longitudinal wave generator (L), respectively, or a hybrid of both. The tone burst signal was used to excite the piezoelectric crystal and the reflected ultrasonic waves are sensed by the same crystal system after finite time duration. The sensor is represented along with typical signal shapes of the transmitted and received ultrasonic waves in Fig. 1. The duration of the tone burst, the amplitude, the frequency, the length of the two rods, the material of the rod, etc., are selected based on the type of measurement.

PLANE WAVE MODEL

In order to better understand the various parameters involved, a simple plane wave model was developed using the superposition principle of two sinusoidal postreflected waves. It is assumed that the length (L) to diameter (D) ratio of the delay line was selected such that the reflections and mode conversions at the outer surface of the delay line can

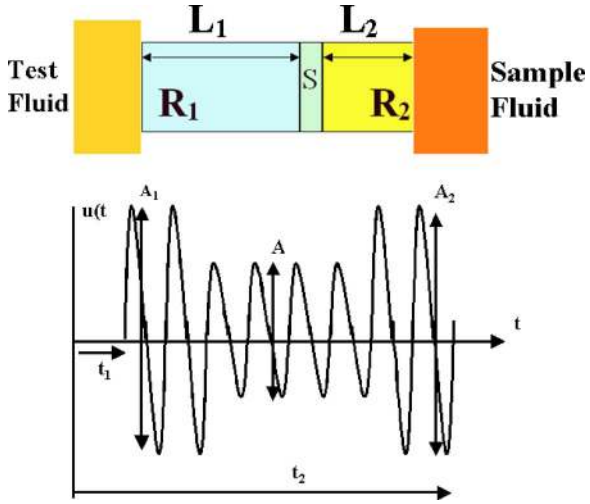

FIG. 2. (Color online) The schematic representation of (a) the plane wave model and (b) the nomenclature of the features of the signals received.

be avoided, i.e., depending on the beam divergence of the wave mode the L/D ratio was chosen to be small so that the diverging beam will not be reflected at the outer surface before it reflects from the end of the delay line. In the experiments, the ratio chosen was 1. Also, the frequency of the ultrasonic wave was high enough so that guided waves are not generated. This model is developed for the situation where only pure shear waves are generated in the delay lines as illustrated in the Fig. 2(a).

The reflection coefficient (R_i) is a complex number and operates on the transmitted sinusoidal ultrasonic wave (u_0) with an amplitude of A and phase (ϕ),

$$u_0(t) = A\cos(\omega t + \phi). \tag{1}$$

The reflected sinusoidal waves interfere and the received signal is represented by the displacement $u(t)$ as shown below:

$$u(t) = R_1 A_1 \cos(\omega t + \phi_1) + R_2 A_2 \cos(\omega t + \phi_2). \tag{2}$$

Here, the reflection coefficient is given by

$$R_i = \mathrm{abs}[(Z_f - Z_s)/(Z_f + Z_s)], \tag{3}$$

where the acoustic impedance of the viscous fluid is

$$Z_f = (i\rho_f \eta_f \omega)^{0.5}, \tag{4}$$

where ρ_f is the density of the fluid, η_f is the viscosity of the fluid, and ω is the circular frequency of the ultrasonic wave. The acoustic impedance of the solid is

$$Z_s = \rho_s c_s, \tag{5}$$

where ρ_s represents density and c_s represents wave speed in the solid. The phase delay for either of the reflected waves is given by

$$\phi_j = 2L_j/c_s + \tan^{-1}[\mathrm{Im}(R_j)/\mathrm{Re}(R_j)]. \tag{6}$$

A typical interfered signal is shown in Fig. 2(b). The signal consists of three regions. The middle portion shows the interfered signal while at the ends, the reflected signals are observed. The nature of this signal will depend upon (a) the frequency and number of cycles of tone burst, (b) the normalized difference in delay-line lengths abs$[(L_2 - L_1)/\text{wavelength}]$, and (c) physical properties of the delay

line and the two fluids. It must be ensured that the pulse duration is long enough or the difference in the lengths of the two delay lines is small enough such that the two reflected signals will interfere.

EXPERIMENTAL APPARATUS AND PROCEDURE

A piezoelectric crystal [type Lead Zirconate Titanate (PZT)-4] was used to send the mechanical waves. In the experiments reported here, separate crystals are used for longitudinal and shear waves. A 5 MHz crystal was used for longitudinal waves and 2.25 MHz crystal for shear waves. The wedge consists of two cylindrical Plexiglass rods, each of which is 25 mm in diameter and 25 mm in length with a taper on the initial 5 mm of its length. The crystal is bonded using epoxy based glue and tested. A 20 cycle tone-burst signal (near monochromatic) was generated using a MATEC TB1000 pulser and the received interfered signals (by the same transmitter crystal) were filtered, amplified, and digitized using a National Instruments PCI 5102 20 MHz digitizer card that was resident in a Pentium personal computer.

The main principle used for measuring density is the acoustic impedance mismatch at the boundary between the two Plexiglas delay lines and the liquid with which it is in contact. The reflection coefficient at the liquid-probe interface is used along with the known velocity of sound in the fluid to measure the density, and the interference of reflected waves (from either side of the piezoelectric crystal) was used to measure the viscosity of the fluid (the velocity is measured using time of flight measurements as explained later). The shear impedance of fluids is measured on the basis of shear wave interference technique. In this setup, the shear wave is generated at near monofrequency and propagated on two rods. One end of the rod is in contact with a liquid of known density, while the other end is in contact with the fluid whose properties are to be measured (see Fig. 2). The lengths of the rods are chosen such that the two shear wave reflected signals are allowed to partially interfere at the crystal, such that the two reflected signals along with the interfered portion can be simultaneously recorded. This is accomplished by taking two identical rods of precisely the same length and then polishing one of the rods down by about a couple of wavelengths of material from one side. The amount of material removed need not be carefully monitored as long as this material is of the order of the ultrasonic wavelength, since the frequency of the wave can be used to adjust for any differences in this process. This is one of the implicit advantages present in the method.

The two waves coming from either side of the crystal are allowed to interfere, and the superposed signals are sensed by the crystal. Initially both sides of the probe are in contact with the reference fluid, and the frequency of the input sinusoidal excitation to the shear crystal is continuously changed till a particular frequency maximum destructive interference takes place. This is called nulling of the probe. Hence, any phase change that occurs at the reflection interfaces due to changes in the shear impedance (which contains viscosity) will be recorded as a change in the signal magnitude.

Due to the damping effect of the two delay lines, the frequency bandwidths of the PZT crystals were found to be broad. Hence, the excitation frequency could be varied within the bandwidth of the crystal. For a 2.25 MHz crystal, the −9 dB bandwidth was found to be from 0.7 to 3.5 MHz. The point of maximum destructive interference was found by trial and error to be 1.54 and 2.31 MHz. (There may be more than one frequency corresponding to the point of maximum destructive interference. At these two frequencies, the null was more apparent than others due to the 0.01 MHz resolution of the tone burst frequency selector.) Now as the fluid is changed on one side, the amplitude at the point of complete destructive interference changes. For initial verification of the model the experiments were conducted using NIST calibration standards obtained from Cannon Inc., PA, USA. For the experiments conducted using glycerin-water mixtures, distilled water was used as reference fluid throughout the experiments

During the experiments using longitudinal waves for the absolute measurement of density × velocity of fluid, only the magnitude of reflected wave needs to be known and hence the fluid at one end is enough i.e., the reference fluid is air. However, for the measurement of subtle variations in the density × velocity of the fluid, an appropriate reference fluid must be used.

MODEL VERIFICATION AND SIMULATION RESULTS

In order to gain confidence in the model, the interfered signals were simulated and also obtained experimentally at different frequencies. A typcial result is shown in Fig. 3 which was obtained by keeping both sides in distilled water; the crystal used was a shear type *Y*-cut crystal. It can be observed from the results that the relative magnitudes of the interfered signals, A, A_1, and A_2, for the simulation compares well with the experimental results. However, the experimental results are of lower amplitude. This may be attributed to the plane wave nature of the model which does not take the beam divergence into account.

The effect of the variation of the interference length, i.e., the difference in the lengths of the twoPlexiglas delay lines $\delta L = L_1 - L_2$, while keeping the frequency at 2.25 MHz is illustrated in Fig. 4(a) using simulation model for three different fluid viscosities. Here again, the shear wave sensor was simulated. It can be observed that the magnitude A varies as a function of δL in a rectified cyclic fashion (as expected). Since this was difficult to verify experimentally, an experiment was conducted by keeping δL constant (0.1 mm) and by varying the frequency within the bandwidth of the 2.25 MHz damped crystal. The experiment was conducted using water as the reference fluid. Two fluids were evaluated having 0 (water) and 25 Pa s (NIST traceable fluid from Cannon Inc) viscosities. The plot in Fig. 4(b) shows the magnitude A for different frequencies in the experiments and the simulation for the experimental conditions. It can be observed from these results that the interference pattern obtained by changing the frequency is similar to the one obtained by changing the interference length δL, which is to be expected. The experimental results are encouraging and again show the reduced amplitude, but similar behaviors for

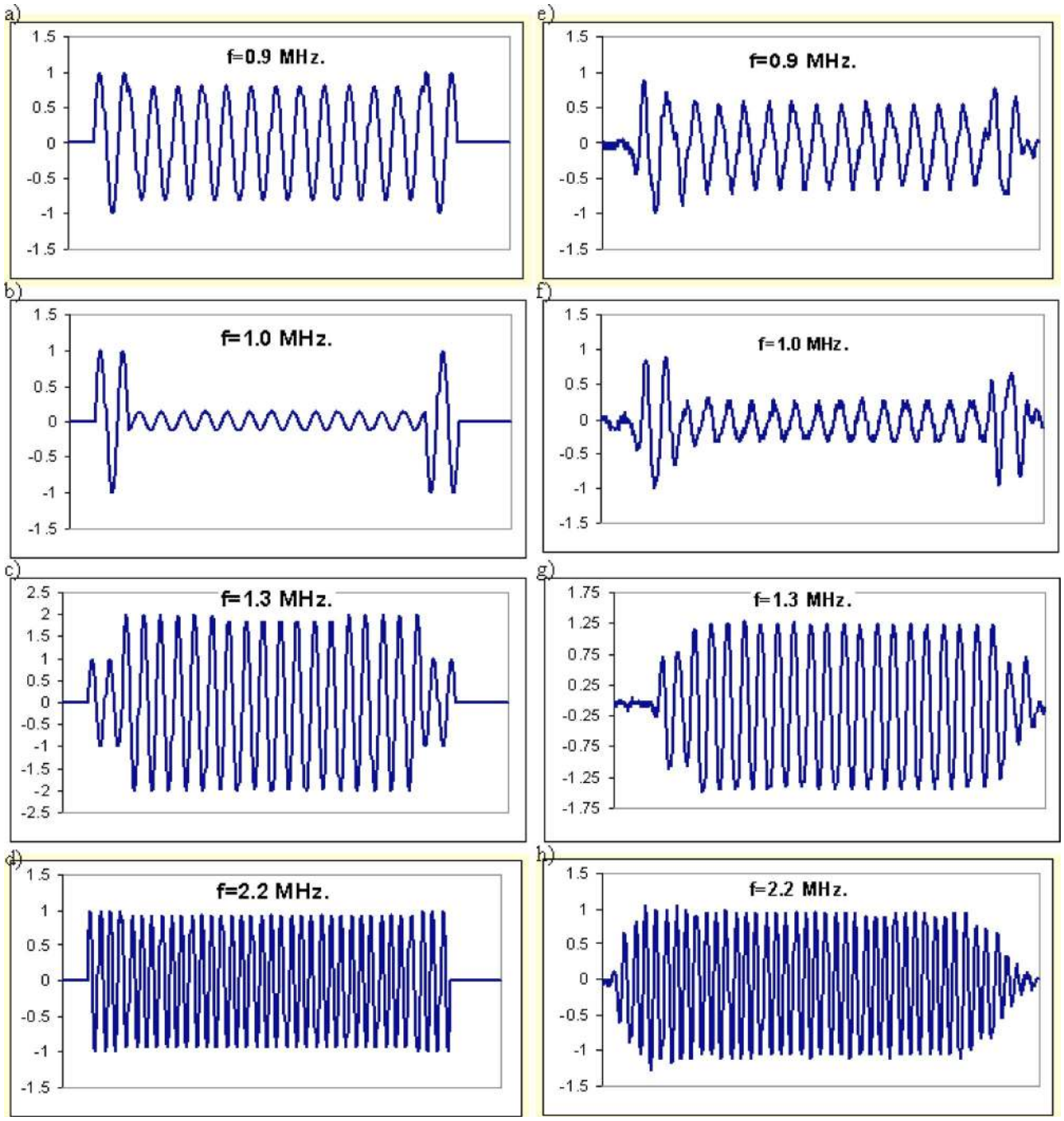

FIG. 3. (Color online) Comparison between the theoretical plane wave model results [(a)–(d)] and the experimental results [(e)–(h)] for different frequencies of the ultrasonic wave using two Plexiglas wedges with distilled water on both sides.

the two fluids are considered. The minima and the maxima were found to be in the same frequencies for both the experiment and the simulations. Hence, the simulation results can be used to provide a means for optimizing the experimental parameters.

Figure 4 shows that regions of sensitivity for measuring changes in the viscosity of the fluids can be either at the maxima or at the minima. However, it must be noted that, in practice, the choice of a frequency or δL to achieve either one of the maxima or a minima is crtical in achieving desired measurement results. It can be argued that the choice of a minima is a better choice and has been used extensively in other areas such as optics. This has been demonstrated in Fig. 5 using experiemental data obtained at two different frequencies, one at one of the maxima [Fig. 5(a)] and the other at a minima [Fig. 5(b)]. While the absolute value of the difference between the two interfered signals may be comparable for similar changes in the viscosity, the relative change in the signal shows significant sensitivity while choosing the minimum freqeuency. The Figure 5(a) shows less than 5% change in the amplitude, while the result for the minimum frequency in Fig. 5(b) shows an almost 100% change in the magnitude of the interfered signal. For improving measurement robustness, high fidility amplification of the smaller signal can be used.

For shear waves, the A/A_1 and the A/A_2 ratios were

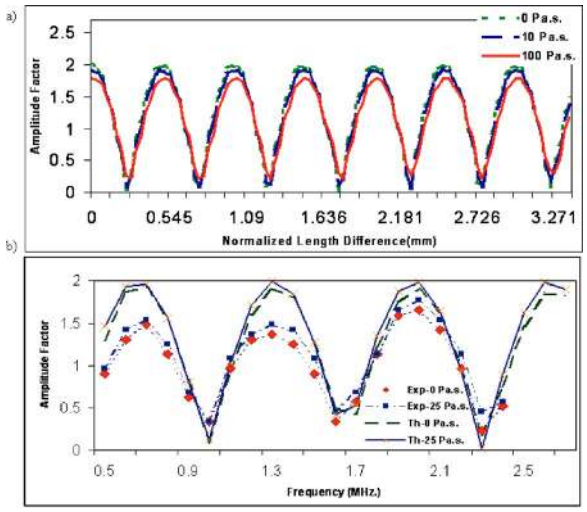

FIG. 4. (Color online) The effect of frequency and interference length (L_1-L_2) for different viscosity fluids. (a) Simulation results for a fixed frequency and varying lengths. (b) Simulation and experimental results for fixed lengths and varying frequencies.

found to be monotonically increasing functions over a very large range of viscosity values (assuming a constant density over the range), while the A_1/A_2 ratio was found to decrease and then increase back again. This is illustrated in Fig. 6. This would mean that the proposed technique may be used for the measurement of the properties over a wide range which will be necessary during applications such as the cure monitoring of polymers.

The effect of the reference fluid is demonstrated through results obtained by simulations using the model in Fig. 7. Here, only the interfered portion is plotted. Figures 7(a) and 7(b) show that, when the relative difference between the reference and the fluids to be measured is small, the sensitivity is more. Here, when trying to measure a difference of 10 Pa s, a reference fluid of 20 Pa s would be more sensitive when compared to that of 0 Pa s. However, when a smaller range of viscosity is being measured, as shown in Figs. 7(c) and 7(d), the reference viscosity of 0 Pa s can be used. It is also observed that, by an appropriate choice of the reference fluid, the changes in the viscosity as small as 0.1 Pa s can be measured. Hence, the sensivity of the sensor is highly dependent on the choice of the reference fluid properties.

This simulation result is confirmed by the earlier discussed experimental result in Fig. 5(b) where a comparable level of sensitivity can be observed. In order to compare the results in Fig. 5(b) with Figs. 7(a) and 7(c), the amplitudes in Fig. 5(b) must be normalized with the maximum amplitude of Fig. 5(a) (reference fluid at 0 Pa s). The accuracy of measurement is about 0.02 V, and hence, the changes in the signal amplitudes in both Fig. 5(b) and Fig. 7 are measurable.

EXPERIMENTAL RESULTS USING GLYCERIN-WATER MIXTURES

For the density and viscosity measurements, solutions with different percentages of glycerin were mixed. Air was used as the reference fluid. Initially, the density was measured, assuming that the bulk modulus of the mixture was known. A 5 MHz longitudinal wave crystal was used in the measurement and the interferometric method was employed. The results along with the linear curve fit (in dashed line) with the error bars are plotted in Fig. 8 and the data is provided in Table I. Ten data sets were obtained for each concentration, using different samples from the same glycerin-water mixture, and the mean and standard deviations were plotted in Fig. 8. An average precision of approximately 1%–2% was observed in the density measurements. The density of the fluid wave calculated, for an inviscid fluid, using Eq. (3) is represented as follows:

$$\rho = (A_1/c_f)[(1-A_2)/(1+A_2)]. \tag{7}$$

Here, $A_1=3.51$ V for the experiments and the values of A_2 are provided in Table I. The density of the water-glycerin mixtures were also measured independently using standard densitometer using the classic Archimedes techniques and used here during the calibration phase of the experiment. It can be observed from Fig. 8 that the results are reasonably close to a linear fit, which is expected. The 0% glycerin (100% water) was expected to be around 1000 kg/mm^3. From the data, it was observed that the errors between the expected density values and the measured density values are higher in the low percentage of glycerin. This error is caused by (a) measurement error in the measurement of the amplitude, since the total change in the amplitude is only 0.012 V over the 100% change in the glycerin concentration and

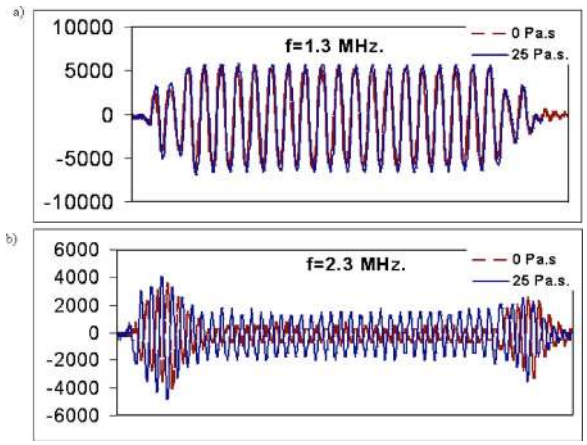

FIG. 5. (Color online) The experimental results demonstrating the effect of a null minumum region through the appropriate choice of excitation ultrasonic frequency.

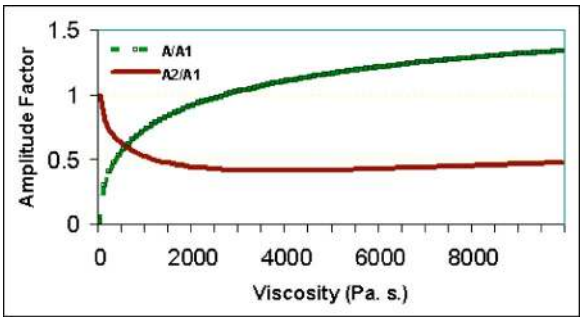

FIG. 6. (Color online) The monotonic behavior of the amplitude factor A/A_1 compared to the nonmonotonic behavior of the amplitude factor A_2/A_1.

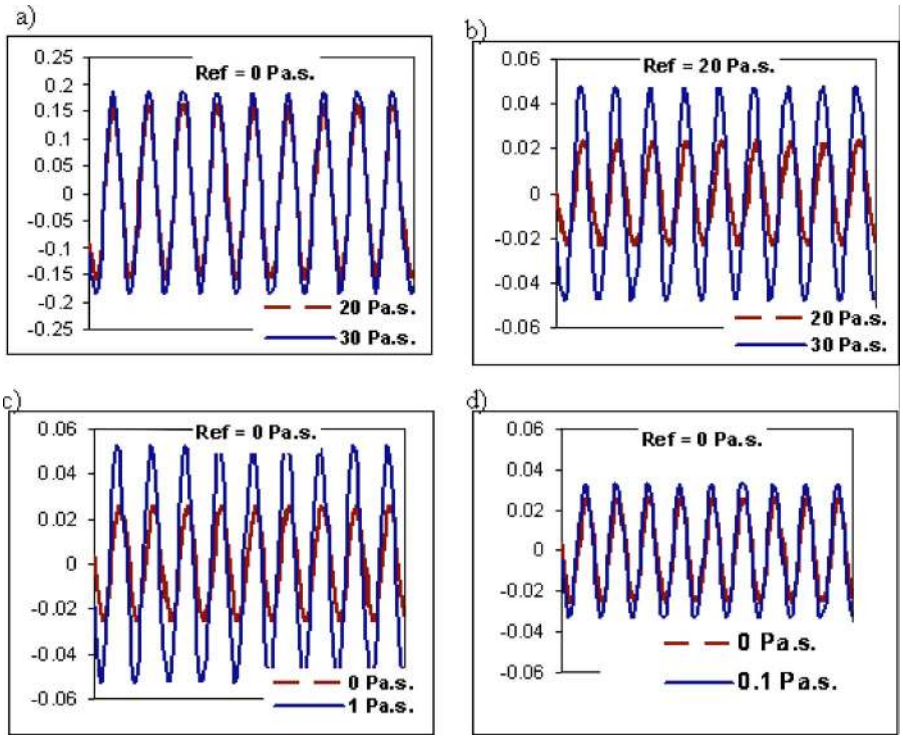

FIG. 7. (Color online) Simulation results demonstrating the appropriate choice of reference fluid [(a) and (b)] for improving sensitivity and the ability to resolve (c) 1 Pa s and (d) 0.1 Pa s changes in viscosity using the interferometer sensor.

since the measurements were carried out using an 8 bit analog to digital (A/D), and (b) the fact that since air was used as the reference for this measurement and hence for densities close to water, the measurement errors are more pronounced. In Table I, the measured maximum/minimum amplitude ratio does not behave linearly with the computed maximum/minimum density ratio, which were calculated to be higher. This can be explained by the fact that the measured amplitude change is the result of the effects of change in bulk modulus and density and the relationship is not linear. However, an improvement in the resolution of the amplitude measurement using a higher bit A/D converter will improve the robustness of the amplitude and consequently the density measurements.

The results in Fig. 9 show the viscosity measurement using a 2.25 MHz shear wave crystal with water as reference fluid and the measurement side having mixtures of water and glycerin. The corresponding data is provided in Table II. The results were compared with the predicted values, which are deduced using the manufacturer provided viscosity data for 100% glycerin as well as measurements using a Saybolt rotating viscometer on the glycerin-water mixtures (Table III). Again, the average values of ten subsequent measurements have been plotted with error bars representing measurement errors. The following procedure was adopted for computing the viscosity from measured amplitudes from the shear wave interferometric sensor:

(1) Step 1: The density for the different mixtures was measured using the longitudinal wave sensor, and using the expression density $(\rho)=2.4A+1188$, the densities were calculated.
(2) Step 2: For the null frequency used in the experiment, the analytical model was used to calculate the calibration plot between viscosity and interfered amplitude (A),

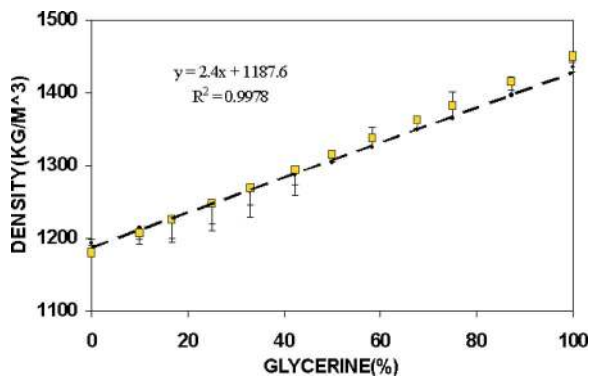

FIG. 8. (Color online) Experimental measurement of the density using longitudinal crystal interferometer technique (using the bulk modulus provided from manufacturer data) and a calibration fit for the data.

TABLE I. Experimental data using the interferometer based on longitudinal wave crystal.

Concentration (% glycerin)	Longitudinal wave amplitude A_1 (V)	Estimated velocity (m/s)	Average density (kg/m^3)	Expected density (kg/m^3)
0.00	0.327	1492	1193	1032
10.00	0.328	1464	1214	1179
16.66	0.329	1445	1227	1215
25.00	0.329	1421	1247	1240
33.00	0.330	1398	1265	1272
42.33	0.331	1371	1286	1301
50.00	0.332	1350	1304	1334
58.33	0.333	1326	1325	1344
67.66	0.334	1299	1349	1370
75.00	0.336	1278	1365	1386
87.23	0.338	1243	1397	1420
100.00	0.339	1207	1436	1450

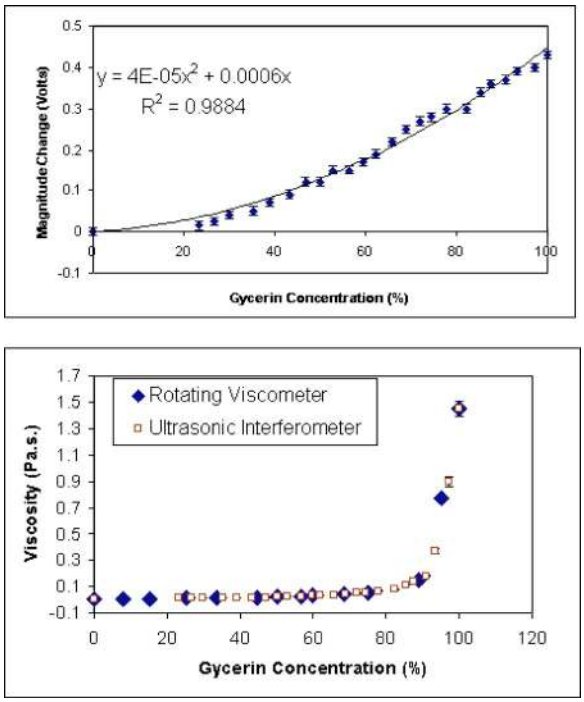

FIG. 9. (Color online) Experimental measurements of the viscosity using shear crystal interferometer technique (using the density provided by the longitudinal wave measurement calibration data in Fig. 8). (a) The magnitude changes as a function of glycerin concentrations and (b) ultrasonic measurement of viscosity and comparison with rotating viscometer results.

incorporating the density values for the glycerin-water mixtures from step 1.

(3) Step 3: The measured amplitude values from the shear wave interferometric sensors was then converted into viscosity values using the calibration plot obtained from step 2.

In Fig. 9(b), the measured shear wave data (with error bars) was compared with the rotating viscometer results. The average error in measurements was found to be approximately 4%. It can be observed that the measured results (when compared with the rotating viscometer results) are within 2% of the expected values, in up to 80% concentration of glycerin. However, there are discrepancies at higher concentrations above 80% glycerin. In this range, the viscosities of solution increases rapidly and relatively larger errors were encountered. It must also be noted that the above procedure works well, since the calibration was also performed with glycerin-water mixtures. Hence, the density could be obtained without the explicit calculation of the longitudinal wave velocity of the fluid mixtures. Only one of the parameters, either longitudinal velocity or density, can be measured using the longitudinal wave interferometric sensor described here.

The method can be successfully used for the quantification of viscosity for light liquids that are often encountered in many industrial processes. However, small errors may be expected due to the fact that Plexiglas has a relatively higher value of acoustic impedance among commonly used materials. The higher the acoustic impedance of the wedge, the higher will be the impedance mismatch and, hence, the measurements would be prone to error. The sensitivity at a lower range of viscosity is about 0.01 Pa s for a unit change in magnitude using an 8 bit analog-digital conversion. Also the size of the probe is very small and can be used for *in situ* measurements during process monitoring applications.

TABLE II. Experimental data using shear wave 2.25 MHz crystal.

Concentration (% gycerin)	Measured shear wave amplitude (V)	Estimated density (kg/m^3) using curve fit in Fig. 8.	Measured viscosity (Pa s) using model derived calibration curve
0.00	0.00	1188	0.0010
23.26	0.02	1243	0.0110
26.66	0.02	1252	0.0118
29.79	0.04	1259	0.0127
35.29	0.05	1272	0.0138
38.88	0.07	1281	0.0144
43.10	0.09	1291	0.0155
46.77	0.12	1300	0.0183
50.00	0.12	1308	0.0197
52.78	0.15	1314	0.0199
56.41	0.15	1323	0.0208
59.52	0.17	1330	0.0294
62.22	0.19	1337	0.0302
66.00	0.22	1346	0.0357
69.09	0.25	1353	0.0408
72.13	0.27	1361	0.0495
74.47	0.28	1366	0.0521
77.77	0.30	1374	0.0648
82.35	0.30	1385	0.0767
85.37	0.34	1392	0.1114
87.50	0.36	1398	0.1375
90.90	0.37	1406	0.1798
93.33	0.39	1412	0.3664
97.22	0.40	1421	0.9012
100.00	0.43	1428	1.4500

DISCUSSION

The simple plane wave reflection model for the ultrasonic interferometeric sensor agrees well with experimental

TABLE III. The measurement of the viscosity of the mixtures using Saybolt viscometer.

Concentration (% glycerin in water solution)	Viscosity(Pa s)
0.00	0.0010
8.00	0.0058
15.00	0.0093
25.00	0.0115
33.33	0.0133
44.44	0.0157
50.00	0.0197
56.52	0.0220
60.00	0.0315
68.75	0.0409
75.00	0.0557
88.88	0.1447
95.00	0.7789
100.00	1.4500

results provided that the effect of the sides of the two rods can be avoided by an appropriate choice of the geometry of the sensor. The ultrasonic interferometer method was found to be quite reliable over a wide range of viscosities when using a shear wave crystal. For experiments using the sensor on glycerin-water mixtures, the results were encouraging except at the high concentrations of glycerin. However, this method involves calibration and nulling that may create difficulties in practice. This sensor has potential for measurement of subtle changes in the fluid properties on one side of the sensor by appropriate choice of reference fluid and using the A/A_2 coefficient. Using a combination of A/A_2 and A_1/A_2 ratios, one can use this technique for a wide range of viscosity measurements from centipoise range to thousands of poises.

The ultrasonic signals were digitized using an 8 bit digitizer which limited the resolution of the measurement (depending on the range of voltage measurement, which in our experiments was ±2 V, leading to a resolution in amplitude measurement of 0.0156 V). The use of higher bit digitizers will improve the resolution. For example, a 12 bit digitization will improve the resolution of measurement to 0.001 V and a 14 bit digitizer will improve this to 0.000 244 V. This technique is sensitive to temperature gradients and it is important to ensure that the two sides of the sensor are both kept at identical temperatures. Techniques for compensating temperature changes are possible. The application of these techniques to industrial needs of high temperature process such as glass, metal forming, and normal temperature applications such as lubrication oil and soap industries can be envisaged with appropriate adaptations of the technique.

Here, the first reflected waves from both sides have interfered. Another potential modification that can be incorporated for improvement in the sensitivity of the technique would be to explore the feasibility of using the interference of the multiple reflection (reverberation) signals. By using a signal that has undergone more number of reflections at the sensor-liquid interface, caused by the reverberations, the sensitivity is expected to increase in geometrical progression of the reflection coefficient.[12]

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