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Ultrasonic measurement of viscosity: Signal processing methodologies

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ABSTRACT

This work deals with two alternative methodologies for data post-processing resulting from the ultrasonic shear-wave reflectance method used for liquid viscosity measurement. In the shear-wave reflectance method, the measurement principle is the small transference of energy to the liquid when the wave strikes a solid–liquid interface, causing a detectable change in the reflection coefficient. A measurement cell that uses mode conversion for the generation of the shear waves was employed and samples of five different substances were tested, covering a viscosity range of three orders of magnitude. Ultrasonic results were compared to the values obtained by conventional viscometry. Despite the wide range of viscosity and the different nature of the liquids, Newtonian behavior was observed with all samples at the working frequencies. This can be concluded from the coincidence between the values obtained by ultrasound and by the rotational viscometer. However, the viscosity values show an oscillating behavior when calculated for different frequencies along the band of the transducer. This oscillating behavior induces big errors when the viscosity is calculated at a single frequency, forcing the development of alternative methodologies. Two methodologies that calculate the reflection coefficient in a frequency band instead of a single frequency were analyzed, showing more accuracy and precision.

1. Introduction

The propagation of shear waves in a liquid is directly affected by its rheological properties. In general, it is established that liquids cannot sustain shear waves because the attenuation is high and the waves travel very small distances, making it difficult for directly measuring the liquid properties [1]. This problem can be circumvented by two approaches. In the first, the shear wave is transmitted through a thin layer of liquid sample trapped between two solids [2], but this technique is only useful for fluids of high viscosity. The second approach uses the reflection of the shear waves at a solid–liquid interface, where the small transference of energy to the liquid can be detected in the reflection coefficient [3].

The reflectance technique has some important advantages. The most remarkable is the ability to perform real time and in situ monitoring. It can be used with relatively light liquids, such as edible oils [4,5]. The liquids can be static, for example a polymeric resin curing in a mold cavity [6], or in movement, such as a fluid flowing in a pipe [7] or stirred as the lubricant in an engine [8]. This is possible because the sensing element is a solid surface that can be embedded in the pipe or mold wall. Although measurements can be done in a wide range of pressure and temperature, changes in these physical properties, specially temperature, during the test are problematic. This is an unsolved issue that requires additional research to allow out-of-laboratory applications.

When the shear-wave propagating in a solid reaches the solid–liquid interface a small portion of the energy is transmitted to the liquid, causing a change in the magnitude and phase of the reflection coefficient. The experimental measurement requires a calibration fluid, with air being the most used fluid because the large mismatch in the acoustic impedances generates a complete reflection. The comparison between the signals obtained with air and with sample is carried out in the frequency domain.

The measurement sensitivity depends on the acoustic mismatch between solid and liquid interface [9]. The magnitude and phase of the reflection coefficient are related to changes in the amplitude and arrival time, respectively, of the signals. The experimental determination of the reflection coefficient magnitude is a relatively easy task with viscous liquids. As the sample viscosity drops, the difference between the calibration and measurement signals is reduced. Additionally, an oscillating behavior of the reflection coefficient as a function of frequency has been observed, leading to a high uncertainty in the viscosity when calculated at a single frequency [10]. This unexpected behavior deserves a special attention.

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The reflectance method is applicable to liquids with viscosity above 0.01 Pa s [11], approximately one order of magnitude greater than that of water. The measurement of the phase is not an easy task because propagation velocity depends on temperature and the expected phase drift is small. Therefore, a small change in the temperature of the sample or in the temperature of the delay lines can generate big uncertainty in the phase [12]. The measurement method is applicably to non-Newtonian fluids where both magnitude and phase of the reflection coefficient is required. In Newtonian regime only the more stable and easy-to-measure magnitude is enough to determine viscosity.

Regarding the shear-waves generation, they can be directly generated by a transducer [13] or by the mode conversion phenomenon [14]. Despite the more complicated measurement device, including a liquid delay line, the second approach has some advantages, such as purer shear-waves and a wider range of working frequencies.

Researchers have used the reflectance method for measurement of the viscoelastic properties of lubricants [14], liquid crystals [15], viscosity standards [12,16] and a wide variety of petroleum-derived products [17–20]. An important field of application is the food industry for the study of the rheological properties of edible oils, honey, chocolates, among others [21,13]. Another interesting application, which shows the technique flexibility, is the monitoring of the cure process of concrete [22,23].

In this work, the shear-wave reflectance method was employed for the viscosity measurement of liquids and two signal processing methodologies intended to circumvent the problem of the oscillating behavior of the reflection coefficient were tested. These proposed methodologies, that use a frequency band instead of a single frequency, show more accuracy and precision. The liquid samples were three edible substances and two petroleum derivatives, covering a viscosity range of three orders of magnitude. The measurement cell was a mode-conversion device with working frequencies of 1.0 and 2.25 MHz.

2. Theoretical background

The complex reflection coefficient (R^*) of plane shear waves striking a solid–liquid interface is defined in terms of the acoustic impedance of the media, as follows [24]:

$$R^* = \frac{Z_L^* - Z_S}{Z_L^* + Z_S}, \qquad (1)$$

where Z_L^* and Z_S are the shear acoustic impedances of the liquid and of the solid, respectively. The acoustic impedance in the solid is considered a real value, because its attenuation is very small when compared with the attenuation in the liquid. Then $Z_S = \rho_S c_S$, where ρ_S is the density and c_S is the shear-wave propagation velocity in the solid. For a Newtonian liquid, the shear acoustic impedance is [25,20]:

$$Z_L^* = \sqrt{j\omega\rho_L\eta}, \qquad (2)$$

where ω is the angular frequency of the wave, ρ_L and η are the density and viscosity of the liquid, respectively, and $j = \sqrt{-1}$ is the imaginary unit.

The substitution of (2) into (1) and some algebraic manipulations lead to a relationship that provides the liquid viscosity [10]:

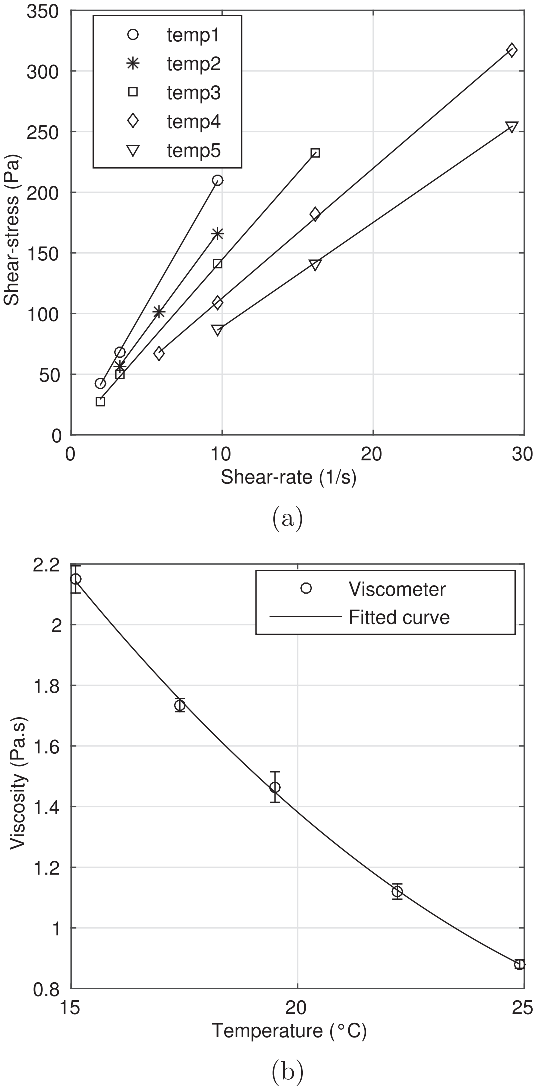
$$\eta = \frac{2Z_S^2}{\rho_L\omega}\left[\frac{1-r^2}{1+r^2+\sqrt{r^2(6-r^2)-1}}\right]^2, \qquad (3)$$

where $r = |R^*|$ is the magnitude of the complex reflection coefficient.

3. Experimental

3.1. Liquid samples

The set of samples consists of five different liquids covering a viscosity range from 0.025 to 25 Pa s. The liquids are two petroleum derivatives (mineral oil and SAE 40 engine lubricant) and three edible substances (glycerin, corn syrup and olive oil). All samples were acquired from local suppliers.



(a)

(b)

Fig. 1. Flow curves (a) and viscosity as a function of temperature (b) for the glycerin tested in this work.

The dynamic viscosity (η_0) of all samples was measured by the rotational viscometer Rheotest 2.1 (MLW, Mendigen, Germany) using the concentric cylinder configuration. Viscosity was measured in the range of temperature from 15 to 25 °C using three different shear rates. Flow curves were plotted and Newtonian behavior was observed in all cases. Finally, a quadratic polynomial was fitted in order to have a continuous function of viscosity. Fig. 1a and b show the flow curves and the viscosity as a function of temperature, respectively, as obtained in the rheometry test.

The density was measured using a pycnometer calibrated with distilled water. In the corn syrup-water mixture case, the viscosity as a function of the volume fraction of corn syrup was fitted using a cubic polynomial and the density was modeled by the rule of mixtures. Table 1 shows the physical properties of the samples.

3.2. Ultrasonic device

The measurement cell used in this research is shown in Fig. 2a and b. It is composed by a piezoelectric ceramic transducer, a water buffer, an aluminum prism with inclination of 60°, a 5-mm-thick acrylic buffer

Table 1
Physical properties of the liquid samples as a function of temperature ($15 \leqslant T \leqslant 25$ °C) or volume fraction of corn syrup ($0.7 \leqslant \xi \leqslant 1.0$ and $T = 20.0 \pm 0.3$ °C).

Sample	Density (kg/m^3)	Viscosity (Pa·s)
Glycerin	$\rho = 1183$	$\eta(T) = 0.0054T^2 – 0.346T + 6.129$
Mineral oil	$\rho = 781$	$\eta(T) = 4.476 \times 10^{-5}T^2 – 0.003T + 0.061$
Olive oil	$\rho = 882$	$\eta(T) = 1.706 \times 10^{-4}T^2 – 0.011T + 0.213$
Corn Syrup-water	$\rho(\xi) = 1498\xi + 998(1 – \xi)$	$\log_{10}\eta(\xi) = 8.76\xi^3 – 1.25\xi^2 – 7.99\xi + 1.88$

rod, and a sample chamber with a volume of 10 ml.

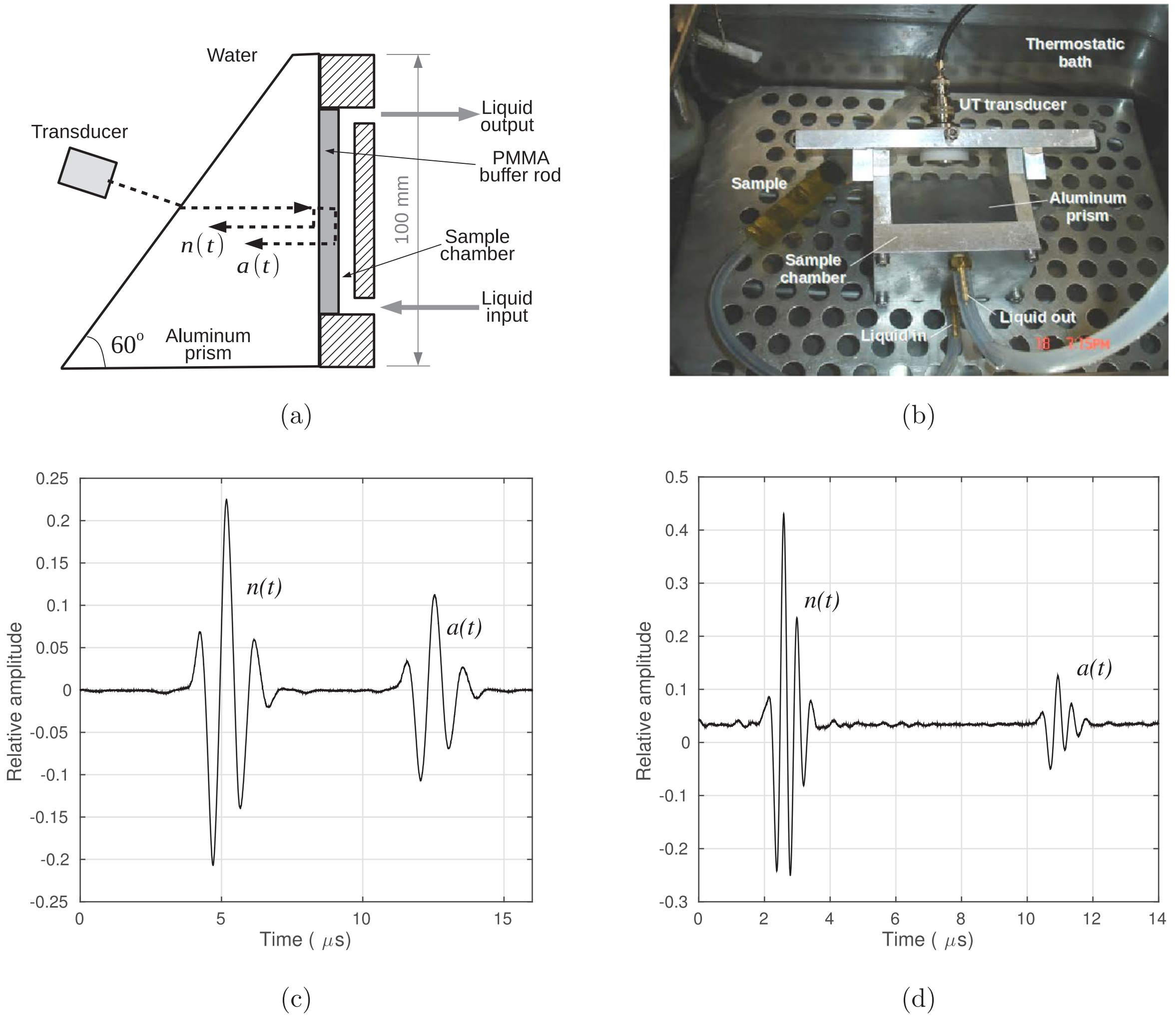
Sensitivity depends on the impedance coupling in the solid–liquid interface. The better impedance coupling, the better sensitivity because more energy is transmitted to the liquid, which results in a bigger change in the reflection coefficient [9]. Therefore, the best choice for the solid in the measurement interface is a material with both low density and low shear velocity. Acrylic was choose because its relatively low shear impedance (1.56 Mrayl), in addition to its availability and low cost. The shear acoustic impedance of the acrylic is determined by the product of density and shear velocity. Density is a well known and stable property, and the shear velocity can be experimentally determined in each test, by calculating the delay time between the $n(t)$ and $a(t)$ signals without liquid sample.

On the other hand, acrylic has high attenuation and the total conversion from longitudinal to shear waves occurs at big incidence angles. Therefore, the acrylic delay line must be the shortest possible and, consequently, the acoustic prism has to be made of a different material. Aluminum is known to have a low attenuation and an acoustic impedance for longitudinal waves (8.2 Mrayl) lower than most metals, then the impedance coupling with water (1.5 Mrayl) is appropriate.

Normalization using the signal reflected from the aluminum-acrylic interface improve accuracy because the compensation of external error sources, such as temperature gradients and diffraction, in the water and aluminum delay lines. This technique is required in order to have accurate and precise results [14].

The cell is immersed in water in a thermostatic bath. Mode conversion occurs at the oblique face of the prism, i.e., the water-aluminum interface. The angle of incidence of the longitudinal waves into the prism was 20° at 20 °C. This is above the critical angle for the longitudinal waves in the water-aluminum interface. The shear wave inside the prism propagates and reaches two interfaces normally: reference (aluminum-acrylic) and measurement (acrylic-sample) interfaces, causing the reflection of the waves $n(t)$ and $a(t)$, respectively. The reflected shear waves reach the water-aluminum interface, where they are converted into longitudinal waves. These waves reach the transducer, generating the RF signals.

Fig. 2c and d shows the signal acquired with the 1.0 MHz transducer (Panametrics V302-SU) and with the 2.25 MHz transducer (Panametrics V304-SU), respectively. Both figures present the reference $n(t)$ and



(a) (b)

(c) (d)

Fig. 2. Ultrasonic measurement device: (a) scheme, (b) image of the device inside the thermostatic bath and (c) and (d) signals obtained in the reception with the transducers of 1.0 and 2.25 MHz, respectively, showing the echoes from the aluminum-acrylic ($n(t)$) and acrylic-liquid interfaces ($a(t)$).

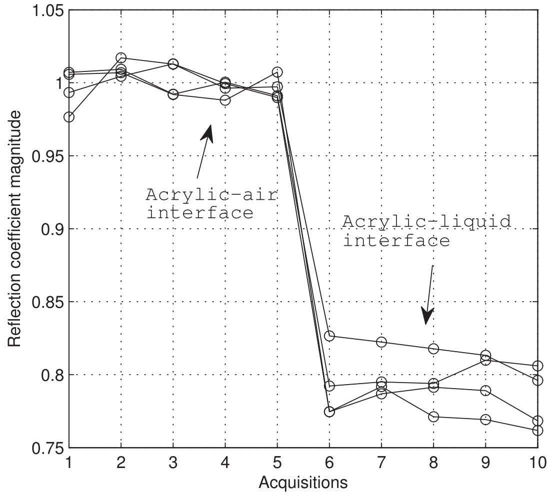


Fig. 3. Reflection coefficient magnitude of the glycerin samples calculated at the central frequency with the 1.0 MHz transducer.

measurement $a(t)$ signals.

The generation of shear waves by mode conversion has some important advantages, compared to the direct generation using shear-wave transducers. Mode conversion uses longitudinal-wave transducers, which are less expensive and are available in a wide range of frequencies. Additionally, shear-wave transducers require a solid coupling and generate a residual longitudinal wave that can induce errors. By the authors experience, mode conversion generates purer shear waves in a wider range of frequencies, leading to better results than the direct generation by means of shear-wave transducers [5].

An ultrasonic pulser-receiver (Panametrics 5077PR) is used to drive the transducers with an electric square wave pulse of high voltage (200 or 300 V) and variable width (0.1 to 10 MHz). The pulse width is adjusted to obtain the maximum amplitude of the signal. The signal received is amplified by the broadband (1 kHz to 35 MHz) instrumentation amplifier. Despite the long distance traveled by the wave, the gain required is less than 20 dB. The signals are digitalized using the oscilloscope (Keysight DSOX2022A) and transferred to a computer for storage and later processing using Matlab.

3.3. Reflection coefficient measurement

Three methodologies for the calculation of the reflection coefficient magnitude were explored. All the three methodologies work in the frequency domain. The idea is to study the behavior of the measurement quantities as a function of frequency and to improve accuracy using all the information contained in a frequency band.

The magnitude of the reflection coefficient is obtained by referring, in the frequency domain, the signal from the acrylic-liquid interface to the one from the acrylic-air interface, recorded in a previous experiment. When there is air in the sample chamber, a total reflection is obtained and the magnitude is 1. To reduce the problems related to equipment drift between these two measurements, the method employs normalization with respect to the reflected signal at the aluminum-acrylic interface. Then, the magnitude of the reflection coefficient as a function of frequency is obtained by:

$$r(f) = \frac{|A_{liq}(f)||N_{liq}(f)|^{-1}}{|A_{air}(f)||N_{air}(f)|^{-1}}, \tag{4}$$

where $N(f)$ and $A(f)$ denote the Fourier transforms of the pulses reflected from the reference $n(t)$ and measurement $a(t)$ interfaces, respectively, and f is the frequency. The viscosity value at frequency f can be calculated by substitution of $r(f)$ in (3).

The evaluated methodologies use the $r(f)$ data in order to generate a $\hat{r}$ value which leads to a more accurate and stable viscosity.

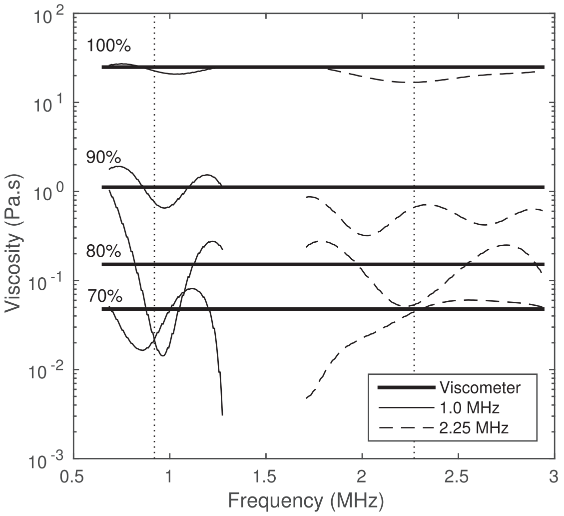


Fig. 4. Viscosity as a function of frequency $\eta(f)$ for the corn syrup-water mixtures (70%, 80% and 90%) and pure corn syrup (100%). The central frequency of the transducers is indicated with a vertical dotted line. The temperature of measurements was 22.3 ± 0.8 °C.

Table 2
Dynamic viscosity (Pa·s) of corn-syrup water mixtures measured by ultrasound at working frequencies of 1.0 and 2.25 MHz, using the central frequency (CF) and average frequency (AF) methods. The value in parenthesis is the percentage deviation with respect to the viscometer.

Method	70%	80%	90%	100%
		1.0 MHz transducer		
CF[a]	0.0407 (15.1%)	0.0116 (89.4%)	0.6575 (41.1%)	21.1783 (15.0%)
AF[b]	0.0408 (14.8%)	0.2059 (35.6%)	1.2428 (11.4%)	23.6264 (5.2%)
		2.25 MHz transducer		
CF[a]	0.0457 (4.7%)	0.0547 (63.9%)	0.6783 (39.2%)	16.8448 (32.4%)
AF[b]	0.0406 (15.3%)	0.1566 (3.2%)	0.5483 (50.9%)	20.0174 (19.7%)

[a] f_c is 0.92 and 2.27 MHz for the 1.0 and 2.25 MHz transducers, respectively.
[b] −3 dB frequency band.

3.3.1. Central frequency method (CF)

The central frequency method (CF) consist on the use of the reflection coefficient magnitude at a single frequency, preferably the frequency with the highest signal-to-noise ratio, that is the transducer central frequency (point of maximum amplitude):

$$\hat{r} = r(f_c) \tag{5}$$

is the frequency of maximum amplitude of signal $N(t)$. This is the most commonly found method in literature.

3.3.2. Average in a frequency band (AF)

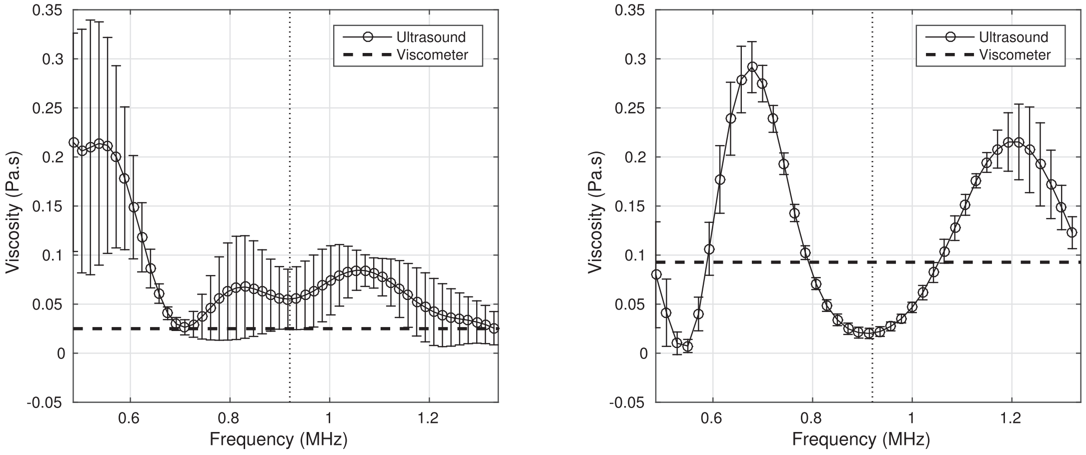
This method consists of calculating an average value in a frequency band:

$$\hat{r} = \frac{1}{f_b - f_a}\int_{f_a}^{f_b} r(f)df. \tag{6}$$

The values f_a and f_b are calculated in order to use the frequencies of highest amplitude, where the best signal-to-noise ratio is obtained. In this work a band of −3 dB was used, because it provided the best results among the tested options (−3 and −6 dB).

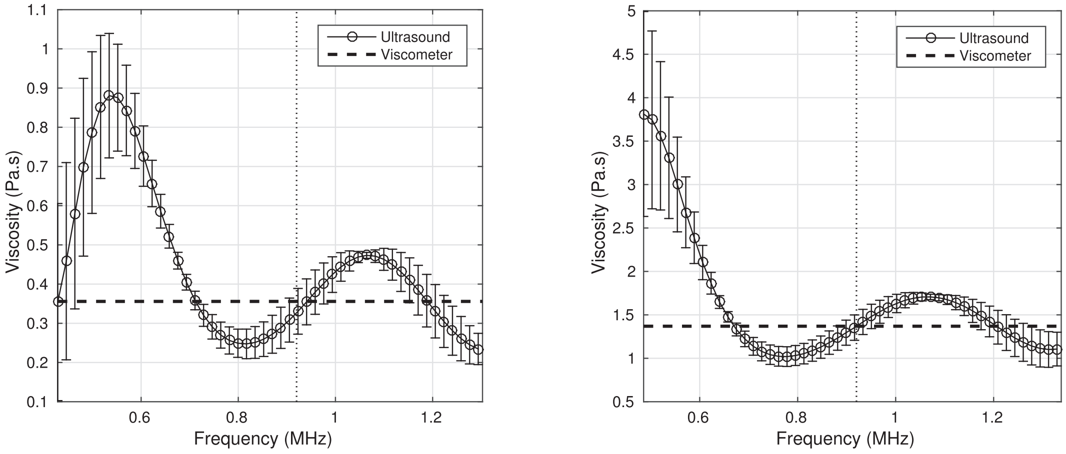
3.3.3. Integral ratio in a frequency band (IR)

This signal processing technique also calculates the magnitude at a frequency band instead of the single center frequency. The following



Mineral oil at $18.3 \pm 0.1°\mathrm{C}$

Olive oil at $15.0 \pm 0.1°\mathrm{C}$



SAE 40 at $20.1 \pm 0.2°\mathrm{C}$

Glycerin at $20.0 \pm 0.2°\mathrm{C}$

Fig. 5. Viscosity results for mineral oil, olive oil, SAE 40 and glycerin as a function of frequency (−3 dB band) compared to the values obtained with the rotational viscometer. The central frequency of the transducers is indicated with a vertical dotted line. In the CF method the viscosity is calculated at the central frequency and in the AF method the final viscosity is the mean value of all viscosity values in the −3 dB band.

equation was used:

$$\hat{r} = \frac{\int_{f_a}^{f_b} |A_{liq}(f)||N_{liq}(f)|^{-1}df}{\int_{f_a}^{f_b} |A_{air}(f)||N_{air}(f)|^{-1}df}, \qquad (7)$$

where $f_a = (1-\alpha)f_c$ and $f_b = (1+\alpha)f_c$. f_a and f_b define a frequency band centered in f_c and $2\alpha f_c$ wide. Parameter α ($0 \leqslant \alpha \leq 1$) defines the frequency bandwidth. For $\alpha = 0$, r is calculated by (5).

In Eq. (7), numerator and denominator represent the area under the curve of the normalized amplitude ($|A(f)|/|N(f)|$) for the cases with liquid sample and with air in the sample chamber, respectively. The magnitude was calculated by the quotient of those two areas. This technique is less sensitive to the random noise induced in the system. A similar approach was used by some authors for the measurement of liquid density by ultrasound [26].

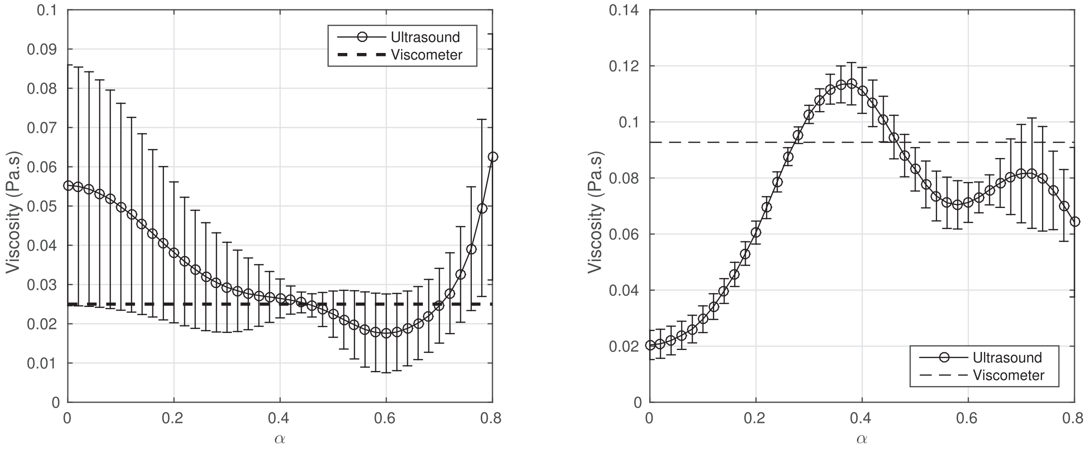
Fig. 3 shows the reflection coefficient magnitude as a function of frequency obtained with the four ultrasonic tests with glycerin. Each test consists of five acquisitions with air (reference fluid) followed by another five acquisitions with the liquid sample. This set of ten acquisitions is considered a single measurement. The reflection coefficient is obtained by normalization, dividing all values by the mean of the first five, and the final value is obtained by calculating the mean value of the last five. The time between acquisitions is 30 s, approximately.

4. Results

Fig. 4 shows the dynamic viscosity of the corn syrup-water mixtures as a function of frequency. Ultrasonic results were plotted in the frequency band of −3 dB, for a 1.0 and a 2.25 MHz transducer, and compared to the viscometer results. The central frequency of each transducer is marked with a vertical dotted line. An oscillating viscosity value along the frequency band of each transducer is observed. The oscillations occur around the viscometer value, specially for the 1.0 MHz transducer. But some averaging method might lead to more accurate values.

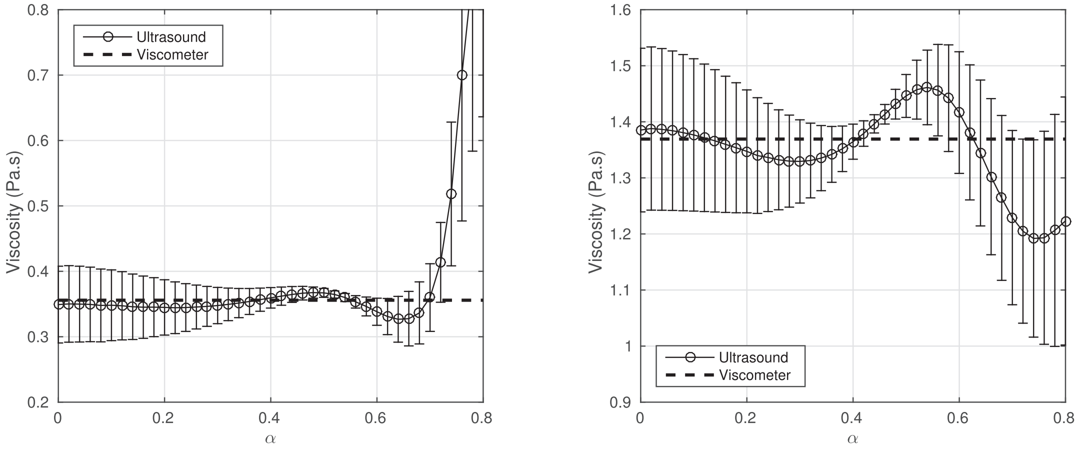
Table 2 summarizes the viscosity results obtained using the CF and AF methodologies. It was observed a reduction in the maximum percentage deviation (δ_η) from 89.4% in the CF case to 35.6% in the AF case, with the 1.0 MHz transducer. Similarly, from 63.9% in the CF case to 50.9% in the AF case for the 2.25 MHz transducer. These results show the AF method seems to be a better option for the determination of the dynamic viscosity. However, it is important to consider that only one measurement was carried out with each sample.

Fig. 5 shows the viscosity as a function of frequency in the corresponding −3 dB band for mineral oil, olive oil, SAE 40 lubricant and glycerin, using a working frequency of 1.0 MHz. Each sample was tested four times and the viscosity as a function of frequency is presented in the form of mean and standard deviation. Results are compared to those



Mineral oil at 18.3 ± 0.1°C

Olive oil at 15.0 ± 0.1°C



SAE 40 at 20.1 ± 0.2°C

Glycerin at 20.0 ± 0.2°C

Fig. 6. Viscosity results for glycerin, mineral oil and olive oil as a function of the parameter α.

Table 3
Dynamic viscosity (Pa·s) measured by ultrasound at working frequencies of 1.0 MHz, using the central frequency (CF), average frequency (AF) and integral ratio (IR) methods. The value in parenthesis is the percentage deviation with respect to the viscometer.

Method	Mineral oil	Olive oil	SAE 40	Glycerine
CF[a]	0.0552 ± 0.0304 (120.8%)	0.0203 ± 0.0052 (78.1%)	0.3424 ± 0.0587 (3.8%)	1.3531 ± 0.1460 (1.2%)
AF[b]	0.0595 ± 0.0234 (138.0%)	0.0109 ± 0.0044 (17.5%)	0.3619 ± 0.0323 (1.7%)	1.3301 ± 0.0860 (2.9%)
IR[c]	0.0254 ± 0.0026 (1.8%)	0.0953 ± 0.0030 (2.8%)	0.3647 ± 0.0055 (2.5%)	1.3963 ± 0.0163 (2.0%)

[a] f_c is 0.92 MHz for the 1.0 MHz transducer.
[b] −3 dB frequency band.
[c] $\alpha = 0.44$ for mineral oil and glycerin, $\alpha = 0.52$ for SAE 40 and $\alpha = 0.16$ for olive oil.

obtained with the rotational viscometer.

Fig. 6 shows the viscosity as a function of the parameter α for the mineral oil, olive oil, SAE 40 lubricant and glycerin samples. For three liquids (mineral oil, SAE 40 and glycerin), there is an α value where the minimum standard deviation occurs. The viscosity calculated at these α values reproduce the viscometer values with a percentage deviation less than 2.5%.

The viscosity calculated with the three evaluated methodologies is presented in Table 3. Results are presented in the form of mean and standard deviation of the four tests and the percentage deviation with respect to the viscometer values reported in parenthesis. A consistent reduction is observed in the percentage deviation when the IR methodology is used, with maximum values of 120.8% and 138.0% in the CF and AF cases, respectively, to 20.6% in the IR case.

5. Discussion

The ultrasonic viscosity oscillates around the viscometer value using the 1.0 MHz transducer and around a lower value when the 2.25 MHz transducer is used. As the operation frequency of the transducer rises, the dynamic behavior of the liquid becomes viscoelastic (the viscosity does not match that obtained by the rotational viscometer, Fig. 3). Keeping a constant frequency, as the liquid gets more viscous, its behavior becomes more viscoelastic. Under the exposed conditions (higher frequency and higher viscosity), the liquids become undesirably viscoelastic. In order to avoid that, the frequency of the transducer should be kept within the 1 MHz limit (considering viscosities of up to 25 Pa s, as those measured here). On the other hand, the frequency cannot be so small because the variation of the echo amplitudes measured with liquid and air samples could be undetectable.

Theoretically, this Newtonian behavior can be established qualitatively by means of the simple Maxwell model. Assuming a harmonic excitation, the liquid viscosity depends on the frequency of the shear wave and can be given by $\eta(\omega) = \eta_0/(1 + \omega^2\tau_m^2)$ [27], were η_0 is the dynamic viscosity at low frequencies, ω is the angular frequency and τ_m is the Maxwell relaxation time, defined by $\tau_m = \eta_0/G_\infty$, where G_∞ is the instantaneous shear elastic modulus. Thus, when $\omega\tau_m \ll 1$, the liquid is characterized as a viscous medium, that is, the viscosity does not depend on the shear strain rate. In this work, the maximum value of the normalized frequency $\omega\tau_m$ was approximately one order of magnitude smaller than 1. This was determined using the maximum measured viscosity ($\eta_0 = 25\,\mathrm{Pa\,s}$), the operation frequency of 1.0 MHz, and $G_\infty = 10^9$ Pa. For most liquids G_∞ is found to be about 10^9 Pa, giving τ_m (in s) $\approx 10^{-9}\eta_0$ (η_0 in Pa s) [1]. This should be enough to assure Newtonian behavior, much needed for the ultrasound technique applied in this work to be valid.

An important finding using the ultrasonic measurement of viscosity is the oscillation around the expected viscosity value, which is constant for a liquid assumed to be Newtonian. The oscillation can be attributed to the level of inherent noise. The oscillation decreases as the viscosity increases (Fig. 3). The greater the viscosity of the liquid, the greater is the transmission of energy (shear waves) into the medium, so the amplitude of the echo reflected at the solid–liquid interface will be smaller. This results in a larger difference of amplitude when compared to the echo reflecting from the solid-air interface, reducing the effect of noise.

Higuti and Adamowski [26] showed that there are oscillations in the computed density value as a function of frequency and that the density calculation is strongly influenced by the signal-to-noise ratio (SNR). In practice, the noise does not affect all frequencies in the same way. For this reason, they developed the energy method that uses a band of frequencies for the calculation of the reflection coefficient. A similar approach is used here to obtain the liquid viscosity from the reflection coefficient magnitude which is calculated using the signals from the interface with air and liquid sample. Calculating the magnitude of the reflection coefficient at a frequency band instead of at a single central frequency reduces the effect of the inherent noise.

6. Conclusions

The shear-wave reflectance method for liquid viscosity measurement was implemented in this work. Samples of five different substances were tested and the viscosity results were compared to values provided by the rotational viscometer. Three different methodologies for determining the viscosity from the acquired signals were tested.

In theory, the tested liquids exhibit Newtonian behavior at the working frequencies employed in this work. Viscosity should have a constant value or slightly decrease with frequency. However, oscillating values along the −3 dB band of the transducer were observed. This is influenced by the SNR. As the SNR is improved, the oscillations decrease, as observed in the liquids of higher viscosity. In this case, the transmission is higher, the reflection is smaller, and the difference between the reflected amplitude in air and in liquid is larger, minimizing the effect of noise.

The intention of testing different methodologies for the viscosity calculation is to circumvent the effect of the oscillating results. The viscosity calculated at a certain frequency could strongly vary. Therefore, two alternative methods, where the reflection coefficient magnitude is calculated in a frequency band centered in f_c, were proposed. The idea behind these methods is to compensate for the oscillations, taking into account that they occur around the expected value of viscosity.

A matter of fact, ultrasonic shear-wave reflectometry is more suitable for liquids of high viscosity. However, this work attempts to use the technique with liquids of relatively low viscosity, trying to expand the capabilities of the technique by exploring different signal processing methodologies.

Even though the intention in this work was the measurement of viscosity in Newtonian regime, the technique is suitable for non-Newtonian liquids too. It have been reported in literature tests carried out with polymeric resins, liquid metals, bitumen, among others. Achievements obtained with Newtonian liquids can be useful in all cases.

A fundamental issue to be solve is the lost of the SNR when viscosity decreases. Some ideas will be explored in the future, such as the development of transducers with a higher transmission power, probably changing the excitation voltage or the signal waveform. Another option is to concentrate the shear waves in a smaller area, using some focalization approach.

Acknowledgments

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