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ACOUSTIC MONITORING OF VISCOUS FLUIDS

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ABSTRACT

The acoustic signature is essential in the characterization of liquids and the non-destructive evaluation of microstructural damages in materials. It closely relates to the sample's molecular structure, providing insight into its material properties. Studies have reported the measurement of B/A for the characterization of industrial materials ranging from geophysics to biological fluids such as silicon oil and gelatin. However, none of the studies has focused on investigating B/A for quality monitoring of viscous fluids such as syrups. As viscosity is a critical factor for these fluids' shelf-life, processing, and packaging, it is vital to monitor their quality during production. However, most current techniques rely only on the laboratory-based rheological method for quality monitoring and assessment. Thus, this paper aims to provide a non-destructive, real-time monitoring tool to monitor the viscosity of honey using a nonlinear acoustical approach based on the Second harmonic generation method (SHGM). A simultaneous study is performed to obtain the linear acoustical parameter, such as speed of sound and attenuation, for a similar setup. Both results are compared to see the viscosity correlation with each parameter. This research will help the food industry provide a fast and efficient way of inspecting consumable food products.

Keywords: *sugar syrup, ultrasonic monitoring*

1. INTRODUCTION

Viscous solutions such as sugar syrup and honey are used in a large variety of food products and in sweetened beverages. Rheological and structural attributes for these fluids, such as viscosity and texture, become key criteria for the quality control of these products. In addition, in-line monitoring is vital in controlling the shelf life during production, processing, and packaging [1,2]. However, most current techniques rely only on the laboratory-based methods for characterization and assessment [3,4] of such fluids.
Recently, non-destructive methods, including X-Ray, optical, spectroscopic, and ultrasonic techniques, have been applied to characterize various kinds of food products [5–7]. However, only a few studies deal with the characterization of viscous fluids such as honey [8,9]. Nevertheless, ultrasound is one of the widely used non-destructive inspection tools in the rheological characterization and monitoring of various kinds of liquid, including vegetable oil [10], organic liquids [11,12], biological fluids [13] and colloidal suspension [14]. However, only a few studies reported its application for quality monitoring of highly viscous food products such as honey. One such recent study reports the shift in the received nominal frequency as the ultrasound wave propagates through the honey sample [8]. It relates the FFT with the texture properties of honey. However, the characterization is specific to each variety of honey. In another investigation, the characterization is obtained based on ultrasonic velocity and attenuation. However, the technique is limited to only laboratory use [9]. Thus, a real-time, non-destructive monitoring tool is essential for the quality inspection of viscous fluids.
As the finite amplitude high-pressure ultrasonic wave propagates through the fluid, it gets distorted in time and space due to the non-linear effects. As a result, it produces higher harmonics in the received signal spectrum.

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The amplitude of these harmonic terms is closely related to the molecular and structural dynamics of the medium and, therefore, can be related to the non-linearity parameter (β). A considerable amount of literature has been published on the determination of β for a variety of liquids [15–19]. One recent study shows the temperature dependence of the non-linear acoustic harmonics in water [20].

Thus, in this work, a linear and non-linear acoustical investigation is carried out to characterize three varieties of commercially available honey samples, namely Dennen, Lavendel, and Paardenbloem. In addition, the correlation of the relative non-linearity parameter concerning viscosity is investigated by analyzing β for a range of concentrations of sucrose solutions. This preliminary research will help the food industry provide a fast and efficient way of inspecting consumable food products.

2. MATERIAL AND METHODS

2.1 Theory

The acoustic non-linearity of a liquid is based on the relationship of the pressure and density for the medium as in related to its fundamental and the second-order harmonic component as in Eqn. (1) where p and ρ are the pressure and density respectively and A, B represents the constants for a medium.

$$p = p_0 + A\frac{\rho - \rho_0}{\rho_0} + \frac{B}{2}(\frac{\rho - \rho_0}{\rho_0})^2 \tag{1}$$

The phase velocity can further be related to the particle velocity (u) as in Eqn. (2). Without dissipation, the plane waves attain infinite slope wavefront reaching the continuity distance(l) as defined in Eqn. (3).

$$c = c_0 + [\frac{B}{2A} + 1]u \tag{2}$$

$$l = \rho_0 c_0^3 2[\frac{B}{2A} + 1]\pi P_1(0) f^{-1} \tag{3}$$

where, $P_1(0)$ and f represent the source signal's peak acoustic pressure and frequency, respectively. Based on the above equations and power series expansion, the relation between the second harmonic and non-linearity parameter is obtained and given by Eqn. (4) [21].

$$\beta = \frac{B}{A} + 2 = \frac{2\rho_0 c_0^3}{\pi f}\frac{P_2(x)}{x P_1(0)^2} \tag{4}$$

Here, $P_2(x)$ represents the pressure of the second harmonic at a distance x from the source. Thus, based on the above relation, a graph representing the slope of the $P_2(x)/P_1(0)^2$ v/s x is directly proportional to β.

Therefore, in the current study, a relation between the non-linearity ratio ($P_2(x)/P_1(0)^2$) is plotted for the axial distance between the transducers (x) for different kinds of viscous fluids.

2.2 Experiment

2.3 Linear measurements

The immersion ultrasonic transducers with a center frequency of 1MHz and element diameter of 0.5″ are used as transmitters and receivers in all the linear experiments. The ultrasonic burst of 1MHz and 20 cycles are generated using the 30MHz synthesized function wave generator. The ultrasonic waves are transmitted through the fluid placed in a container and received at the other end using a transducer. The received signal is analyzed and recorded using the LeCroy oscilloscope (64Xi) with a sampling rate of 25MHz. SH-2 hot plate stirrer is used to stir and heat the fluid. An omega HH800 thermocouple is used to record the temperature of the fluid. The complete setup is shown in Fig. 1.

2.4 Non-linear measurements

The experimental setup is shown in Fig. 2. A piezoelectric transducer with a center frequency of 2.25 MHz and an element diameter of 0.375″ with a focal length of 1.35″ (in water) is used for the emitting ultrasound pulses. These pressure waves propagate through the liquid and are measured by a calibrated needle hydrophone with a sensor diameter of 1mm (Precision Acoustics HP series) placed along the axis of the transducer. The generation of the high amplitude burst signal is carried out by the RITEC Advanced Measurement System (RAM-5000). The RITEC system provides the ability to generate high-power RF tone bursts with the flexibility to control the input gain of up to 5kW. The burst input comprising of a sinusoidal signal with a center frequency of 2.25MHz and a burst of 20 cycles is used in the experiments. The distance between the source transducer and needle hydrophone is varied from 28mm to 90mm using a mechanical arm and recorded using the Polar C-Scanner with an average of 100 cycles. The time domain signals are then processed using signal processing software to obtain FFT spectrum. The pressure value is obtained from the spectrum for the

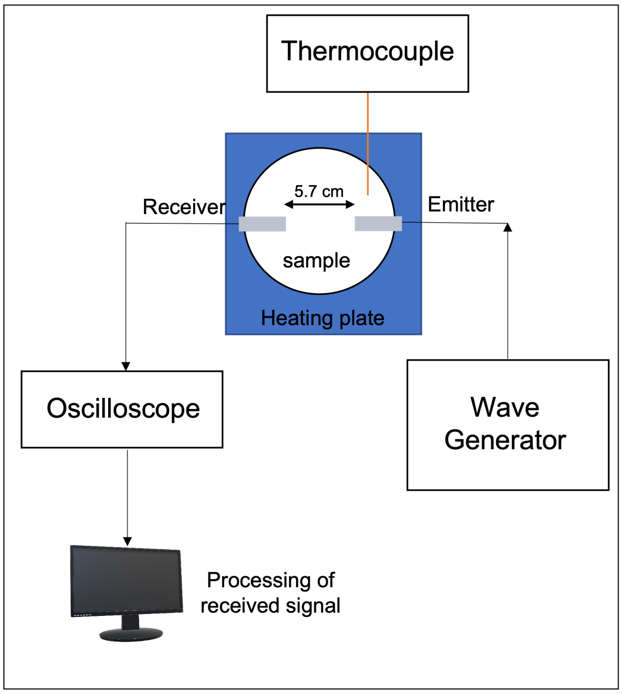

Figure 1. Experimental setup for linear investigation.

fundamental frequency (P_1) and the second (P_2). The ratio of the pressure amplitude P_2 and P_1^2 is calculated and plotted as a function of axial distance x between the ultrasonic transmitter and receiver. This curve's relative slope is analyzed to relate it to the non-linearity parameter. The results are further compared for a range of viscous solutions.

3. RESULTS AND DISCUSSION

3.1 Linear results

The measurements are recorded in transmission mode with three different honey samples, namely Dennen, Lavendel, and Paardenbloem. The honey temperature is varied from 20°C to 40°C to change its viscosity. A sinusoidal input of 20 cycles with a frequency of 1MHz is emitted. The ultrasonic transducer waves propagate through the sample and are received by another transducer of the same center frequency placed in-line at 5.7cm.
The speed of sound is calculated based on the time of arrival of the first peak of transmitted (t_{trans}) as well as received (t_{rec}) sinusoidal burst as given by Eqn. (5),

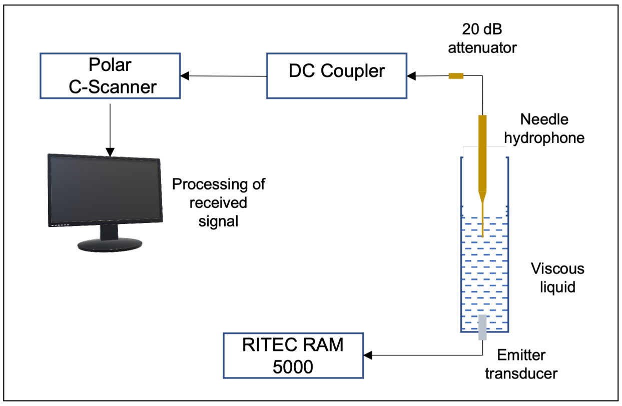

Figure 2. Experimental setup for non-linear investigation.

$$c = \frac{\text{distance between transducers}}{(t_{rec} - t_{trans})} \tag{5}$$

The obtained speed of sound for each variety of honey is tabulated in Tab. 1.

Table 1. Speed of sound for different variety of honey.

Type of honey	Speed of sound (m/s)
Dennen	5300
Lavenden	4005
Paardenbloem	4080

As the speed of sound varies due to the difference in the fluid properties for each sample, it acts as a characterizing criterion to differentiate between different liquids. However, it fails to categorize the viscous properties of honey as the temperature of honey is varied by heating.
Further, the attenuation coefficient is calculated by heating all samples and observing the amplitude of the input signal (A_{trans}) and the received output (A_{rec})Eqn. (6) after each 1°C. Fig. 3 shows the temperature effect in the attenuation coefficient (α) for different variety of honey sample. The value of α is normalized over distance. The results show a growing trend of attenuation for Paardenbloem honey as the viscosity increases from 20°C to 40°C. However, for the other variety of honey, the increase in attenuation is

not very prominent. Thus, it is concluded that the attenuation parameter is specific for each kind of honey.

$$\alpha = 10log_{10}(\frac{A_{rec}}{A_{trans}})^2 \tag{6}$$

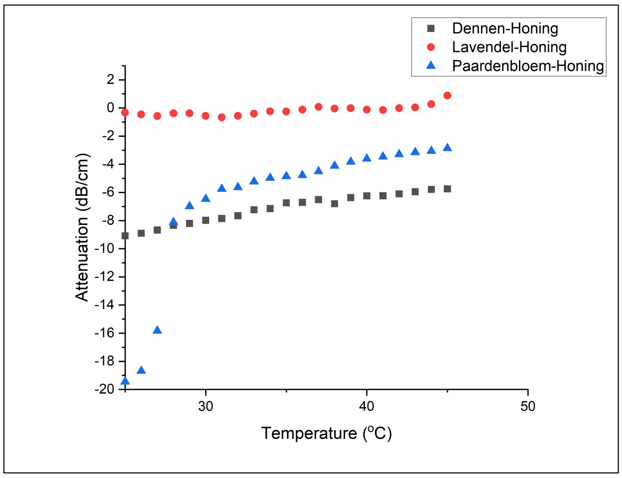

Figure 3. Normalized attenuation coefficient vs temperature for different variety of honey samples.

3.2 Non-linear results

The non-linear experiments use RITEC RAM 5000, generating very high input power. Three different sucrose solutions of known viscosity are prepared to obtain the relation between the non-linearity parameter and viscosity. This is achieved by mixing 10% , 15%, and 20% w/w of sugar into de-mineralized water [22] and continuously stirring it to dissolve all the particles uniformly.

Fig. 4(after processing with Hanning window) and Fig. 5 show an example of the measured waveform and its frequency spectrum, respectively. In the example, the hydrophone acquires the time domain signal at a distance of 70mm from the emitter. The emission frequency for the experiment is 2.25MHz. Fig. 5 shows the presence of higher harmonics generated due to non-linearity in the liquid. The fundamental and second harmonic at frequencies of 2.25 MHz and 4.5MHz, respectively, are extracted for further analysis.

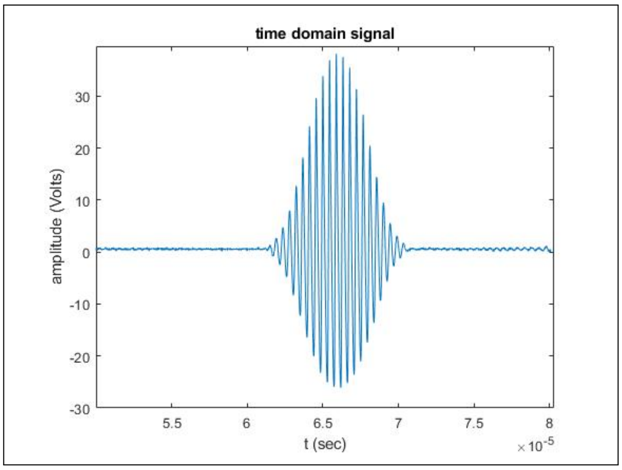

Figure 4. Time signal obtained for obtained for 15% w/w sugar solution at a temperature of $20°C$ with a distance of 70mm from the source.

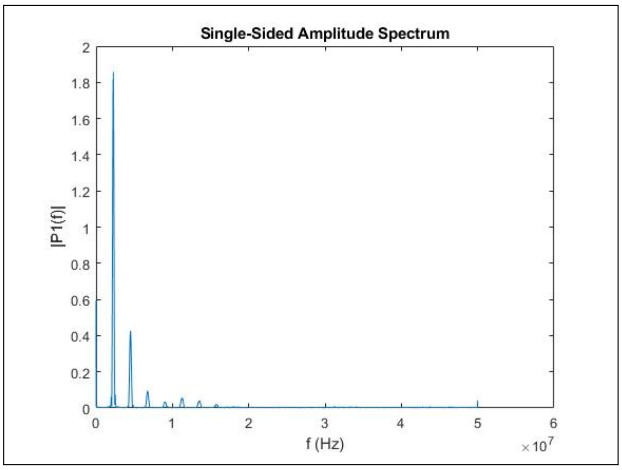

Figure 5. Frequency spectra obtained for the received signal shown in Fig. 4.

Fig. 6 compares the second harmonic with the axial distance between the source and the receiver hydrophone. It is observed from the plot that the pressure in the second harmonic for a viscous solution does not show a steep rise when compared with pure water. Also, the non-linearity effects occur at a much shorter axial distance as the viscosity of the medium increases. Another observation is the appearance of the attenuation peak (the point at which attenuation dominates on the non-linear effects) at an earlier axial distance with the increase in viscosity. Thus, the attenuation peak for 20% w/w sugar solution is observed first in the plot compared to water and lower viscous solution.

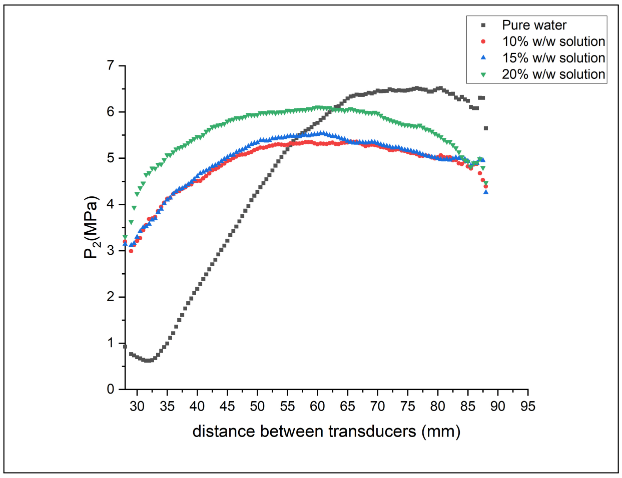

Figure 6. Measured second harmonic P_2 with axial distance for viscous solution as compared to pure water.

Fig. 7 shows the measured changes in the pressure harmonic ratio P_2/P_1^2 with the axial distance from 28mm to 90mm. For the 2.25MHz immersion transducer with element diameter of 0.375″, the near field distance (N) for water is found out to be 34.29mm using the Eqn. (7).

$$N = \frac{d^2 f}{4v} \tag{7}$$

In Eqn. (7) d,f,v depicts the element diameter, frequency, material velocity respectively.

In order to avoid near-field effects, the normalized slope which is linearly related to β is estimated only in the far field region for each sample. The relative values obtained as compared with pure water for the viscosity of 1.26, 1.31 and 1.96 mPa.s of sucrose solution is found out to be for 1.3207, 1.31, 0.94 respectively. It is noted from the results that the relative β parameter decreases with the increase in the viscosity.

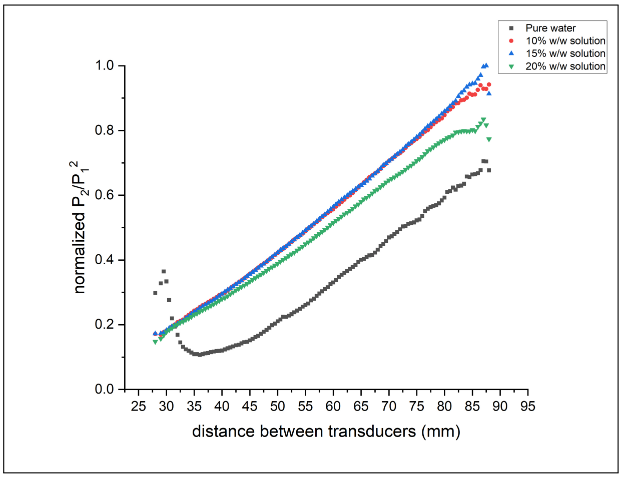

Figure 7. Non-linearity ratio for a variety of viscous sucrose solutions.

A further investigation on non-linearity as applied to consumable viscous products is done with a sample of lavender honey. The variation in temperature from 37°C to 40°C for this variety of honey causes a viscosity change of 6.86 mPa.s to 5.421 mPa.s. Fig. 7 shows the difference in slopes of the non-linear ratio for each temperature, depicting the technique's efficiency for its use in real-time inspection of viscous food products.

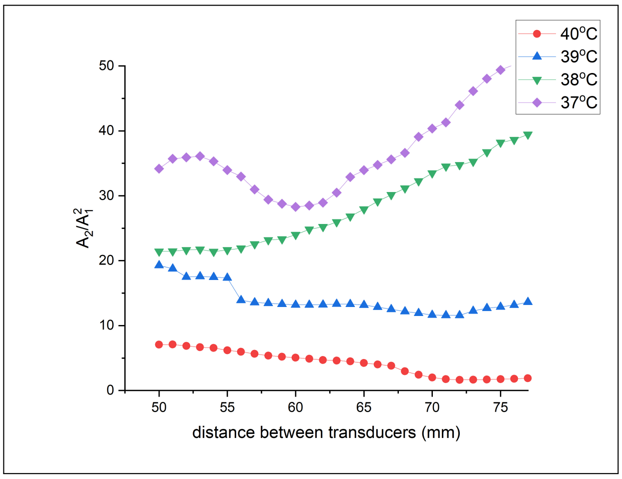

Figure 8. Ratio profile of amplitude $\frac{A_2}{A_1^2}$ with axial distance between source to receiver transducer for different temperature value of lavendum honey.

4. CONCLUSION

Speed of sound and attenuation measurements are found to be case specific as applied to different varieties of honey. However, the non-linearity parameter is an efficient way of characterizing different viscous liquids. A significant amount of variation is observed in β for a slight change in the viscosity of the medium showing the high sensitivity of this technique for characterization.

5. ACKNOWLEDGMENTS

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