Evaluation of measurement uncertainty of speed of sound in soybean oil

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Abstract. Ultrasound can be used to measure several physical and acoustic properties of oils and fuels. However, most studies do not introduce an assessment of measurement uncertainty. It is well known that uncertainty assessment is important to ensure the quality of measurement results. This work presents the evaluation of the factors that influence the measurement uncertainty of the speed of sound in soybean oil. A detailed uncertainty budget of measurement was shown. The speed of sound in soybean oil was measured by the pulse-echo technique (@ 1 MHz), and the result was 1483.4 m·s⁻¹ ± 2.8 m·s⁻¹ (k = 1.96; p = 0.95).

Keywords. Measurement uncertainty, ultrasound, speed of sound, metrology.

1. Introduction
In the industrial sector, the characterization of liquids is a fundamental activity for the quality control of raw materials, products, and residues. Ultrasonic methods for analysis have been widely used in the characterization of liquids as they typically are non-destructive, robust, accurate, and low-cost [1]. Ultrasound can be used to measure several physical and acoustic properties of oils and fuels [2][3][4][5][6]. The commonly measured acoustic parameters are the speed of sound and attenuation coefficient [7].

The literature discloses works that determined these parameters for some vegetable oils, varying the ultrasonic frequency [8][9][10] and temperature [11] within the interesting purpose to link such parameters with viscosity, density, rheology, triglycerides composition, among other properties. However, most studies do not introduce an assessment of measurement uncertainty according to the Guide to the Expression of Uncertainty in Measurement (GUM) [12].

In both industry and research, decision-making is based on experimental analysis results. Due to the fast development of analytical methodologies, it is important to ensure the quality of measurement results. In this sense, the importance of metrology and its introduction in the experimental analysis is becoming more prominent [13][14] [15]. The quantitative indication of the quality of the measurement result is given by the measurement uncertainty [12].

Reliable and traceable measurements directly impact product quality. Furthermore, analyses of factors that influence uncertainty allow the identification of inappropriate instrumentations, the reduction of incorrect decisions, and waste decreasing.
Thus, this work aims to evidence and evaluate the sources of uncertainty in the measurement of the speed of sound in soybean oil and to understand its effects on the measurand.

2. Materials and methods

2.1. Measuring system

To evaluate the factors influencing the measurement uncertainty of the speed of sound in liquids, soybean oil was chosen as the test sample. Its properties are well described in the literature [15][16]. The soybean oil (Liza®) was inserted in a mini-reactor and the measurement of the speed of sound was performed using the experimental setup described in [16][17]. The measurement system is composed of a thermal bath, a cell with soybean oil, and an ultrasonic transducer of 1 MHz model A303S (NDT-Panametrics, Olympus Corporation, Japan). The pulse-echo method was employed, in which the ultrasonic transducer acted as a transmitter and a receiver. The transducer was excited with a wave generator model 33250A (Agilent Technologies, CA, USA). The acquired signals were digitized with an oscilloscope model DSO-X 3012A (Agilent Technologies, CA, USA) and transferred to a computer through a program developed in LabView (National Instruments, TX, USA).

The speed of sound (SoS) was determined through the measurement of the time \( t \) that the ultrasonic signal takes to cross the sample, reaches the reflector target, and returns to the same transducer and through the distance \( x \) between the face of the transducer and the reflector target, as seen in equation (1):

\[
SoS = 2 \cdot \frac{x}{t}
\]

The distance \( x \) was previously determined based on the time of flight (ToF) and the speed of sound in the water. Details about this measurement can be found elsewhere [16]. The soybean oil measurements were carried out with temperature variation in the range of 20.0 °C to 21.0 °C to evaluate the influence of this temperature variation on the uncertainty of the measurand. The temperature was monitored using a temperature measuring device model 34970A (Agilent Technologies, CA). The measurements were performed under repeatability conditions [17], with twelve acquisitions for each soybean oil sample.

2.2. Uncertainty analysis

The uncertainty assessment is based on the identification and quantification of the effects of influence parameters on global uncertainty. The parameters were evaluated for the standard uncertainty of type A and type B. Type A evaluation is based on the statistical distribution of a series of measurements. The type B evaluation can be characterized by other means, such as a measuring instrument manual, calibration certificate, or other information [17].

The expanded uncertainty was calculated according to the Guide of the Expression of Uncertainty in Measurements [12], by a coverage factor \( k \) that takes into account the \( t \)-distribution with coverage probability of 0.95, and the effective degrees of freedom.

3. Results and discussion

The speed of sound was determined in the soybean oil sample. Table 1 presents the measurement results obtained in 12 acquisitions.
Table 1. Speed of sound of soybean oil.

| Acquisitions | T [°C]  | SoS [m·s⁻¹] |
|--------------|---------|-------------|
| 1            | 20.01   | 1485.16     |
| 2            | 20.09   | 1484.86     |
| 3            | 20.15   | 1484.55     |
| 4            | 20.22   | 1484.25     |
| 5            | 20.32   | 1483.94     |
| 6            | 20.45   | 1483.63     |
| 7            | 20.55   | 1483.33     |
| 8            | 20.64   | 1483.02     |
| 9            | 20.71   | 1482.41     |
| 10           | 20.80   | 1482.11     |
| 11           | 20.89   | 1481.80     |
| 12           | 20.99   | 1481.50     |
| Average      | 20.49   | 1483.38     |
| Standard deviation | 0.33  | 0.82        |

According to Table 1, the 12 acquisitions made within the analyzed range represent an average temperature of 20.49 °C and an average speed of sound of 1483.38 m·s⁻¹.

As previously mentioned, it is important to ensure the quality of measurement results. A detailed uncertainty assessment enables the identification of possible measurement errors and the need for optimization, providing more reliable results. An uncertainty budget of measurement of the speed of sound considering the relative uncertainty approach is shown in Table 2 and Figure 1.

Table 2. Uncertainty budget.

| Source                          | Standard uncertainty | Unity | Cᵢ · uᵢ [m·s⁻¹] | Cᵢ · uᵢ [%] |
|---------------------------------|----------------------|-------|------------------|-------------|
| Time of flight in soybean oil (t) |                      |       |                  |             |
| Repeatability                   | 1.45E-8              | s     | 0.35             | 33.74       |
| Time base – oscilloscope        | 5.46E-10             | s     | 0.01             | 1.27        |
| Distance (x)                    |                      |       |                  |             |
| SoS water – Temperature         | 0.10                 | °C    | 0.33             | 31.20       |
| SoS water – Equation [18]       | 0.0028               | m·s⁻¹°C⁻¹ | 0.002             | 0.15       |
| ToF water – Repeatability      | 3.33E-9              | s     | 3.27E-1          | 31.10       |
| ToF water – Time base           | 2.71EE-10            | s     | 2.67E-2          | 2.54        |

Cᵢ is the sensitivity coefficient and uᵢ is the uncertainty contribution of the quantity. For more details see [12].
Figure 1. The relative uncertainty of each contribution of uncertainty.

From the data in Table 2 and Figure 1, one can observe that the factors that contributed most to the increase of the final uncertainty derived from the repeatability for the time of flight both in oil and water, representing 33.7 % and 31.1 % of total uncertainty, respectively. As said, these values are obtained by measuring the time that the ultrasonic wave takes to travel through the medium (soybean oil or water) and returns to the transducer.

As expected, this result is due to temperature variation that directly impacts propagation velocity, since the higher the temperature, the lower will be the speed of sound. Also, it is possible to note that a variation of 0.98 °C in soybean oil temperature results in a variation of 3.67 m·s⁻¹ in the speed of sound. This assessment is important for process line measurements (monitoring online) [19], for example, where despite having good temperature control, variations of approximately 1 °C are typical.

Another factor that contributes significantly to the final uncertainty is the uncertainty associated with temperature measurement to determine SoS in water, representing 31.2 % of total uncertainty. This value is obtained by measuring the water temperature using a calibrated thermocouple. Water temperature is an indirect quantity. It is used in the literature equation [18] to assess the speed of sound in water to define the distance x. Although the temperature measurement system used is calibrated (U = 0.16 °C; k = 2), the use of a more accurate measurement system can reduce temperature uncertainty. The other uncertainty contributions correspond to approximately 4 % of the total uncertainty.

Finally, the speed of sound in soybean oil was 1483.4 m·s⁻¹ ± 2.8 m·s⁻¹ (k=1.96; p= 0.95). Comparing this result with previous studies [16], it is noted that this result is consistent with the literature that reports a speed of sound of 1484.1 m·s⁻¹ ± 4.3 m·s⁻¹ at 20 °C.
4. Conclusions

This work is a contribution to the study of uncertainty contributions in the measurement of vegetable oil propagation velocity using the pulse-echo technique. In this work, the results indicated that the main source of uncertainty is due to the repeatability of the time of flight measurement at the liquid, and the second greatest is due to water temperature measurement to determine the SoS in the water. The evaluation of measurement uncertainty contributions has allowed a detailed assessment of the measurement system. Thus, the metrology acts as a tool for measurement optimization as it identifies where efforts to reduce uncertainty should be concentrated. This study contributes to the dissemination of the importance of uncertainty budget and metrological reliability in measurement results.

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