A Study of Acoustic Parameters of Transformer Oil Based on Its Water Content Utilizing a Single Ultrasonic Sensor

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Received 23 March 2024; received in revised form 01 June 2024; accepted 02 June 2024

DOI: https://doi.org/10.46604/aiti.2024.13503

Abstract

The health of a transformer is affected by several aspects, including water content in transformer oil. Researchers have introduced various techniques for measuring water content in transformer oil. In the case of acoustical measurement, researchers typically utilize two ultrasonic sensors to detect acoustical parameters. This study proposes a novel technique to characterize transformer oil based on its water content using a single ultrasonic sensor. This technique employs an indirect measurement approach, where a substrate separates the oil from the sensor. The echoes from measurements are observed and presented in terms of three acoustical parameters, i.e., the acoustic speed, acoustic impedance, and density. Based on measurement results, the acoustic speed of the samples is successfully calculated from the time of flight and the thickness of the chamber. However, only four materials used as substrate 1, i.e., 3mm, 5mm, 8mm acrylic, and 3mm glass, successfully produce similar plots of acoustic impedance and density.

Keywords: transformer oil, ultrasonic, acoustic speed, acoustic impedance, water content

1. Introduction

One of the most important and expensive parts of the transmission and distribution process of electricity is the transformer. Throughout its operational lifespan, oil-immersed transformers are exposed to electrical, thermal, and chemical pressures that potentially deteriorate their paper-to-liquid insulation, leading to decreased efficiency. This underscores the significance of transformer oil as the primary factor influencing the transformer's durability. Various factors can impact the staged production during the operation of transformers, especially moisture contamination. Ensuring the moisture levels in the insulation system are properly controlled holds great significance as it can decelerate the aging of paper insulation and protect the system. A survey by IEEE shows that almost 50% of transformer failures are caused by insulation damage. This further substantiates the importance of diligently upholding the integrity of the insulation system [1].

To enhance the efficiency of the transformer, improvements to the insulator materials i.e., oil and paper must be done. One way to improve insulator material is by adding nanoparticles to transformer oil, which can improve heat transfer and voltage breakdown of transformer insulation. Observations of the addition of MWCNTs-OH nanofluid on transformer performance have been successfully carried out, which shows that the addition of MWCNTs-OH nanofluid has better thermal performance than pure oil, which prevents temperature increases in the transformer and can also be used as electrical insulation in transformers [2]. This research was then continued by adding MWCNTs-doped TiO_2 nanoparticles synthesized in transformer oil, which showed that nanofluid with 0.1 wt% had good performance compared to other nanofluid concentrations

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English language proofreader: Chih-Wen Teng

[3]. From previous research [2-3], a comprehensive discussion on the potential of $ZnFe_2$ and TiO_2 nanofluids in transformer oil successfully increases the heat transfer efficiency and reduction of breakdown voltage for maintaining transformer insulation [4].

Another way to enhance the efficiency of the transformer is by monitoring the moisture condition of insulating paper and oil. The presence of water (moisture) in transformer oil influences the breakdown voltage of transformer oil [5-6]. More moisture causes the breakdown voltage of transformer oil to drop, increasing the potential of transformer failure. Therefore, it is important to inspect the water content in transformer oil. An optical method, D-shaped optical fiber coated with a thin layer of platinum is used to measure moisture content detection in transformer oil. Experimental results have confirmed that the Transverse Electric power of D-shaped fibers changes significantly to lower values when insulating oils with different water contents are detected. However, this research requires further research to determine the correlation between the amount of water measured in the laboratory [7].

Micro-nano fiber (MNF) based optical sensor is used to establish a connection between moisture in oil and the distribution of the evanescent field. The experimental results show that the detection can achieve real-time measurement of moisture with a sensitivity of 1.8 ppm at a diameter of 800 nm. These sensors are also possible to be immersed directly into the transformer tank for measurement [8]. Polyimide-coated fiber Bragg grating (FBG) is also used for monitoring water content in transformer oil [9]. Those optical methods [7-9] show their ability to determine water content in transformers with some advantages.

However, for some reason, the optical method will face difficulties when measuring opaque material or indirect measurement. For this matter, acoustical measurement is superior compared to optical measurement. Several studies of water content in the transformer oil are also possible by utilizing acoustic waves [10-12]. In those studies, the authors utilize two ultrasonic sensors which stand as transmitter and receiver. Those sensors are touching the transformer oil to obtain oil parameters.

This study proposes a novel technique to characterize transformer oil based on its water content using a single ultrasonic sensor. This technique employs an indirect measurement approach, where five substrates — 3 mm, 5 mm, and 8 mm acrylics, and 3 mm and 5 mm glasses are used to separate the oil from the sensor. The echos from measurements are taken, calculated, and presented in terms of three acoustical parameters, i.e., acoustic speed, impedance, and density. In the future, it is expected that the indirect measurement approach will provide a better solution, where measurements can be made directly on the outside of the transformer body, thus simplifying the measurement process.

2. Materials and Methods

This chapter explains the configuration of the system used in this study, including the block diagram, measurement chamber, ultrasonic sensor, and transformer oil. Measurement points are also described since this is also an essential part of obtaining the acoustic parameters in this study.

2.1. Transformer oil characteristic

The main characteristic that determines the condition and age of a transformer is its insulation system, comprising insulating oil and insulating paper. Insulating paper tests can be known by conducting the degree of polymerization (DP) test [13-14]. Insulating oil is determined by the presence of material, such as air bubbles, fibers, metallic particles [15-16], and water [10-12], which is affected by temperature [17]. In this study, transformer oils produced by APAR, POWEROIL TO 20, which is an uninhibited transformer oil meeting IEC 296 Class I: 1982 standard specification are provided by PT. Bambang Djaja, a transformer company in Indonesia. Three transformer oil-water mixed with 8 ppm, 23 ppm, and 33 ppm, verified by moisture in the oil meter from Vaisala are used as the samples and shown from left to right in Fig. 1.

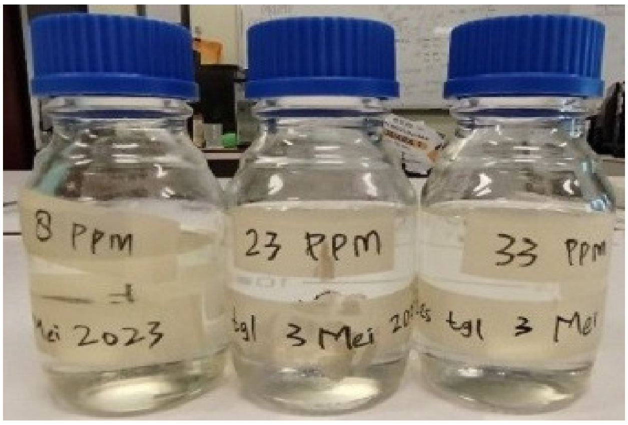


Fig. 1 Transformer oil-water samples with varying water content

2.2. *Ultrasonic wave*

An ultrasonic wave is a longitudinal mechanical wave whose frequency exceeds the hearing limit of the human ear (above 20 kHz). Employing ultrasonic waves as a sensor device offers numerous benefits, such as its simplicity and ability to penetrate within the tested object or material [18]. In ultrasonic testing applications, extremely brief ultrasonic pulse waves are directed toward objects to identify internal fractures or to characterize the object itself [19-22]. Fig. 2 shows two distinct echo signals. The first and third echoes are reflected signals from the front and rear sides of the sample, respectively, while the second echo indicates the presence of the fracture within the investigated object.

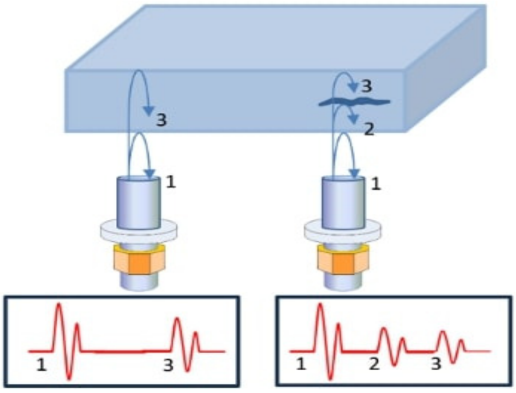
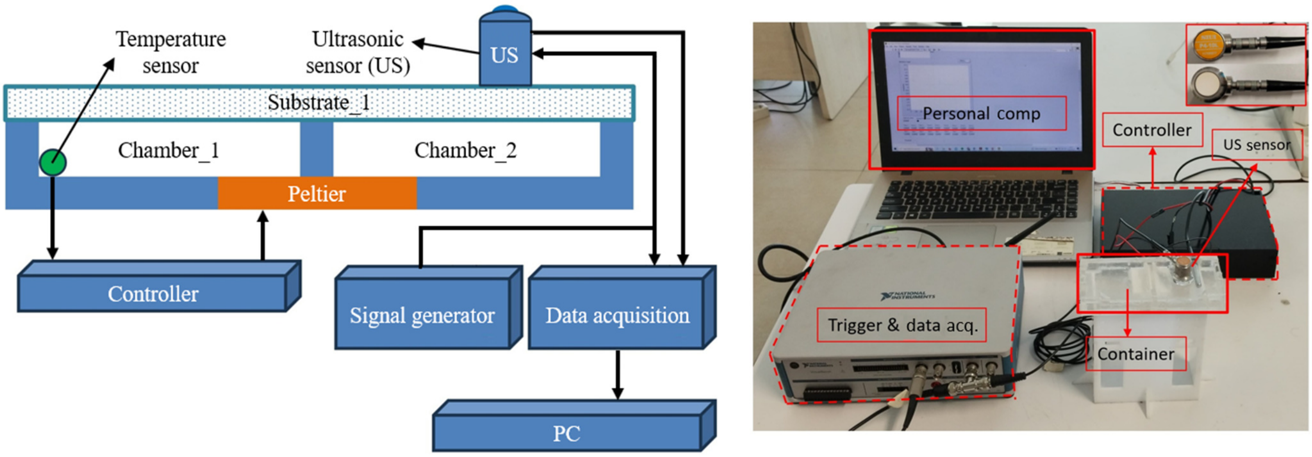


Fig. 2 Principle of ultrasonic testing

2.3. *The proposed system*



(a) Block diagram system (b) Experimental setup

Fig. 3 The proposed system

Fig. 3 shows the proposed system. The sample is placed in the measurement container, which has 60 mm for length, 140 mm for width, and 10 mm for height as shown in Fig. 3(b). The measurement container is divided into two chambers, chamber_1 is filled with pure water as a reference, while chamber_2 is filled with a sample. An ultrasonic sensor, P4-10L from SIUI operating at 4 MHz is employed to convert the electric signal from the signal generator into an acoustic signal. This sensor is positioned at the top of the substrate to measure the sample indirectly. Both the trigger and the echo signal are captured by the data acquisition module and then transmitted to a personal computer for observation and analysis as shown in Fig. 3(a). A sample will undergo a measurement process 20 times, taken from five different locations on substrate 1, where each location undergoes four measurements. During measurement, the temperature is kept at 24 °C.

As shown in Fig. 4, this system comprises 3 layers. Acrylic or glass as a substrate 1 is used for the first layer. The second layer consists of the observed sample, divided into two chambers: one for the reference (i.e., pure water) and the other for transformer oil. The third layer is the acrylic layer.

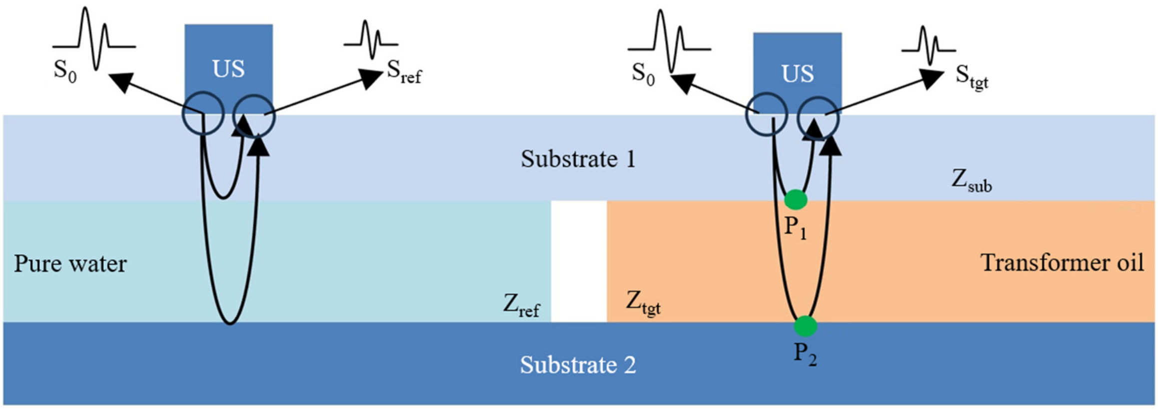


Fig. 4 Measurement chamber

Two test points, i.e., P_1 and P_2 are determined. P_1 represents the interface between substrate 1 and the sample. At this point, root means square voltage (Vrms) and peak-to-peak voltage (Vpp) of echoes are measured to obtain the intensity of ultrasonic shown in the voltage unit. P_2 represents the interface between the sample and substrate 2. At this point, it is possible to measure the time of flight (ToF) of the ultrasonic wave in the reference and sample. Furthermore, since the case in this measurement involves only normal incident waves, therefore only pressure wave is taken into consideration.

3. Results and Discussion

This chapter shows the result of measurement based on material used as substrate 1 and also explains the objective of measurement at P_1 and P_2. After the result was obtained, a keen discussion was provided and shown in the comparison between each material for substrate 1.

3.1. Measurement at P_1 utilizing 5 mm of acrylic as substrate 1

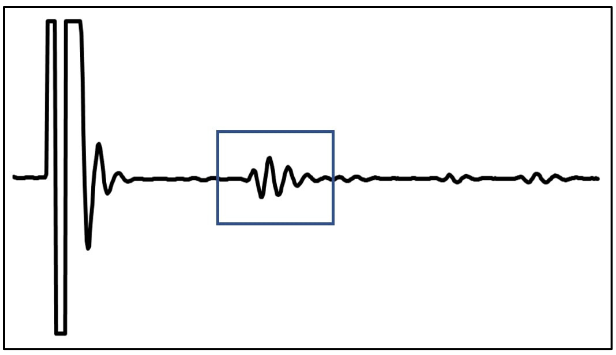


Fig. 5 Typical acoustic wave from P1

Fig. 5 shows a typical acoustic wave from this measurement. Several echoes are coming up from the measurement, caused by the different number of acoustic impedances of the material. Therefore, the correct echo must be chosen for appropriate calculation. The wave inside the blue rectangle shown in Fig. 5 is the first echo of the acoustic signal from the first layer where P_1 is measured.

In the first step, a reference is needed before measuring the oil transformer. Since this study is related to water content inside oil, thus, pure water is chosen as the reference and measured at P_1. The result shows 23.67 mVrms and 75.113 mVpp. Using a similar manner, samples are measured and the result is shown in Table 1.

Table 1 Measurement at P_1

No.	Sample	Vrms (mV)	Vpp (mV)
1	Pure water	23.67	75.113
2	33 ppm	26.505	96.008
3	23 ppm	26.681	98.157
4	8 ppm	27.468	102.001

These results show that the more water mixed in the oil, the lower the intensity of the ultrasonic echo. The formula for the transmission and reflection coefficient is given below [18].

$$R_p + 1 = T_p \tag{1}$$

$$\frac{1}{Z_1}\left(1 - R_p\right) = \frac{T_p}{Z_2} \tag{2}$$

Eq. (1) and Eq. (2) can be solved to give the pressure transmission and reflection coefficients as follows:

$$T_p = \frac{2Z_2}{Z_1 + Z_2} \tag{3}$$

$$R_p = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{4}$$

where, R_p and T_p are the reflection and transmission coefficients of the pressure wave, and Z_1 and Z_2 are the acoustic impedance of the first and second material.

Utilizing Eq. (4), the larger the difference in acoustic impedance between the first material and the second material, the higher the value of the signal return ratio. Since acrylic is used as substrate 1, it means that 8 ppm water-oil mixed will have the highest intensity of echo compared to 23 ppm, 33 ppm, and pure water. The result of measurement shown in Table 1 agrees with Eq. (4). Fig. 6 and Fig. 7 show the graph of Table 1.

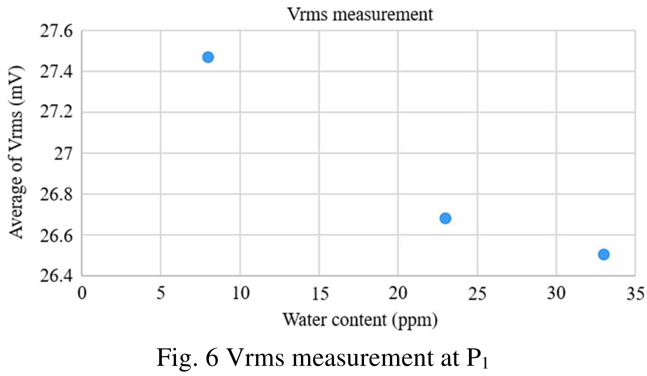


Fig. 6 Vrms measurement at P_1

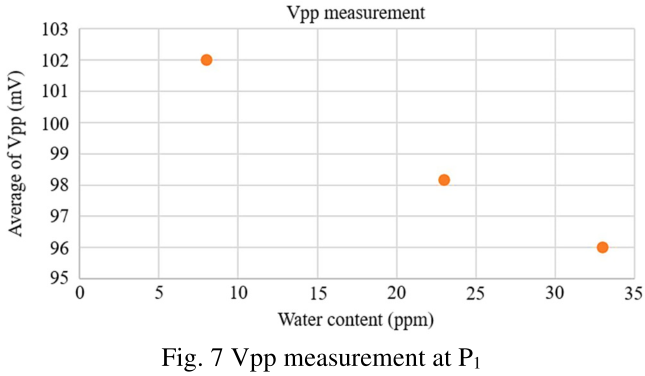


Fig. 7 Vpp measurement at P_1

Based on Table 1, it is also possible to obtain the acoustic impedance of the sample. It is known that the acoustic impedance of pure water at 24 °C is 1.494 Mrayl. To evaluate the acoustic impedance of the sample, the following formulas may be used [23].

$$S_{ref} = \frac{Z_{ref} - Z_{sub}}{Z_{ref} + Z_{sub}} S_0 \tag{5}$$

$$S_{tgt} = \frac{Z_{tgt} - Z_{sub}}{Z_{tgt} + Z_{sub}} S_0 \tag{6}$$

where S_0 is the transmitted signal, S_{tgt} is the reflected signal from the target, S_{ref} is the reflected signal from the reference, and Z_{tgt}, Z_{ref}, and Z_{sub} are the acoustic impedances of the target, reference, and substrate, respectively. However, since the transmitted signal is unknown, these two equations are combined to obtain the acoustic impedance of the target, as demonstrated below.

$$Z_{tgt} = \left[\left(1 - \frac{S_{tgt}}{S_{ref}} \times \frac{Z_{sub} - Z_{ref}}{Z_{sub} + Z_{ref}} \right) \Big/ \left(1 + \frac{S_{tgt}}{S_{ref}} \times \frac{Z_{sub} - Z_{ref}}{Z_{sub} + Z_{ref}} \right) \right] \times Z_{sub} \tag{7}$$

The acoustic impedance of acrylic ranges from 3.08-3.26 Mrayl [18, 23], and pure water at 25 ℃ is 1.494 Mrayl [18]. The transformer oil is 1.28 Mrayl and 920 kg/m^3 for acoustic impedance and density, respectively [18, 23]. The acoustic impedance of acrylic used in this system is unknown, however, its density can be measured by knowing its weight and volume. Therefore, utilizing the following formula, the acoustic impedance can be obtained by multiplying the result of acoustic speed and its density. Since the thickness of each acrylic is known, the acoustic speed can be calculated by measuring ToF.

$$Z = \rho \times v \tag{8}$$

where Z, ρ, and v are acoustic impedance, density, and acoustic speed respectively.

Table 2 shows the result of this measurement. The time flight of acoustic wave inside each acrylic is measured. By knowing the thickness of each acrylic, the acoustic speed inside the acrylic can be calculated. Acoustic impedance can be obtained as acoustic speed multiplied by its density. The average acoustic impedance of acrylic in this study is 3.24 Mrayls and is considered to be used during this study.

Table 2 Acoustic impedance of acrylic

Acrylic	ToF (ns)	Speed (m/s)	Density (kg/m^3)	Impedance (MRayls)
3 mm	2284.25	2626.68	1213	3.186
5 mm	3655.06	2735.93	1198	3.277
8 mm	5860.348	2730.21	1195	3.262
			Average	3.24

Using different ways, the acoustic impedance for the reference and sample is calculated utilizing Eq. (7). The intensity of the reflected signal from reference and sample are measured using Vrms and Vpp measurements. The comparison results of the acoustic impedance of the reference and sample expressed in Vrms and Vpp measurements are shown in Table 3.

Table 3 Acoustic impedance of reference and samples

No.	Sample	Acoustic impedance (MRayl)	
		Vrms	Vpp
1	Pure water	1.494	1.494
2	33 ppm	1.349	1.170
3	23 ppm	1.340	1.139
4	8 ppm	1.301	1.085

Based on Table 3, the higher the water content in the sample, the greater the acoustic impedance, as observed in both Vrms and Vpp measurements. These results agree with Eq. (4), which indicates that the larger difference in acoustic impedance between Z_1 and Z_2 leads to higher acoustic reflection intensity, as shown in Table 3 and confirmed in Table 1. Both Vrms and

Vpp measurements show a positive increase in acoustic impedance as the water content increases. Referring to the acoustic impedance of new transformer oil as 1.28 Mrayl [18, 23], the measurement result from Vrms makes more sense compared to Vpp. This is because the sample in this study is derived from new transformer oil and supplemented with water. Since water has a higher acoustic impedance compared to new transformer oil, it implies that the acoustic impedance of new transformer oil will be equal to or below 1.301 Mrayl (8 ppm), a condition met by the Vrms measurement. It shows that the measurement result from Vrms is more accurate compared to Vpp. Therefore, for subsequent measurements, only Vrms measurement is utilized in this study.

3.2. Measurement at P_2 utilizing 5 mm of acrylic as substrate 1

Measurement at P_2 is utilized to obtain the ToF of the ultrasonic wave inside the sample. For this purpose, several techniques, i.e., threshold, zero crossing, and cross-correlation method [24-28] are investigated to obtain the best way to determine ToF. Utilizing the same chamber as illustrated in Fig. 3, with a gap of 10 mm, pure water is initially used for investigation. The acoustic speed of pure water at 24 °C is 1497 m/s. Since the ultrasonic wave travels go and back, the total distance of the ultrasonic wave is 20 mm. Table 4 presents the result of the ToF measurement. The distance is obtained by multiplying ToF and acoustic speed. Based on the measurement, the cross-correlation method yields the best result compared to the other two methods and is thus utilized to determine the ToF during this study.

Table 4 Time of flight measurement using pure water

Measurement	Threshold method	Zero cross method	Cross-correlation method
Speed (m/s)	1497	1497	1497
ToF (ns)	12569.77	12607.91	13275.50
Distance (mm)	18.817	18.874	19.873
True distance (mm)	20	20	20
Error (%)	5.915	5.630	0.633

By dividing 20 mm by ToF, the acoustic speed inside samples is determined. The data presented in Table 5 indicates that as the water content in the transformer oil increases, the acoustic speed propagating through the oil also increases. These findings align with a similar trend observed in research conducted by Zhu et al. [29]. Knowing the acoustic impedance of samples from Table 3, the density (ρ) of the sample can then be calculated by dividing acoustic impedance by acoustic speed. Table 5 shows the ToF, acoustic speed, acoustic impedance, and density of the samples. As it is known that the density of pure water at 25 °C is 0.998 kg/dm3 and transformer oil is 0.92 kg/dm^3 [18], when they are mixed, the density should be between 0.92–0.98 kg/dm^3. It is also known that the more water in transformer oil, the density becomes higher.

Table 5 ToF, speed, impedance, and density of transformer oil samples

Measurement	Samples			
	8 ppm	23 ppm	33 ppm	Pure water
ToF (ns)	14022.25	13863.94	13798.64	13275.5
Speed (m/s)	1426.3	1442.59	1449.42	1497
Z (MRayl)	1.301	1.34	1.349	1.494
r (kg/dm^3)	0.912	0.929	0.930	0.998

3.3. Measurement at P_2 using 3 mm and 8 mm of acrylic as substrate 1

In this sub-chapter, the result of 5 mm of acrylic as already explained in the previous sub-chapter will be compared to the 3 mm and 8 mm of acrylic. Using a similar way for investigation, Table 6 and Table 7 show the result for 3 mm and 8 mm of acrylic respectively. The ToF of 8 ppm, 23 ppm, and 33 ppm of transformer oil and pure water as shown in Table 5, Table 6, and Table 7 are the same, as the samples are identical and investigated under the same environmental condition. Therefore, the acoustic speed of the samples remains unchanged. However, for acoustic impedance calculation, the results shown in Table

5, Table 6, and Table 7 are different, even though they exhibit a relatively small discrepancy. This is caused by substrate 1, which is composed of a different acrylic material. Therefore, the reflected signal S_{tgt} captured by the sensor is different, resulting in different acoustic impedance. This disparity will have an impact on its density calculation, as the density is obtained by dividing acoustic impedance by acoustic speed.

Table 6 ToF, speed, impedance, and density of transformer oil samples using 3 mm of acrylic

Measurement	Samples			
	8 ppm	23 ppm	33 ppm	Pure water
ToF (ns)	14022.25	13863.94	13798.64	13275.5
Speed (m/s)	1426.3	1442.59	1449.42	1497
Z (MRayl)	1.299	1.34	1.348	1.494
r (kg/dm^3)	0.910	0.929	0.930	0.998

Table 7 ToF, speed, impedance, and density of transformer oil samples using 8 mm of acrylic

Measurement	Samples			
	8 ppm	23 ppm	33 ppm	Pure water
ToF (ns)	14022.25	13863.94	13798.64	13275.5
Speed (m/s)	1426.3	1442.59	1449.42	1497
Z (MRayl)	1.291	1.336	1.346	1.494
r (kg/dm^3)	0.905	0.926	0.928	0.998

3.4. Measurement at P_2 using 5 mm and 3 mm of glass as substrate 1

In this study, authors also involved 5 mm and 3 mm of glass in observation, utilizing a similar approach as described for acrylic as a substrate 1. A problem arises because the acoustic impedance of the glass used in this study is unknown. According to the literature by Cheeke [18], the acoustic impedance of glass spreads from 10.1 to 16 Mrayls, depending on the constituent material. To address this problem, measurement of ToF is conducted to obtain acoustic speed and measuring weight and volume of glass to obtain its density. Subsequently, acoustic impedance is calculated using Eq. (8). As depicted in Table 8, the acoustic impedance of the two types of glass is different significantly. Therefore, in the calculation, the authors consider Z = 11.475 Mrayls for 3 mm of glass and Z = 13.91 Mrayls for 5 mm of glass.

Table 8 Measurement of acoustic impedance of glass

Glass	ToF (ns)	Speed (m/s)	Density (kg/m^3)	Impedance (MRayls)
3 mm	1238.81	4839.45	2371.22	11.475
5 mm	1869.252	5349.73	2600.40	13.91

Table 9 and Table 10 show the ToF, acoustic speed, acoustic impedance, and density of samples using 3 mm of glass and 5 mm of glass respectively. The ToF and acoustic speed are unchanged as shown in Tables 5, 6, and 7. However, there is a significant difference in the measurement results between 3 mm and 5 mm of glass for its acoustic impedance and density. This disparity may be attributed to the uncertain value of the acoustic impedance of glass, as glass exhibits a wide range of acoustic impedance. Other potential factors include disturbances during echo measurement or inhomogeneous in the glass material especially for 5 mm of glass. All results of this study are shown in Fig. 8 and Fig. 9 in the graph form.

Table 9 ToF, speed, impedance, and density of transformer oil samples using 3 mm of glass

Measurement	Samples			
	8 ppm	23 ppm	33 ppm	Pure water
ToF (ns)	14022.25	13863.94	13798.64	13275.5
Speed (m/s)	1426.3	1442.59	1449.42	1497
Z (MRayl)	1.309	1.339	1.357	1.494
r (kg/dm^3)	0.918	0.928	0.936	0.998

Table 10 ToF, speed, impedance, and density of transformer oil samples using 5 mm of glass

Measurement	Samples			
	8 ppm	23 ppm	33 ppm	Pure water
ToF (ns)	14022.25	13863.94	13798.64	13275.5
Speed (m/s)	1426.3	1442.59	1449.42	1497
Z (MRayl)	1.228	1.296	1.336	1.494
r (kg/dm^3)	0.861	0.898	0.921	0.998

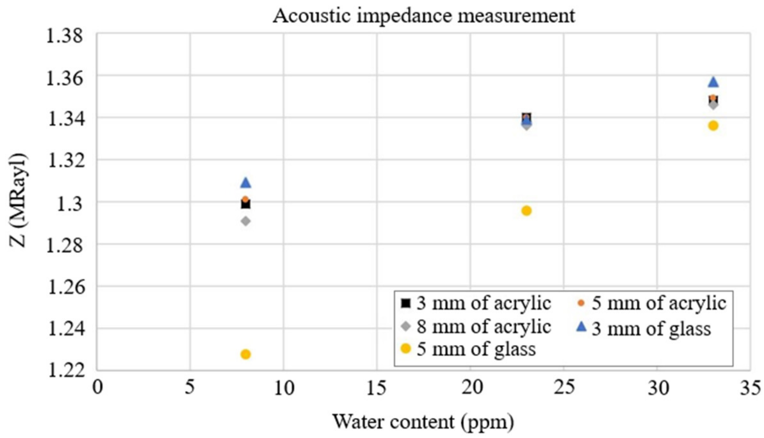


Fig. 8 Acoustic impedance measurement results from several substrates

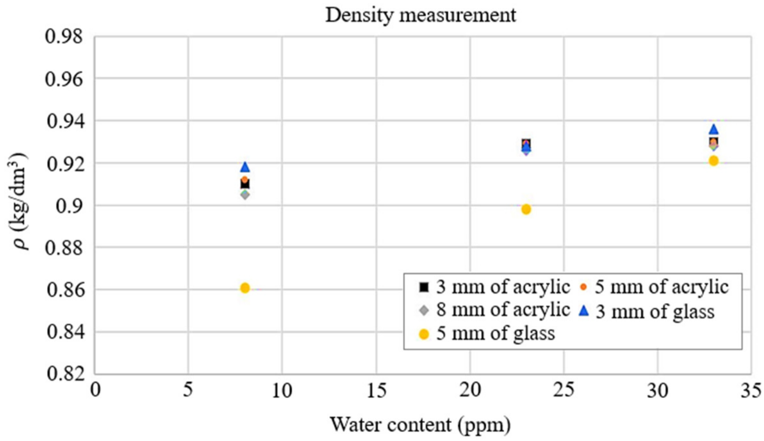


Fig. 9 Density measurement results from several substrates

Based on measurement results, acoustic speed is successfully calculated from ToF and the thickness of the chamber. In this measurement, the presence of substrate 1 will not affect on the measurement process. Therefore, the value of acoustic speed is always the same, as shown in Tables 5-10. Theoretically, the calculation of acoustic impedance and density for all samples must be the same as well, even though substrate 1 is composed of different materials. Based on the measurement results shown in Fig. 9 and Fig. 10, measurements using 3 mm, 5 mm, 8 mm of acrylic, and 3 mm of glass as substrate 1 successfully produce similar plots. This result shows that these materials can be used to characterize the water content in transformer oil in terms of acoustic impedance, and density. However, measurement using 5 mm of glass produced a significantly different plot. This plot will certainly produce incorrect characterization for the acoustic impedance and density. This discrepancy may occur due to the inhomogeneity of the 5 mm glass material resulting in aberrations of the echo [30].

4. Conclusions

This study investigates acoustic parameters in transformer oil based on its water content using a single ultrasonic sensor, which serves as both transmitter and receiver. A single ultrasonic sensor, both transmitter and receiver, is used to measure samples through an indirect measurement approach. In this approach, five substrates i.e., 3 mm, 5 mm, and 8 mm of acrylics, and 3 mm and 5 mm of glasses are used to separate the oil from the sensor. To determine acoustic speed, acoustic impedance, and density, voltage measurements at P_1 and P_2 are required. Vrms measurements were chosen because they provide more accurate information compared to Vpp measurements. Meanwhile, ToF is calculated using the cross-correlation method. Based on measurement results, the acoustic speed results of the samples are successfully calculated from ToF and the thickness of the chamber.

However, only four materials used as substrate 1, i.e., 3 mm, 5 mm, 8 mm of acrylic, and 3 mm of glass as substrate 1 successfully produced similar plots of acoustic impedance and density. However, measurement using 5 mm of glass produced a significantly different plot. This may be caused by the inhomogeneity of 5 mm of glass material, resulting in an error due to aberration in the echo signal. Some techniques regarding aberration correction have been introduced to address this issue for future improvements. It is also interesting when this proposed system is exposed to the magnetic field for in-situ measurement.

Acknowledgment

The authors thank to Non-Destructive Test Laboratory of Politeknik Elektronika Negeri Surabaya for providing the measurement instrument, and the authors also extend sincere thanks to Mr. Nuswanggono and Mr. Handipo from PT. Bambang Djaja for providing water-transformer oil mixed as samples during this research.

Conflicts of Interest

The authors declare no conflict of interest.

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