A Wide Range Measurement and Disclosure of Ultrasonic Attenuation for Very Low Concentrations of Solid in Liquids Using Exponential Pulser Technique

M.S. Salim, M.F. Abd Malek and Naseer Sabri

Abstract The low solid concentrations in solutions are discovered and measured based on measurement the attenuation that occurs with a wave propagating through a fluid. Currently methods (Pitch-Catch, Pulse-echo and Immersion method) have some of weak points related with range of detection and power consumption, therefore, to increase the measuring range to include the detection of very low concentrations in solution as well as not relying on the material that the container is made of, a new technique for the pulser was designed to overcome the disadvantages of the three currently methods. This technique has been thoroughly applied to dispensing with the use of a container or reflector with a high reflection coefficient and Expanding the measuring range to include very low concentrations. The new technique demonstrates the system's ability to distinguish the presence of particles in a fluid at a concentration lower than 10 %, which is below the limit of detection of the current method with the same device settings.

1 Introduction

To study the characteristics of fluids many researchers use common methods to measure the attenuation that occurs with a wave propagating through a fluid.

Frequently used containers or reflectors with a high reflection coefficient (H.R.C.), where the benefit of this material lies in strengthening the reflected signal to the

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M.S. Salim
School of Laser and Optoelectronics Engineering, AlNahrain University, Baghdad 64074, Iraq

M.F. Abd Malek
School of Electrical System Engineering, University of Malaysia, Perlis, 01000 Perlis, Malaysia

N. Sabri (✉)
School of Computer and Communication Engineering, University of Malaysia, Perlis, 01000 Perlis, Malaysia
e-mail: muhsabri1967@yahoo.com

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transducer or to generate multi echoes. Figure 1 show some of these methods which are currently used in the study of the characteristics of fluids or detecting small solid concentrations suspended in the fluid. Greenwood et al. used a container made of stainless steel to detect small concentrations of solids in a liquid using a pitch-catch method. The reason for using stainless steel is that it generates several feedback signals (echoes) resulting from transmitting a single pulse, as shown in Fig. 1a using a stainless steel container successfully to measure a concentration of less than 5 % silica (hereinafter referred to as method A) [3].

Secomski et al. developed a clinical method for noninvasive acoustic determination of hematocrit values in vivo. The value of hematocrit was determined initially in vitro from the pulse-echo measurements of acoustic attenuation. The attenuation was determined from the amplitude of echoes reflected from 3 mm diameter stainless steel affixed inside a wall opposite a transducer as shown in Fig. 1b. Using this method, we can increase the sensing of the reflected signal from the reflector which is used here to study the increase in liquid characteristics (hereinafter referred to as method B) [9]. In another method called the immersion method, it was used to immerse the transmitter and receiver in the liquid. This method does not require the use of a container with a high reflection coefficient, because of the direct measurement of the received signal from the transmitter as shown in Fig. 1c (hereinafter referred to as method C) [2, 10].

To sum up the aforementioned methods, the three methods have advantages and disadvantages. However, method A was useful in the accurate detection of small concentrations and also consumed little power; however, these features are satisfied based on using a container made of a high reflection coefficient (H.R.C.) material. Methods B, and C both used the same average transmitted power to detect very specific concentrations (as revealed concentrations depend on the power of the transmitted pulse); in addition method C depends on what the reflector material is made of.

In order to increase the measuring range to include the detection of very low concentrations in solution as well as not relying on the material that the container is made of, a new method was designed to overcome the disadvantages of the three abovementioned methods and continues to give accuracy and a wide measurement range. This new method, named Pulse Power Decay (PPD) technique (Exponential power pulser), has been thoroughly applied to the following:

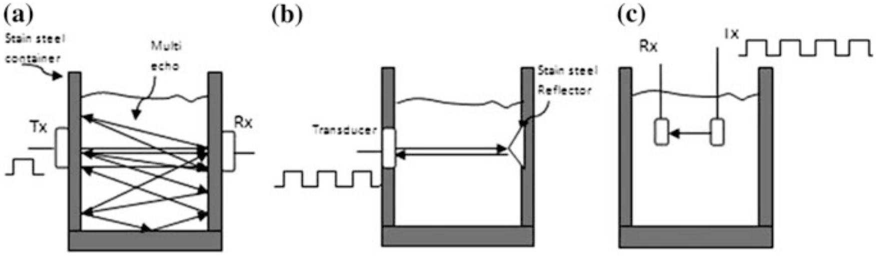

Fig. 1 Experimental method of fluid characteristics measurements and solid concentration content in liquid detection using **a** pitch-catch method, **b** pulse-echo method, and **c** immersion method

Table 1 Comparison between three currently concentration measurement methods and proposed method for transmission power, material of container is made of, measurement range

Method type	Transmitted pulses	Path (distance travelled)	Transmitted power	Material of reflector	Measurements range	PPD average power comparison	Measurements range depends on
A	Single pulse	Multi path (ND + 2W)	Constant (P_a)	H.R.C.	Wide	$Pa < P_{PPD}$	Transmitted pulse power and container type.
B	Multi pulse	Double path (2D)	Constant (P_b)	H.R.C.	Limited	$Pb > P_{PPD}$	Transmitted pulse power and reflector type
C	Multi pulse	Single path (D)	Constant (P_c)	None	Limited	$Pc > P_{PPD}$	Transmitted pulse power
PPD	Multi pulses	Single path (ND + 2W)	Decay (P_{PDD})	None	Wide	P_{PPD}	Decay power pulses

where P_a, P_b, P_c and P_{PPD} are the average power transmitted of method A, method B, method C, and method PPD respectively

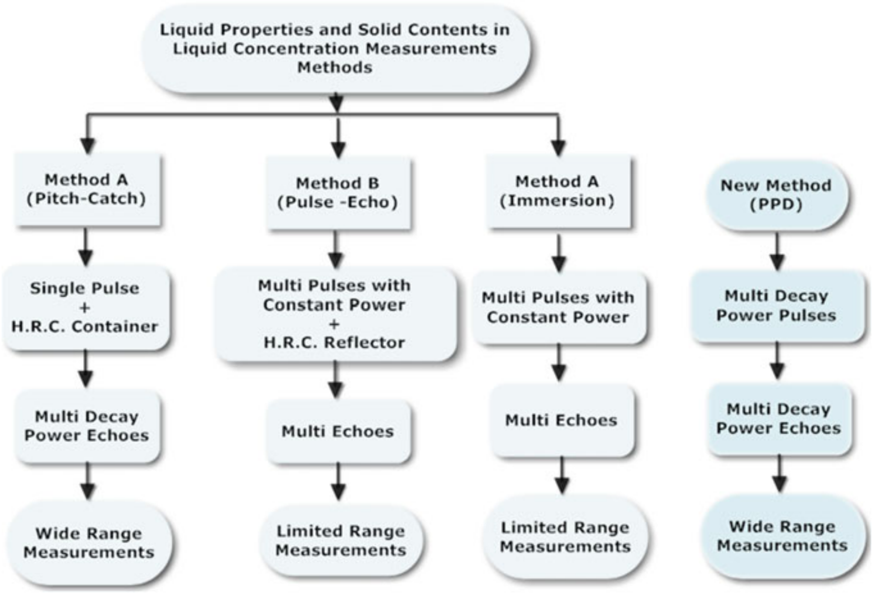

Fig. 2 Principles operation of A, B, C, and PPD method

- Dispensing with the use of a container or reflector with a high reflection coefficient (treatment method A and B).
- Expanding the measuring range to include very low concentrations (treatment method B and C).

Table 1 shows a comparison between currently three methods and the proposed method (PPD). Figure 2 illustrates the principle operations of the three mentioned methods and the proposed method. This new technique was tested using two containers made of stainless steel and Plexiglas, both containers filled in water and 5, 10, 20, 30, and 40 % Kaolin. Subsequent sections will give a detailed explanation of the new technology followed by a practical application.

2 Ultrasonic Pulser Design

The Power-Pulse Decay device (PPD) is a new technique that generates multi-decay power pulses. As mentioned above, the purpose of transmitting decay power pulses through a solution is to detect and measure various the concentrations of various particles.

A block diagram of the proposed ultrasonic pulser system (PPD) is shown in Fig. 3a. The PPD device consists of six hardware parts, panel control software, an I/O serial interface, the main controller, a high DC power supply, a pulse generator

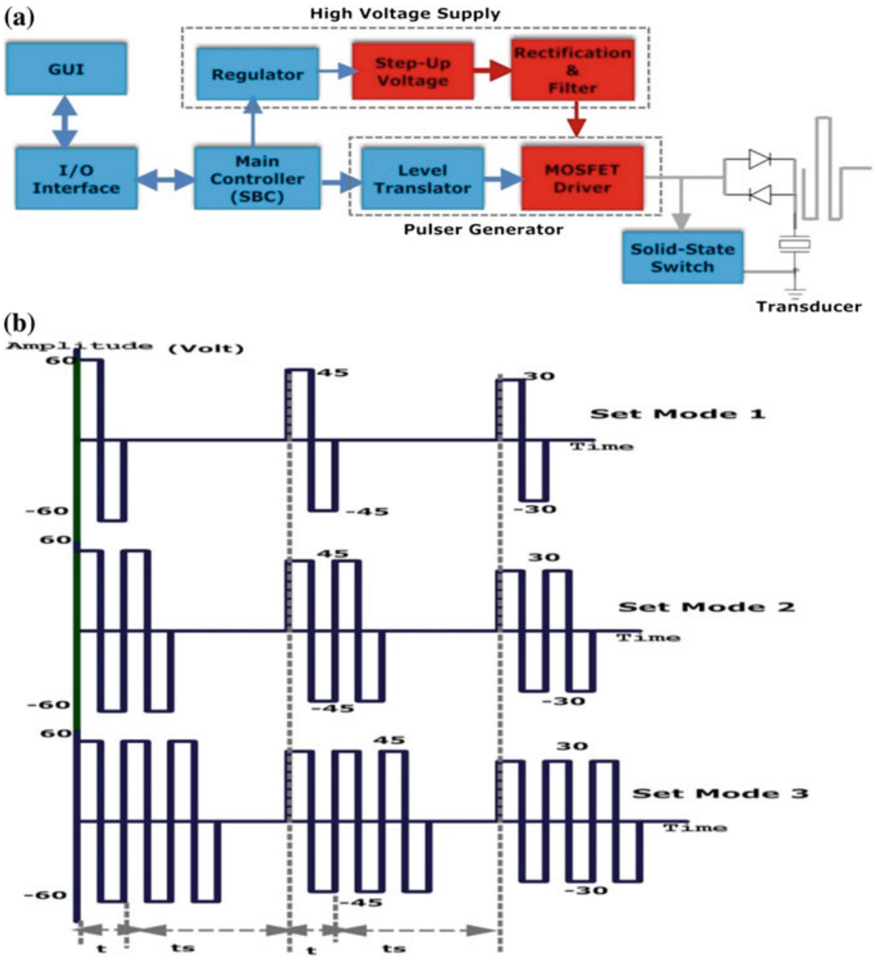

Fig. 3 A block diagram of the pulse-power decay ultrasonic pulser system (**a**), types of pulser sets mode (**b**)

and a solid-state switch. The transducer is driven by pulses from the decay power pulse generator, which delivers sets of high-voltage bipolar pulses. The advantage of using bipolar pulses is that the peak-to-peak pulse voltage can measure twice the voltage rating of the coaxial cable connecting the pulser and the transducer [11].

In addition, a bipolar pulse has a lower undesirable DC and a low-frequency component that may increase the leakage current compared to its unipolar counterpart. As a result, the size and cost of the cable can be substantially reduced, especially when a multi-element transducer array is used. The amplitude of the pulses in one set is determined by the output voltage of the high DC power supply, which converts the battery voltage of 12 V to ±20–75 VDC [1].

The amplitude of the received signal can be improved by increasing the pulse train amplitude, using a container with a low reflection coefficient and by driving the transducer at its resonance frequency. The frequency of the set pulses can be generated either by a programmable oscillator or by an external clock in which both methods are controlled by the main controller via control panel software. The pulse frequency, decay power factor, set size, time interval, set mode and start amplitude are programmed by the main controller with software control implemented by Visual Basic (Microsoft Inc.) [4].

Five modes of the pulse set are available with the PPD device; in the case of mode one, the pulse set transmits one pulse with the proper decay amplitude during one time interval, as shown in Fig. 3b. The schematic of the PPD device is shown in Fig. 3.

For the proposed technique with any experimental setup, the transducer records only the first individual signal (first echo), which corresponds to travel through the liquid. The first echo is the signal of interest (IS), and it occurs at the shortest time. To evaluate the performance of the PPD technique, a laboratory experiment in an industrial application field was conducted to detect and measure the concentration of kaolin in water. After verification of the performance of the PPD, this technique was adopted in our research. To obtain the attenuation measurements as a function of the frequency, the Fast Fourier transform (FFT) of the signal of the peak of interest (IS) for each pulse in the set was obtained for water as a reference and for the slurry [5, 8].

The data were obtained in ten steps, using the appropriate decay factor for the transmitted pulses and the receiver gains. Overlapping signals of interest (IS) were used to determine the effect of changing the amplitude of the pulse travelling through the *slurry*, and the data were normalised to a pulser voltage of ±75 V. Additionally, the data were corrected for the receiver gain. The results of the FFT analysis of the echoes were evaluated for *water*, and 10 % kaolin, Table 2.

3 Validation of PPD Design

The new PPD technique can be adaptive with wide application fields. In this research, the objective of the experiments was to evaluate the performance of PPD technique to gather ultrasound measurements for different percentages of solid concentrations in liquid. Invasive measurement is the most direct method of

Table 2 One set size 10, FFT amplitude of IS for tap-water and 10 % kaolin at 2 MHz

Pulse no.	Tape-water, FFT amplitude at 2 MHz	10 % kaolin, FFT amplitude at 2 MHz
1	3.51	3.262
3	2.089	1.558
5	1.243	0.758
7	0.863	0.505
10	0.425	0.208

achieving an accurate measurement. Hence, this method was used for all the experiments carried out for this paper. Using the assumption that 1 ml of tap water equals 1 g in weight, kaolin was mixed with tap water in concentrations of 10, 20, 30 and 40 % to create the different sets of slurries. These concentrations were measured by the weight of kaolin and tap water.

The vessel, shown schematically in Fig. 4, consists of a Plexiglas container and two transducers with a centre frequency of 2 MHz affixed to the outside of the container on opposite sides, using a pitch-catch method. The vessel walls have a thickness w of 3.2 mm and the inside walls are separated by a distance D of 4 cm. The temperature, measured by temperature sensor (LM35), is recorded. For simplicity, the temperatures for all the experiments were kept at room temperature (20 °C), between ±1 °C [10]. When the vessel is filled with water, less than 10 % of the ultrasound is reflected at the Plexiglas-water interface and the rest is transmitted into the water. At the opposite wall, 91 % is reflected at the water-Plexiglas interface. With the pitch-catch mode operating, the receive transducer records only the first individual signal, as it corresponds to travelling through the slurry. The "signal of interest" (IS) occurs at the shortest time and the path length for the Nth IS (for example the interest received signal of the fifth pulse of set) in the pitch-catch mode is $(2w + D + v \times T)$, where v is the speed of sound through material and T is the total time delay of Nth pulse; and calculated using (1):

$$T = (N - 1)(t_S + t) \tag{1}$$

where the t_s is the pulse spacing time and t is the bipolar pulse width. To obtain attenuation measurements as a function of frequency, the fast Fourier transform (FFT) of the peak of data were corrected for the receiver gain. The results of the FFT analysis of the "peak of interest" are shown for water, 10 %, and 40 % kaolin, Fig. 5. The effects of attenuation for water are clearly observed as the peak amplitude shifts to a smaller frequency as the IS number increases, as shown in Fig. 6.

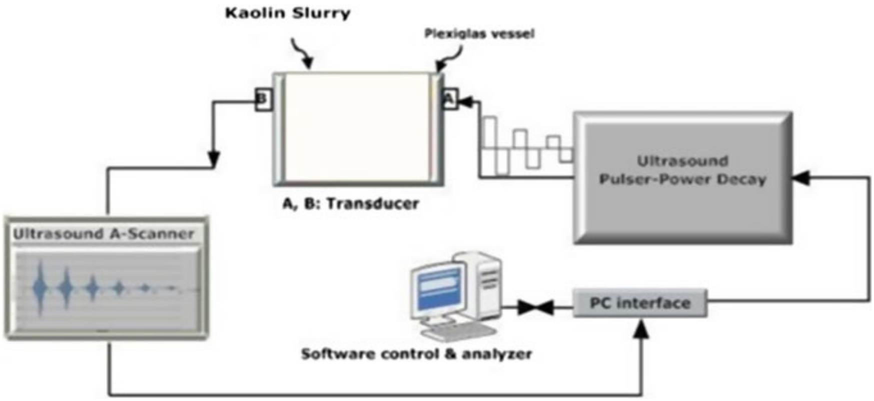

Fig. 4 Sketch experimental setup

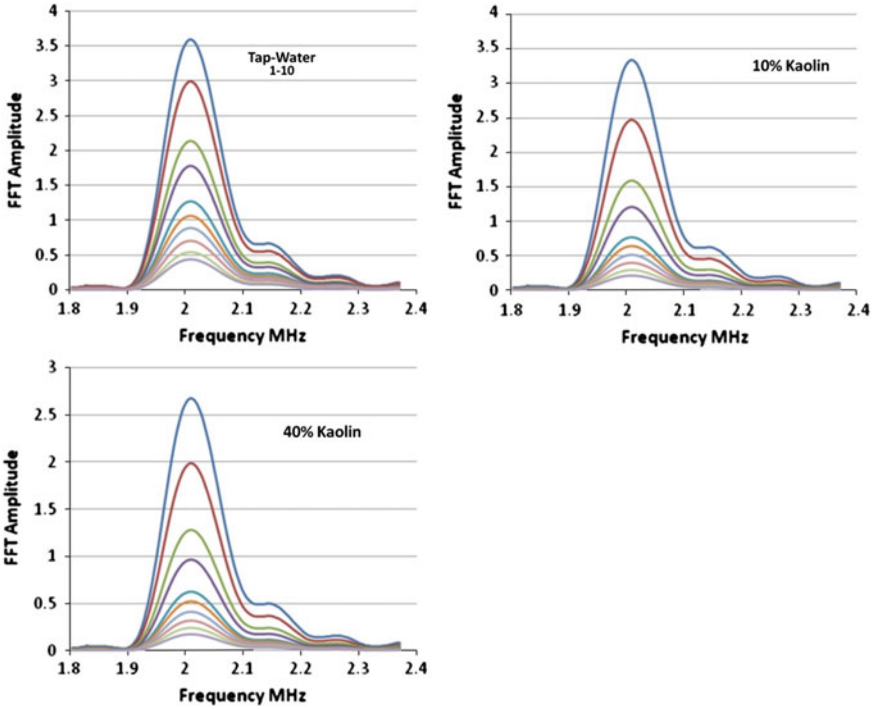

Fig. 5 FFT amplitude for one transmitted set size 10, propagated through water (as reference data), and test 10 % kaolin, and 40 % kaolin

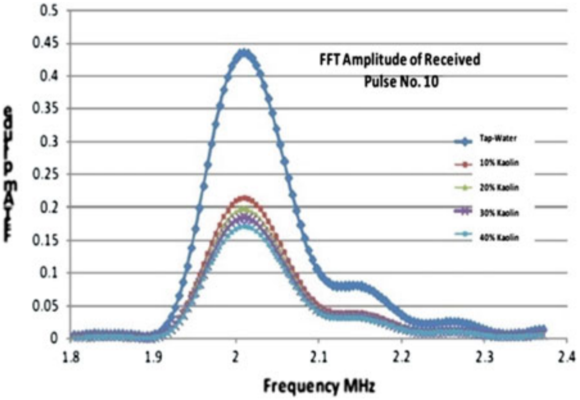

Fig. 6 FFT amplitude comparison of 10th interest signal received for reference data (water) and test data 10, 20, 30, and 40 %

4 Discussion

Data similar to were obtained for the kaolin slurries of 10, 20, 30, and 40 % kaolin by weight. The attenuation due to the 10 % kaolin slurry can be observed in Table 1 by the increasing separation between the FFT amplitudes for water and the slurry. The data for kaolin slurry 10 % wt concentration were compared with that for water by evaluating the natural logarithm of the ratio (FFT amplitude slurry/FFT amplitude water) for a specified frequency (2 MHz). The data exhibit straight lines and the interest signal (IS) for each set pulse was obtained for water and for the slurry. The data were obtained in ten steps, using appropriate decay factor for the transmitted pulses and the receiver gains. Overlapping interest signals (IS) were used to determine the effect of changing the pulser voltage travelling through slurry, and the data were normalized to a pulser voltage of ±75 V. Additionally, the slopes (S) were obtained. The lower pulses-power such as 40, 35, 30 V greatly affected by low concentrations of slurry than the higher pulse power for one transmitted set as shown in Fig. 3b. For example, the received pulse number 10 has 0.425 V while the amplitude of same pulse travelled through 10 % kaolin was 0.208 V (Table 1); therefore, to detect low concentrations with a long range of measurement, the set size should be increased (i.e., decreasing the decay factor leads to incremental increases in the amount of pulsed-power decay). Decreasing the decay factor leads to an increase in the number of pulses in one transmitted set and causes more generated lower-power pulses; this increase is limited by the high voltage supply. Due to the attenuation of the ultrasound waves propagated through slurry, the relationship between kaolin concentration and the attenuation was determined. The attenuation (α) was calculated using (3) [2].

$$\alpha = \frac{-20}{D}\log_{10} e^{S} \tag{2}$$

For a given frequency, a plot of the attenuation (α) versus the kaolin weight percentage (w) displays a straight line, Fig. 7, as expected. For example, when the

Fig. 7 Attenuation measurement (dB/cm) versus kaolin concentration wt%

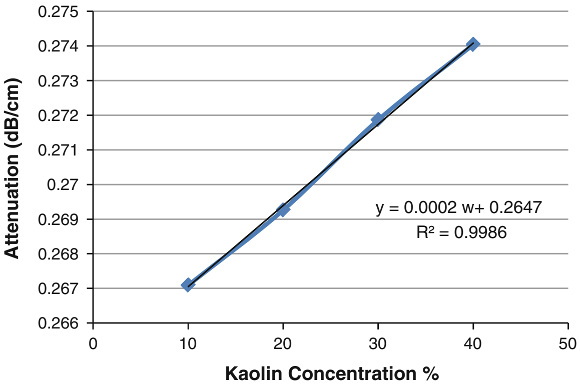

Table 3 The detection comprise between commercial and proposed technique for 10 % kaolin

Set pulse no.	Amplitude of commercial pulser (V)	Amplitude of PPD pulser (V)	Tap water FFT amplitude of		10 % kaolin FFT amplitude of	
			Commercial pulses	PPD pulses	Commercial pulses	PPD pulses
1	75	75	3.51	3.51	3.496	3.494
5	75	55	3.51	1.243	3.496	1.05
10	75	30	3.51	0.425	3.496	0.281

values of the attenuation at 2 MHz are extracted from Fig. 7, such a plot shows the following linear relationship:

$$\alpha = 0.0002\mathrm{w} + 0.2647 \tag{3}$$

where the slope has units of dB/cm wt%. Table 3 illustrates the differences between a commercial pulser and the PPD technique.

5 Conclusion

In this research, we developed a self-contained prototype of an ultrasonic decay power pulser system for the detection and measurement of the particle concentration in a fluid. The new technique demonstrates the system's ability to distinguish the presence of particles in a fluid at a concentration lower than 10 %, which is below the limit of detection of the current method with the same device settings.

The PPD ultrasound system that we built generates a multi-pulsed powered decay train for transducer excitation instead of a single negative pulse, which is used in the current pulser. The PPD also delivers variable transmitted ultrasound energy that will increase the level of the received signal interest for SNR improvement, and the accuracy of the concentration measurement is increased. The number of pulses per transmitted set is determined by the user based on the concentration detection level that is required. Although the pulser can generate pulse amplitude up to 75 V, we found that a pulse set with a set size of 10 and initial amplitude of 75 V was sufficient to distinguish the presence of particles in a fluid at a concentration of less than 10 %. The detection of concentration can be improved by increasing the set size, the pulse amplitude that was optimised in this study and the gain of the interest signal amplifier and by optimising the filter's receiver parameters. The interest signal (IS) was digitised and analysed by an ultrasound A-Scan device. The experimental results for the measurement of kaolin concentration based on the PPD technique are shown in Table 3. It can be clearly observed that the lower-order amplitude pulses are more attenuated than the first-order pulses (higher power pulses). *For example,* the echo of the tenth pulse is 0.425 and 0.281 V through water and water 10 % kaolin, respectively, while the echo for first pulse is 3.51 and 3.494 V. The new technique exhibited high performance as an instrument for measuring the percentage of sedimentation [6, 7], and it is applicable with all container materials. The amount of ultrasound energy received by the transducer can be increased using a transducer with a larger area or by adjusting the position of the transducer and the angle so that the maximum IS amplitude is sensed. The comparison results reveal that the PPD technique is more efficient than the classical technique for the pulser, especially for the detection of very low concentrations (5 %) of particles in a fluid.

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