Measurement of Solid in Liquid Content Using Ultrasound Attenuation

A. Q. Chen[1], S. Freear[2], D. M. J. Cowell

Institute of Integrated Information Systems,
School of Electronic and Electrical Engineering,
Faculty of Engineering, University of Leeds, Leeds LS2 9JT, UK

Emails: alexq.chen@yahoo.com[1], S.Freear@leeds.ac.uk[2]

ABSTRACT

This paper focuses on the relationship between acoustic attenuation and solid content in a liquid carrier. Using such a relationship, two techniques were discussed to enable precise measurements for different concentrations of Kaolin in water. The first technique uses the fast-Fourier-transform (FFT) amplitude, while the second technique uses the attenuation coefficient's gradient to discriminate the different concentrations.

In the past, others have used the ultrasound's velocity and attenuation measurements to characterise the different concentrations of Kaolin in water, but many have focused only on FFT measurements. This hinders precise measurements as it relies heavily on the positional information where the centre frequency is defined. Hence, in this paper the above second technique was suggested. The measurements presented were collected using a pair of transducers placed invasively in a cell facing opposite each other (Figure 1). This is known as the Pitch-catch mode and it is commonly used in ultrasound measurements. Such a method provides a direct and the shortest path for the sound wave to travel from the transmitter to the receiver. This paper discusses the above techniques and gives the comparison of their performances by ultrasonic characterisation of Kaolin slurries.

Keywords attenuation measurement, ultrasound, solid content

1 INTRODUCTION

Measuring the percentages of solids in liquid is desirable as many industries can use this information to control the quality of their products. In the process industries, this can help to monitor the contents of their processes. Using the knowledge of sound theory, preliminary determinations can be made by examining the different parameters such as time-of-flight (TOF) and the received signal's power. The measurements discussed in this paper are limited to a pair of transducers placed invasively in a cell facing opposite each other. This is known as the Pitch-catch mode. This method provides a direct and the shortest path for the sound wave to travel from the transmitter to the receiver. Kaolin was chosen for the measurement of solid in liquid content because of its inert nature and ease of preparation. The type of Kaolin used to create the slurries for all the experiments presented in this paper is Speswhite. It has a particle size distribution of ~60% smaller than 5µm and as many as ~3% having a size of 17µm when measuring with laser diffraction (RICHARDS et al. 2003).

The attenuation of the ultrasound signal is frequency dependant. Hence, analysis work can be carried out by using the FFT of the received signal. This paper discusses the two techniques that were used for analysing the attenuation of the received signal to discriminate the different concentrations of Kaolin slurries. The first technique uses the FFT amplitude to discriminate the Kaolin slurries concentrations; this technique was also described by Greenwood et al. (2006) to discriminate the different concentrations of silica slurries. The second technique extends the first technique by using the attenuation coefficient's (in decibels) gradient computed from the first technique. This technique enables more reliable precise measurements. In order to evaluate these techniques and their performance, they were applied on the experimental ultrasonic measurements.

2 THEORY

2.1 PROPAGATION OF ULTRASOUND

In an elastic material medium, sound wave is transmitted by the means of longitudinal waves. These are waves in which particle motion is in the same direction as the wave energy propagation. Like most signals, these waves can be diverted, scattered, reflected, refracted and absorbed. The additional noise from the surrounding where the sound wave passes through may cause it to distort as well. Interestingly, sound velocity varies between the types of medium it passes through. Hence, using this knowledge it is possible to determine the type of medium sound passes through by extracting its velocity. The velocity of sound (v) is given by

$$v = \sqrt{\frac{\varepsilon}{\rho}} \approx \sqrt{\frac{K}{\rho}} \;\; \textbf{\textit{where}} \;\; K = \frac{\omega}{v} \tag{1}$$

In solids, (ε) denotes elastic modulus and (ρ) denotes mass density. The elastic modulus will be replaced with adiabatic bulk modulus(K) when it is transmitted in fluid. This is because the substance's resistance to uniform compression should be taken into consideration instead (HEDRICK et al. 2005; MCCLEMENTS 1988). The bulk modulus discussed above refers to the negative ratio of stress and strain applied to the object. Similarly, the elastic modulus refers to the elasticity of the different material (HEDRICK et al. 2005).

2.2 ABSORPTION AND SCATTERING

The process of absorption usually refers to the changes of acoustic energy into heat energy. As mentioned by HEDRICK et al. (2005), LERSKI (1988) and MCCLEMENTS (1988), absorption will fall off exponentially with distance. Due to this, an ultrasonic wave will be attenuated when it travel through a material (i.e. its amplitude decreases with distance travelled). The absorption of an ultrasonic beam can be explained by

$$A = A_0 \exp(-\alpha x) \tag{2}$$

here (A) is the amplitude at position x, (A_0) is the initial amplitude of the signal$(x = 0)$, (α) is the attenuation coefficient which has a unit of Nepers per metre(Np/m), and (x) is the distance traversed by the beam. In liquids, shear and bulk viscosity, thermal conduction and molecular relaxation are the main factors for absorption. In solids, absorption is generally lesser at a given frequency when compared to liquid and it is much lesser in gases. Even then, this should not be overlooked, as many forms of absorption are present in solids which have to be considered (BHATIA 1967).

Scattering of an ultrasonic signal usually occurs when a material is not homogeneous. In this paper, this occurs when the signal strikes a Kaolin particle in the liquid which it is passing through. As explained by LERSKI (1988), most of the signal energy passes beyond a single scatter without change. The energy that is loss is redirected in all directions. The magnitude of scattering is dependent on the particles per volume, size, acoustic impedance, and frequency (HEDRICK et al. 2005).

2.3 ATTENUATION

Attenuation can be described as the overall loss of power in an ultrasound pulse. These losses include all forms of energy loss, most of which results from absorption and reflection (Meire and Farrant 1995). The attenuation coefficient of a medium contributes from absorption and scattering. This is medium specific and frequency dependent. Thus

$$\mu = \mu_A + \mu_S \tag{3}$$

where (μ) is the medium's attenuation coefficient, (μ_A) is the absorption coefficient and (μ_S) is the scattering coefficient (LERSKI 1988; HEDRICK et al. 2005). By convention the attenuation coefficient is commonly defined as dB/m, where 1dB = 8.686Np.

In this paper, two techniques were used to analyse the attenuation of the received signal. The first technique uses the different FFT amplitude to discriminate the different concentrations of Kaolin slurries. This can be observed by using a fix centre frequency (f_c). This can be obtained by

$$f_c = \frac{f_{\min} + f_{\max}}{2} \tag{4}$$

where $(f_{\min})$ is the minimum frequency and $(f_{\max})$ is the maximum frequency of your defined frequency bandwidth. From this equation, it can be noticed that the results may change if (f_c) changes due to $(f_{\min})$ and $(f_{\max})$ is defined differently. Therefore, it is important to define them appropriately, as it will affect the precision of the measurement system. The second technique uses the gradient of the attenuation coefficient in decibels to discriminate between the different concentrations of Kaolin slurries. The attenuation coefficient can be expressed in decibels by converting the FFT values calculated in the first technique into logarithmic values. This can be done by using

$$20\log_{10}\left[\frac{I_K}{I_W}\right] \tag{5}$$

where (I_K) is the FFT of the Kaolin slurries concentrations and (I_W) is the FFT of tap water. Plotting the calculated results, it can be observed that the gradient varies between the different concentrations (Figure 5). Therefore, this demonstrates that this technique can be used to discriminate the different concentrations of Kaolin slurries.

The attenuation measurement is not without its flaws. It can be affected by temperature. As explained by Parker (1990), attenuation could increase with temperature and frequency. Hence, in our discussion above, the temperature should be kept consistent and the same frequency should be used to transmit when measuring all the different concentrations of Kaolin slurries.

3 EXPERIMENTAL SETUP

The objective of the experiments was to gather ultrasound measurements for different percentages of solids in liquid. Invasive measurement is the most direct method of achieving an accurate measurement. Hence, this method was used for all the experiments carried out for this paper. Using the assumption that 1ml of tap water equals 1g in weight, Kaolin was mixed with tap water in concentrations of 0%, 10%, 20%, 30% and 40% Kaolin to create the different sets of slurries. These concentrations were measured by the weight of Kaolin and tap water. The analysis work for these measurements will be discussed later in this paper. In order not to complicate matter, the temperatures for all the experiments were kept at room temperature (20°C), between $\pm$ 1°C.

The transducers that were used for transmitting and receiving were setup in a metal cell for invasive measurements. Figure 1 shows the sketch diagram of how the transmitting and receiving transducers were aligned horizontally opposite one another and 20mm apart. This method is known as the Pitch-catch mode. It provides the most direct and the shortest path for the sound wave to travel from the transmitter to the receiver. The same brand and the same model of transducers were used as the transmitter and receiver (Technisonic General Purpose transducer, IPM-0202-GP). In order to receive the best response, the alignment between the transducers is pivotal. Misalignment may result in attenuated received signal (power loss).

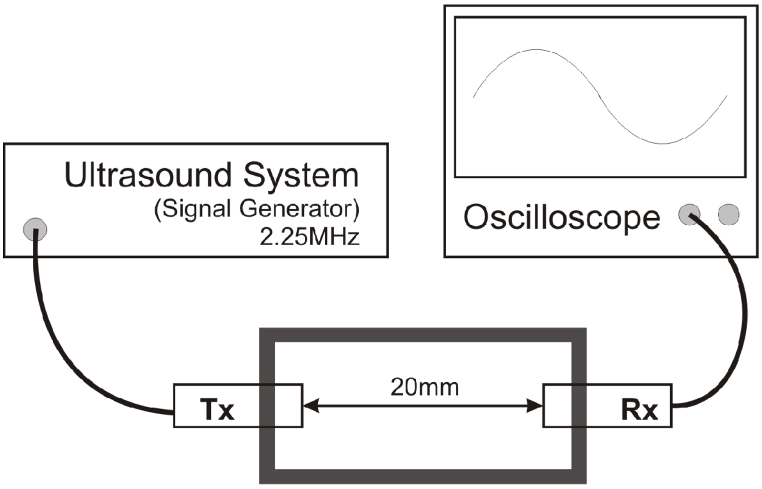
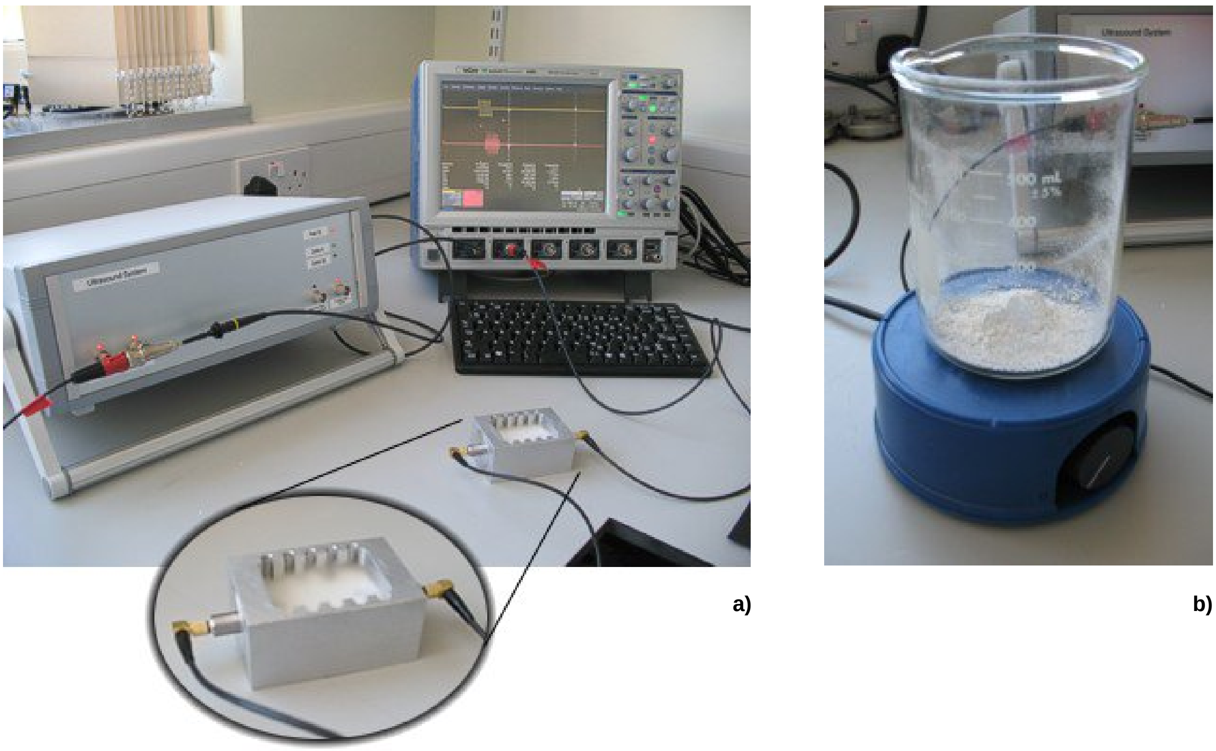


FIGURE 1: Sketched experimental setup

The transducers were connected to other electronic devices to enable measurements and analysis work to be carried out. The transmitting transducer was connected to the ultrasound system that was built by us. It was configured to produce a signal that transmits at a frequency of 2.25MHz, where the peak-to-peak voltages were ± 100 volts. This configuration was used for all the measurements presented in this paper. The plan of the experiment setup and the overall sketched connections for the components is shown in Figure 1. Figure 2a shows the actual experiment setup when an experiment was carried out. It also shows the cell that was used to hold the Kaolin slurries when the measurements were taken. In Figure 2b, it shows the magnetic stirrer and the glass breaker that was used to create the Kaolin slurries.



a) **b)**

Figure 2: Actual experimental setup and equipments

4 RESULTS AND DATA ANALYSIS

The experiments discussed in this paper are focused on slurries of Kaolin mixed with tap water. Different techniques were used to discriminate the different concentrations of Kaolin in water (The different concentrations of Kaolin slurries were measured by weight). The discussions of the analysis techniques used and the measurements that were gathered are presented below.

Figure 3 shows the received signals for tap water and the concentration of 40% Kaolin slurry. Even at this stage, one can observe that there is a difference in TOF measurements. The signal for the 40% Kaolin slurry concentration can also be observed to be more attenuated when compared to tap water. Therefore, from these observations, further investigation on attenuation for the received signals is suggested.

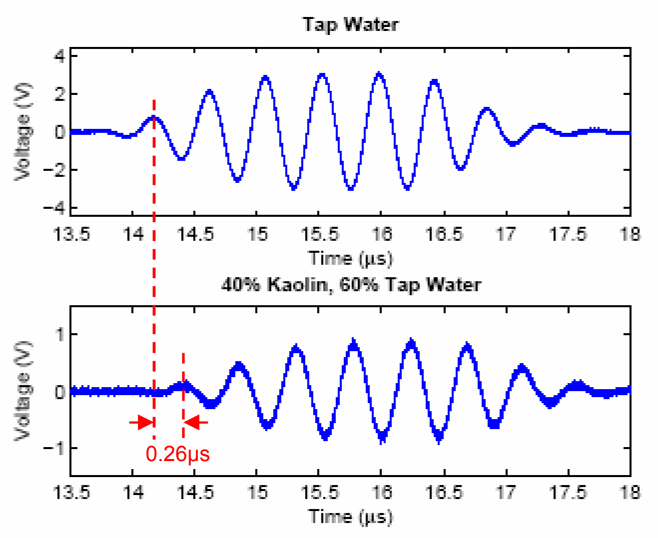


Figure 3: Received signals

In order to examine attenuation, the received signals were transformed into the frequency domain for FFT analysis. Plotting these discrete values, Figure 4 shows the combined FFT graph for all the different concentrations of Kaolin mixed with tap water that were measured. Here the different FFT amplitude for the different concentrations of Kaolin slurries can be determined by using a fixed centre frequency (f_c) as discussed earlier in equation (4). Using this technique, one can notice that the received signal becomes more attenuating as the concentrations of Kaolin increases. The results presented using this technique (Figure 4) can be justified when compared with Greenwood et al. (2006) analysis.

It can be argued that the FFT amplitude for the different concentrations of Kaolin slurries can be inconsistent if $(f_{\min})$ and $(f_{\max})$ is defined differently. This is quite true; furthermore, in the event when the composite of the slurries is more complex; causing multiple interfaces, it may be difficult to compute f_c. Therefore, the approach to retrieve the gradient of the attenuation coefficient in decibels (the second technique that was discussed previously) for the signals is suggested.

The attenuation coefficient in decibels of the received signals for the different concentrations of Kaolin in tap water is presented in Figure 5. As discussed earlier, this can be described by using the decibel scale (dB/MHz/cm). These results were obtained by applying equation (5) to the results of the first technique (Figure 4). It was observed that by applying the second technique, the attenuation coefficient's gradient of the different concentrations of Kaolin slurries could be used to differentiate them. From the graph shown in Figure 5, it was noticed that when the concentrations of Kaolin increases, the steepness of the gradient increases as well. This is a proof-of-concept that using this method to measure the solid in liquid content, it is more reliable as it does not rely on any predefined values. It can notice that the gradient of the attenuation coefficient will be always consistent for the same set of results measured. This can help to improve the reliability of the system's precision.

Observing the results presented in Figure 5, it suggests that a better resolution of Kaolin slurries concentrations is possible to be detected when this technique is applied.

For these claims, the distance between the transmitting and receiving transducers (cm) and the transmitting frequency (2.25 MHz) was kept the same for all the experiments presented. Hence, using a calibrated system to compute the different attenuation coefficient's gradient (in decibel), different concentrations of Kaolin in tap water can be discriminated.

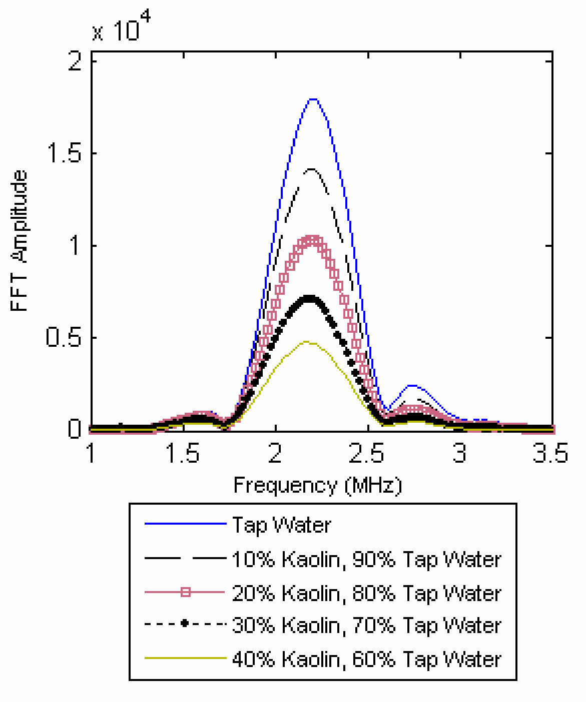


FIGURE 4: FFT Analysis for the different concentrations of Kaolin in tap water

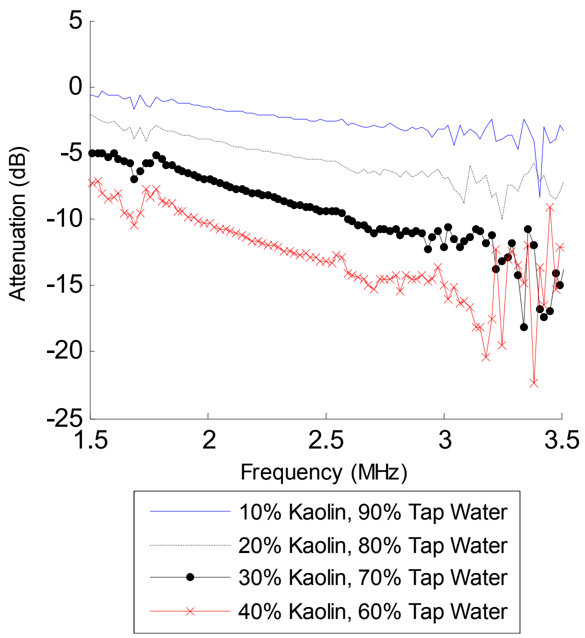


FIGURE 5: Attenuation coefficient for the different concentrations of Kaolin in tap water

5 CONCLUSION

The ability to measure the solids in liquid contents is a useful application both industrially and academically. From the research and experiments presented above, it demonstrated that ultrasound could be used to discriminate the different concentrations of Kaolin slurries. This can be done using a few approaches. The first technique discussed uses the difference in FFT amplitude to discriminate the different concentrations of Kaolin slurries. This is a common technique used where a fixed f_c can be computed by defining $f_{\min}$ and $f_{\max}$. The results gathered from this technique may have some ambiguity. In the event if f_c changes, the result gathered for the same set of measurements may change as well. Hence this will affect the reliability for the precision of the measuring system. The second technique discussed uses the difference in the attenuation coefficient's gradient (in decibel). This technique was suggested due to the inconsistency of using a fix f_c method to do precision measurements or when $f_{\min}$ and $f_{\max}$ are difficult to determine. The results gathered using the second technique for the same set of measurements is a proof-of-concept that this technique is more consistent. Therefore using this technique, precise measurements will be more reliable. From the results presented above in Figure 5, it strongly suggests that a better measurement resolution can be achieved. It is recommended if one intends to use either of the techniques discussed above to measure solids in liquid content, repeated measurements for the concentrations of Kaolin slurries should be taken to get a better average measurement. This will contribute to a more accurate system being created.

6 ACKNOWLEDGEMENT

The first author acknowledged the support in attending the conference from the VCIPT.

7 REFERENCES

BHATIA A.B. (1967), *Ultrasonic Absorption*, Oxford University Press, Inc.

GREENWOOD M.S., ADAMSON J.D., BAMBERGER J.A. (2006), *Long-path measurements of ultrasonic attenuation and velocity for very dilute slurries and liquids and detection of contaminates*, Ultrasonics, vol. 44, pp.461-466

HEDRICK W.R., HYKES D.L., STARCHMAN D.E. (2005), *Ultrasound Physics and Instrumentation*, 4th Edition, Elsevier

LERSKI R.A. (1988), *Practical Ultrasound*, IRL Press Limited, pp.11-13

MCCLEMENTS D.J. (1988), *The Use of Ultrasonics for Characterising Fats and Emulsions*, PhD Thesis, University of Leeds, Leeds, UK

MEIRE H.B., FARRANT P. (1995), *Basic Ultrasound*, John Wiley & Sons, Inc., pp.10-17

PARKER D., LEC R.M., PENDSE H.P., VETELINO J.F. (1990), *Ultrasonic Sensor for the Characterisation of Colloidal Slurries*, IEEE Ultrasonics Symposium, pp.295-298

RICHARDS S.D., LEIGHTON T.G., BROWN N.R. (2003), *Sound absorption by suspensions of nonspherical particles: Measurements compared with predictions using various particle sizing techniques*, J. Acoust. Soc. Am., vol. 114, pp.1841-1850