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Non-contact ultrasonic quality measurements of food products

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Abstract

This paper describes the application of a non-contact ultrasonic system to food inspection, using electrostatic transducers and signal processing techniques. The system, which operates in through-transmission mode, is used to detect physiochemical changes and density variations in food. One application is to monitor coagulation processes, caused by destabilization in milk-based products. It is shown that the amplitude of the signal varies with time after the pH of such samples was lowered, resulting in destabilisation. Various types of samples of different pH values were used in order to illustrate that the air-coupled system was sensitive to such changes. Non-contact imaging has also been performed to follow this process, during which gel formation could be identified. In addition, changes in oil properties due to temperature variations have also been measured using the non-contact system. The measurements can be achieved without contact to the test samples, and thus has the potential for the rapid inspection of various types of food products.

Keywords: Non-contact ultrasound; Agglomeration; Coagulation; Crystallisation

1. Introduction

There is growing pressure within the food industry to improve the measurement of food quality, particularly within packaged food products. This inspection may include looking for time-dependent physical changes, non-uniformity of the product, or contamination. The need for reliable inspection is becoming increasingly critical due to the continued automation within the industry and the shift in consumer choice towards more prepared foods.

There has been recent interest in using ultrasound to investigate factors such as physical change and contamination in food products (Bamberger & Greenwood, 2004; Javanaud, 1998; Zhao, Basir, & Mittal, 2003). One reason for this is that changes in acoustic properties can be related to density changes in the food product (McClements, 1995). Ultrasound has the ability to differentiate between both the propagation velocity within various media, and the differences in acoustic impedance between different regions within a given volume. Thus, using the usual contact or immersion techniques, ultrasound can be used to measure the moisture content of food products (Steele, 1974), oil properties at various temperatures (Chanamai, Coupland, & McClements, 1998) and for liquid level measurement (Hull, Muumbo, & Whalley, 1995). However, to date these techniques require a coupling medium between the test sample and the transducer surface. The use of a couplant such as water may not always be suitable for certain inspection situations, especially when the material property might change, or where contamination or damage would result. For these reasons, X-rays have been widely used to detect anomalies or foreign objects present in food (Dearden, 1996; Patel, Hannah, & Davies, 1994; and Penman, 1996) usually in through-transmission. Other techniques such as magnetic resonance imaging (MRI)

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can be used to study the temperature distribution in food samples (Nott, Hall, Bows, Hale, & Patrick, 2000), although this is an expensive and complicated method. In the past, the authors have successfully applied the non-contact ultrasonic system to measure and image the properties of food in the food containers (Gan, Hutchins, & Billson, 2002). This paper extends the applications of the ultrasonic techniques to measure physiochemical change in palm oil and milk-based drinks.

In the case of palm oil, physiochemical changes such as crystallisation are important in determining the condition of the finished products. The control of the crystallisation process can be complicated, and it is difficult to monitor the process non-destructively (Marshall, Tebbutt, & Challis, 2000), and reprocessing is sometimes required. In some cases, the product can be rendered unusable. It is thus important to have a cost effective and reliable system. Contact ultrasonic approaches have been reported in which the crystallisation behaviour of palm oil has been measured (Hodate et al., 1997). The study was performed using ultrasonic velocity measurements under both cooling and heating processes. The rates of crystallisation of palm oil were monitored by the changes in the ultrasonic velocity values, which increase with increasing amount of fat crystals in the palm oil phase. Here we will study the extension of the technique to easily scanned non-contact methods.

There is also growing pressure within the food industry for the routine monitoring of changes in the quality of complex viscoelastic products after processing, with a view to extending shelf life. An example is milk-based products, where the quality changes according to temperature and environment, especially so when storing these products for a long period of time. Papadakis (1976) described how ultrasonic velocity and attenuation are very valuable properties when studying the physical properties of matter. Coagulating milk, being a liquid to semi-solid system, is especially suitable for ultrasonic measurement (Gunasekaran & Ay, 1994). Nassar, Nongaillard, and Noel (2001) used low-frequency ultrasound to monitor milk gelation, and looked at the relationship between physical properties and ultrasonic time-of-flight, using two piezoelectric contact transducers. Another ultrasonic technique was reported by Bakkali et al. (2001), who measured milk coagulation time using a pulse–echo immersion technique. There are various other methods that can be used to monitor changes in the properties of milk-based products, such as viscometry (Kopelman & Cogan, 1976; Korolczuk & Maubois, 1987; Lopez et al., 1999; Shulz, Seng, & Krenkel, 1999) and thermal conductivity (Bruno, Grasso, Spagna, Matteo, & Micione, 1986; Passos et al., 1999). Optical techniques have also been widely used in measuring coagulation. This was achieved by monitoring the absorption of light due to the change of enzyme activities. The rate of light absorption is also found to depend on the fat content of milk (Castillo, Payne, Hicks, & Lopez, 2000; Herbert, Riaublanc, Bouchet, Gallant, & Dufour, 1999). Work performed by Payne (1995) indicated that the reflectivity of a coagulated area was twice that of a standard milk sample. Another simple method such as visual inspection has also been carried out by Berridge (1952) to measure clotting of milk in bottles and to study the time taken for coagulation process. The applications of these studies are useful for manufacturer especially for food processing, for example in cheese making. The time taken for coagulation to occur (usually referred to as the cutting time) is often used to determine when to cut the curd and drain the whey (Benguigui, Emery, Durand, & Busnel, 1994). The accuracy of cutting time is important to maintain the quality of cheese. In addition, the change in coagulation time is useful in comparing strengths of different enzyme solutions.

To date, ultrasonic measurements on food products have been performed primarily using contact or water-coupled techniques. However, this approach is unsuitable for production line inspection especially when the product is moving on a conveyor belt. The objectives of this work were to study the feasibility of using non-contact ultrasonic techniques to characterise such food materials, with a view to providing a potential method capable of industrial implementation. In this paper, measurements were performed using a pair of capacitive devices in air, with application of a pulse compression signal processing technique (Ermolov, Stor-Pellinen, & Luukkala, 1996; Izuka, 1998; Rao, 1994; Rao & Mehra, 1993). This processing is necessary to recover signals buried in noise, as a result of the large acoustic impedance mismatch between air and the container. Two types of experiments will be described in this paper. Firstly the non-contact ultrasonic technique has been used to study the physiochemical change of palm oil at different temperatures. Secondly the system has been used to study the viscoelastic properties of milk-based products as the pH level changes. In this part of the experiment, different types of samples which have been treated by different acid level were used. This is to illustrate the sensitivity of the air-coupled system in detecting changes caused by different pH reading.

2. Apparatus and experimental procedure

The technique makes use of a broad-bandwidth ultrasonic chirp signal, which can be defined (Gan, Hutchins, Billson, & Schindel, 2001) as

$$C(t) = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi t}{T}\right)\right] \sin\left(\omega_s t + \frac{\pi B t^2}{T}\right) \quad 0 \leqslant t \leqslant T, \tag{1}$$

where ω_s is the starting angular frequency (Hz); B is the bandwidth of the signal (Hz); T is the duration of the pulse (μs).

A compressed pulse signal is produced by correlating the signal that has passed through the container (and which has a very low signal-to-noise ratio (SNR)) with a reference signal in the form of the original chirp (Cook, 1960; Gan et al., 2001). The advantages of the pulse compression approach are

(1) Because a chirp is a complex coded waveform, it can correlate well only at a single well defined time-of-arrival (for each arriving chirp), and therefore the accuracy of time-of-flight measurements can be greatly improved.
(2) A coded waveform has the advantage that it can be detected when the received chirp level is embedded in noise (i.e., since the noise is random and thus uncorrelated with the chirp shape).
(3) High ultrasonic energy levels can be transferred into a material due to the use of a chirp signal, to give a good SNR.

The experimental arrangement used for non-contact inspection of food properties in a container is as shown in Fig. 1. The experiments used a pair of capacitance transducers to generate and detect the chirp signals of the type described above. The design of the transducer has been described previously by Bashford, Schindel, Hutchins, and Wright (1997) Hutchins, Schindel, Bashford, and Wright (1998). The transducer consists of a micro-machined silicon backplate, which contains arrays of small cylindrical holes. These holes act as air springs underneath the Mylar membrane. This type of transducer can be used as either a source or detector. When acting as a source, a transient driving voltage could be applied, together with an optional dc bias

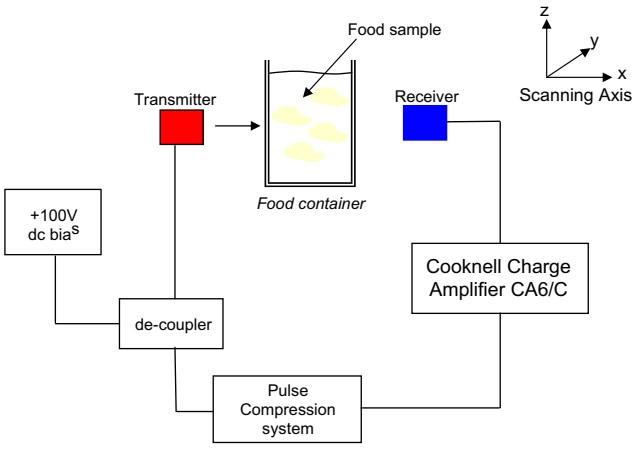

Fig. 1. Apparatus for measuring changes in liquid foods within a Plexiglas container using non-contact air-coupled ultrasound.

voltage and cause the membrane to vibrate and thus generates ultrasound. As a receiver, the bias voltage is required to give charge variations when the membrane moves.

The transducers in the present experiments had an active aperture of 10 mm diameter. The transmitter, which had a membrane thickness of 5 μm, was driven by an NCA1000 pulser/receiver unit. The output chirp signal with the centre frequency of 500 kHz from the NCA1000 system was superimposed upon a +100 V dc bias using a capacitive decoupling circuit before being applied to a capacitance source of bandwidth 1.5 MHz. The transmitted chirp signal across a test sample was captured by another electrostatic transducer, this time with a membrane thickness of 2.5 μm. Two types of membranes thicknesses have been used. A thicker membrane has been used at the source in order to withstand the high voltage generation pulse and to avoid membrane breakdown. As a receiver, a thinner membrane has been used so that the sensitivity can be increased. The distance between the source and receiver was adjusted to fit the length of the test object. The detected signal was then amplified by Cooknell CA6/C charge amplifier with a gain of 250 mV/pC and a 100 V bias. The response was then fed back into the NCA system for further signal conditioning and processing.

2.1. Non-contact ultrasonic measurement of palm oil

The first experiment was carried out to observe the change of acoustic property of palm oil due to variations in temperature. In this experiment, unrefined palm oil has been used, because it can be easily obtained and is of interest to potential industrial partners. The unrefined palm oil used in this experiment was heated to a temperature of 60 °C before being placed within a Plexiglas cell with a 3 mm wall thickness and an area of 70 mm by 70 mm. Time-of-flight data was recorded against temperature, the latter measured with a digital thermocouple device, in order to observe the change in state of the heated palm oil as it cooled down to room temperature. The air-coupled measurements were compared to those obtained using two broadband 10 MHz piezoelectric contact transducers attached to the walls of the container. The transmitter in this case was driven using a Panametrics pulsar/receiver system and the received signal was fed into Tektronix TDS540 digital oscilloscope (Beaverton, USA) for signal averaging. During the cooling period, ultrasonic measurements were performed simultaneously at 5 min intervals. Two parameters were recorded: the time-of-flight of ultrasound in the oil, and changes in through-transmitted amplitude. The former leads to estimates of longitudinal velocity changes, while the latter measures the amount of ultrasonic attenuation caused by changes in the oil. Each experiment was

repeated twice and an average reading was taken from the collected data.

2.2. Non-contact ultrasonic measurement of milk-based products

Experiments were also performed on three types of commercially-available milk-based products: full-fat milk at pH ~ 5.5, a strawberry-flavoured milk drink (a mixture of skimmed-milk, sugar and stabiliser with a pH of ~6.5) and a similar banana-flavoured milk drink at pH 6.4. In order to show that the system can detect changes at different pH levels, various mixtures were used. In these cases, the product was destabilised by reducing the pH with sulphuric acid to the 4.5–5.0 range. The pH reading was measured using litmus paper. The transmitted ultrasonic signals were collected at 60 s intervals, with ultrasonic amplitude the principal parameter measured. Imaging experiments were also performed after the pH had been reduced, by scanning the transducer pair in air parallel to the flat surfaces of the container walls. The transducer pair was moved along the x-axis with a step size of 1 mm, to a total range of 40 mm (see, Fig. 1). When this was done, the transducers were then moved in the z-direction with a step size of 4 mm. The total area of the side scan was 40 mm × 36 mm. Images were then formed of spatial variations in through-transmitted amplitude.

3. Results and discussion

3.1. Non-contact ultrasonic monitoring of palm oil crystallisation

The first experiment was carried out to understand how the frequency of the ultrasonic signal was affected by crystallisation process. Two different chirp centre frequencies at 500 kHz and 700 kHz were used to monitor a palm oil sample during crystallising stage starting from approximately 35 °C. It can be seen from the results in Fig. 2 that attenuation of the ultrasonic signal becomes more sensitive to change in palm oil structure at the higher frequency. This is thought to be due to the wavelength decreasing at higher frequencies, making the ultrasonic signal more comparable to the particle size, leading to increase scattering of the signal and lower transmission amplitudes.

The non-contact ultrasonic palm oil measurements were then repeated with simultaneous measurements using the contact transducers. Changes in the two ultrasonic parameters, i.e., ultrasonic amplitude and time-of-flight between the two transducers were recorded in each case, and the results for received amplitude are shown in Fig. 3. The air-coupled measurements were recorded using a chirp signal with a centre frequency of

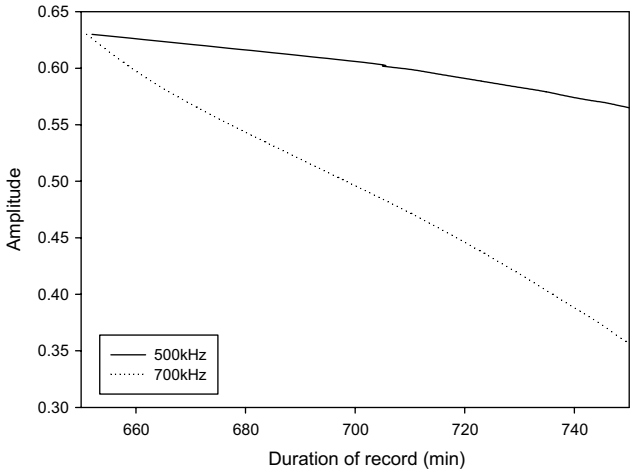

Fig. 2. Change in air-coupled through-transmitted ultrasonic signal amplitude at centre frequencies of 500 kHz and 700 kHz with time, for a palm oil sample. This was cooled and crystallised from a temperature of 60 °C.

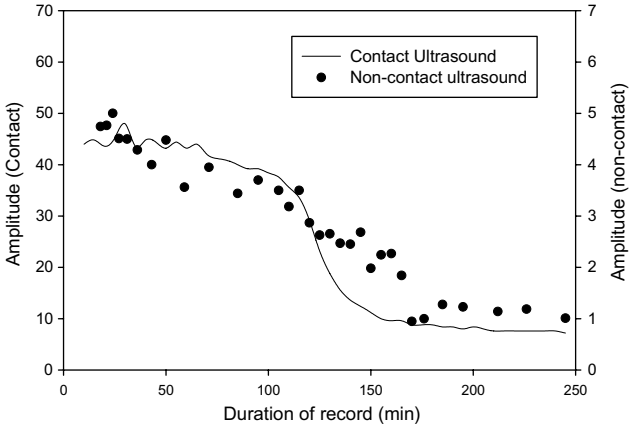

Fig. 3. Comparison of signal amplitudes produced by both contact measurements (continuous line) and non-contact air-coupled measurements (dots) as a function of time, as palm oil was cooled from 60 °C to room temperature.

700 kHz and a bandwidth of 600 kHz. It can be seen from the results that both contact and non-contact measurements are well correlated. The received amplitudes reduced as the temperature itself decreased, as a function of time. Note the discontinuity in the data. Up to approximately 115 min of elapsed cooling time, the sample was in liquid form (see Fig. 4(a)). As the rate of change of the temperature slows down, (i.e., from 115 min onwards), the oil property changed its state, and crystallisation started to form in the oil. This is shown in Fig. 4(b). The steep decrease in amplitude between 115 min and 175 min in Fig. 3 was due to crystallisation, which caused increased scattering of ultrasound. From 175 min onwards, the transition from liquid to solid particles was largely completed. As oil particles merged, attenuation increased due to greater

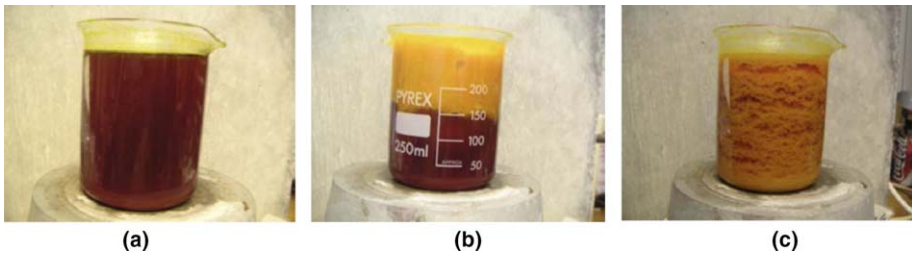

Fig. 4. Photograph of palm oil at different times during the experiment of Fig. 3, taken at (a) 0 min (60 °C), (b) 115 min and (c) 175 min (22 °C).

scattering. The amplitude was also affected by the increased density, and hence the acoustic impedance (the product of density and longitudinal velocity) of the media. The appearance of oil at room temperature is shown in Fig. 4(c).

The time-of-flight was also monitored with time, and the results are shown in Fig. 5. As will be seen, the time taken to travel across the sample decreased as the temperature reduced (i.e., at greater times). The time of arrival data is consistent with the air-coupled through-transmission amplitude data shown in Fig. 3 in that there are phase transitions at $T_1 = 115$ min and $T_2 = 175$ min, shown as discontinuities in slope of the graph at these temperatures. It can be seen from the results that there is a slight variation in the results between the contact and non-contact techniques. This is thought to be due to the fact that the temperature of the medium affects the contact transducer, whereas the non-contact technique is not affected. The results show that the non-contact system was measuring the crystallisation effect, and was less affected by changes in temperature.

3.2. Non-contact evaluation of milk-based products

The sample in the container was now replaced by milk-based products. Experiments were performed in which signals were transmitted across a Plexiglas container filled with full-fat and strawberry milk. The results are shown in Fig. 6. It can be seen that the amplitude of the signal across the strawberry milk (solid line) is much lower when compared to the signal in full-fat milk (dashed line). The greater attenuation should be attributable to the additional proportion of sugar, concentrated strawberry juice and stabilisers in the strawberry milk. In addition, the time-of-arrival of the received signal for the strawberry milk sample is 0.8 μs faster than for the full-fat milk, again indicative of the extra ingredients.

Further tests were performed, in which the elastic properties of the milk drinks were monitored as the pH was lowered. Fig. 7(a) shows the amplitude of the first cross-correlation peak, for the full-fat milk sample which had been contaminated with sulphuric acid. A reduction in the pH to 5.0 caused the milk drink to destabilise, and it can be seen from the figure that the received through-transmission amplitude reduced by approximately 28% over a period of 150 min. The dots represent the actual collected data at intervals of 60 s. A similar test was carried out on a strawberry milk sample which was reduced to a pH level of 4.5. Fig. 7(b) shows that the amplitude reduced from 0.023 to 0.01,

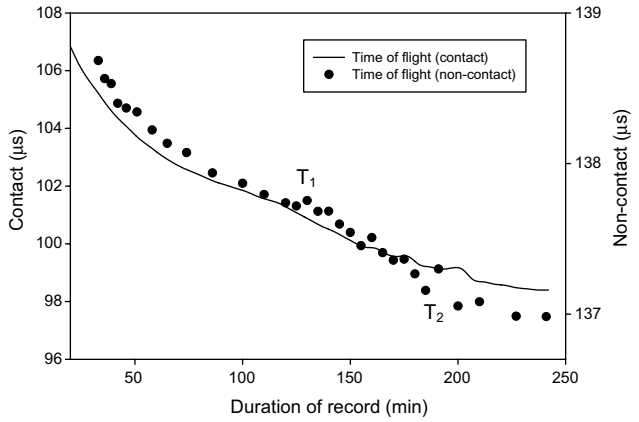

Fig. 5. Variation of ultrasonic time-of-flight across palm oil as temperature changes from $T1$ of 33 °C to $T2$ of 22 °C. $T1$ and $T2$ denote phase transitions.

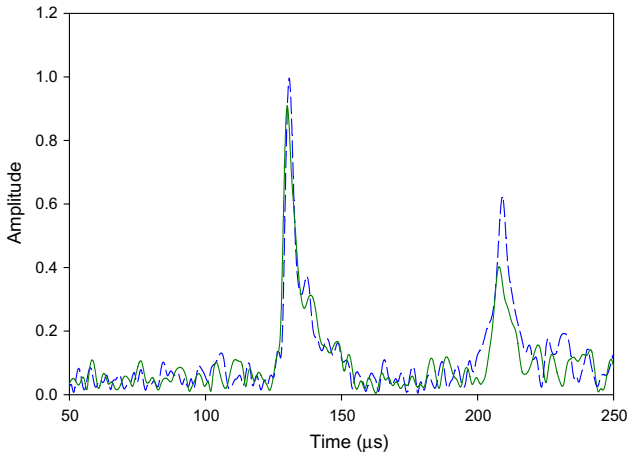

Fig. 6. Comparison of received ultrasonic signals after processing with pulse compression, following propagation across a Plexiglas container filled with either 3.6% full-fat milk (dashed line) or strawberry milk (solid line).

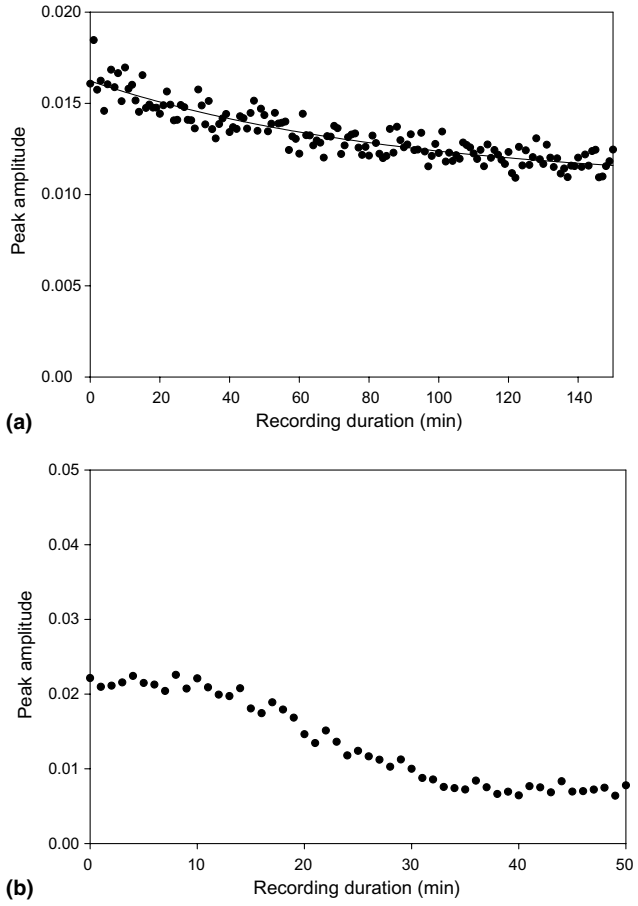

Fig. 7. Variations of peak through-transmitted ultrasonic amplitude with time after treatment with acid at pH 5 for (a) full-fat milk and (b) strawberry-flavour milk drink.

i.e., more than 50%. This figure also shows that at higher pH levels, the rate of change of the coagulation process is much faster compared to Fig. 7(a). The figure also illustrates that not only the amplitude changes drastically at a higher level of acidity but also the rate of change is much quicker, as indicated by the steep gradient in the graph. Fig. 7(b) also shows that the physiochemical changes caused by the addition of acid had reduced after 40 min of recording.

After completing the preliminary measurements, ultrasonic imaging was performed by scanning the container filled consecutively with full-fat milk, strawberry milk and banana milk drinks after treatment with acid. Imaging was first conducted on milk at pH 5.5 (initial pH), and data collected in the form of peak amplitudes of the transmitted signals, as shown in Fig. 8(a). The figure shows the scanned area as highlighted in Fig. 8(b). The milk sample was then treated with sulphuric acid, stirred and left for 10 min before scanning was performed. It can be seen from Fig. 8(a) that the transmitted signal is highly attenuated due to significant destabilisation at the bottom of container (i.e., at $z = 0$ mm). An optical photograph of the container was then taken at the end of the experiment and this is shown in Fig. 8(b). The photograph was taken so as to illustrate the $x - z$ plane. Comparison of Fig. 8(a) and (b) indicate that the air-coupled technique was able to detect structural changes within the sample as variations in the peak amplitude of the transmitted signals. The size of the coagulated areas could also be estimated.

The above experiment was repeated with the strawberry-flavoured milk sample, which again was treated with acid and the pH reduced to 5.0. The mixture was then stirred, and left for 20 min before any measure-

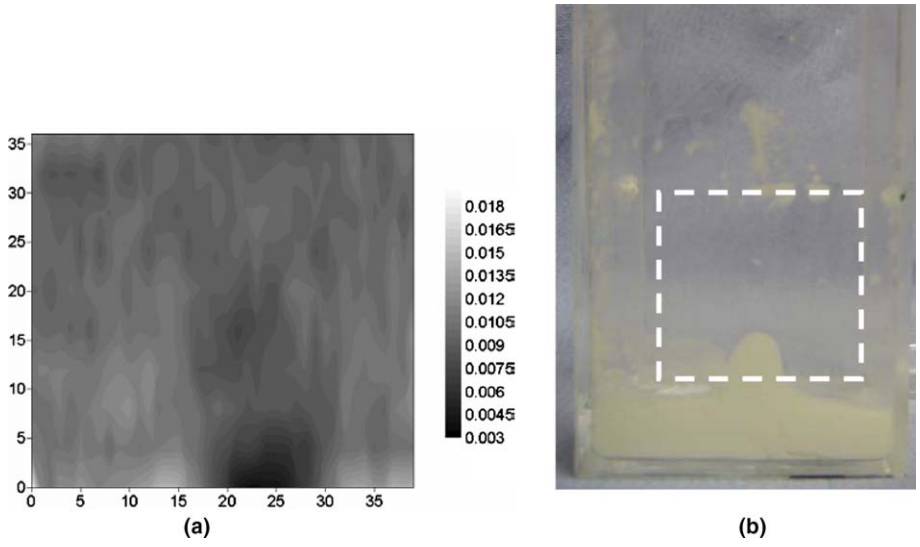

Fig. 8. Non-contact through-transmission imaging of the full-fat milk sample mixed with sulphuric acid. (a) Cross-sectional image formed by scanning the air-coupled ultrasonic system and (b) a photograph of the Plexiglas container showing the resultant coagulated milk attached to the base.

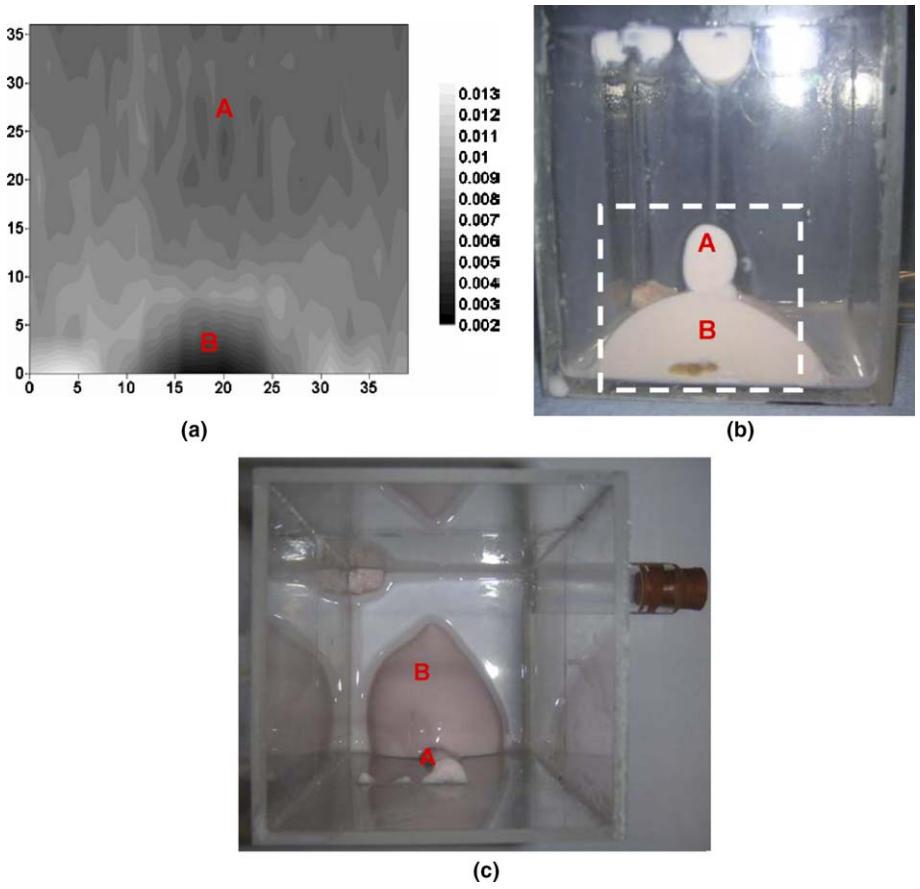

Fig. 9. Non-contact through-transmission imaging of the strawberry-flavoured milk drink, after being mixed with sulphuric acid and left for 20 min. (a) Cross-sectional scan using the air-coupled ultrasonic system, (b) photograph (side view) showing the coagulated region attached to the base of the container and (c) top view of the emptied container.

ments were performed. Visual inspection shows that there was no sign of coagulation. The container was then scanned using the air-coupled system. Fig. 9(a) shows that the ultrasonic image had detected an area of coagulation at the base of the container. Visual inspection (after removing the liquid) indicated that again a coagulated area was attached to the base of the container, visible in the photographs of Fig. 9(b) and (c). The ultrasound has detected the much larger volume of area "*B*" in the photograph, the darker

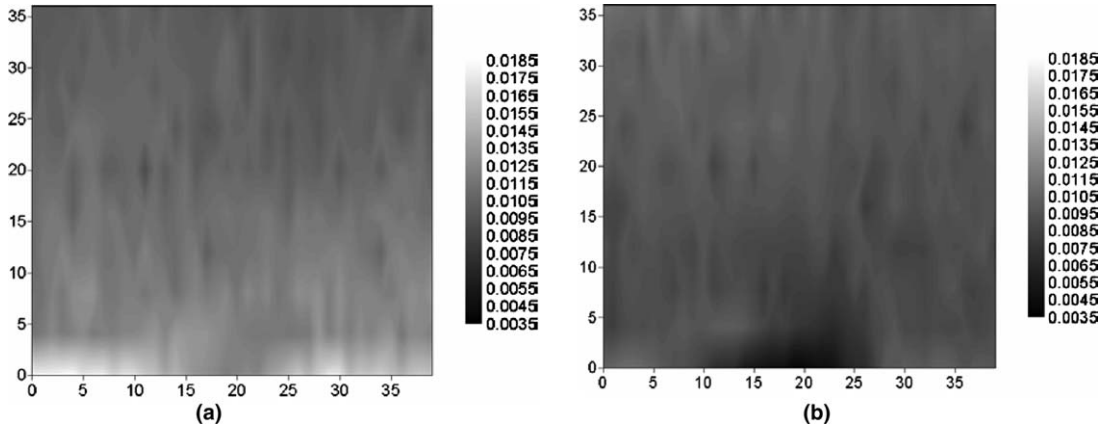

Fig. 10. Non-contact through-transmission imaging of banana milk with pH 5 in a Plexiglas container. (a) Image of sample immediately after it has been injected with acid and (b) image obtained 1 h later, indicating regions of coagulation throughout the sample.

shades indicating where the signal was more highly attenuated. Area "*A*" was not detected due to its small size.

Finally, ultrasonic imaging was then performed by scanning the container filled with banana-flavoured milk drink after treatment with acid. Fig. 10(a) shows the ultrasonic image that was obtained just after treatment with sulphuric acid (which was injected at the bottom of the container), stirred lightly and left for 10 min before scanning was performed. It can be seen from the results in Fig. 10(a) that the image area is fairly uniform throughout. Fig. 10(b) shows the images collected from the through-transmission scan after 1 h. It can be seen from Fig. 10(b) that the transmitted signal is highly attenuated due to significant destabilization towards the bottom of the container (i.e., at $z = 0$ mm). The image in Fig. 10(b) also shows that destabilization had spread throughout the bulk volume of the milk sample. This has been indicated by darker area in the ultrasonic image, which represents attenuation of the ultrasonic signal. From these results, it can be concluded that the air-coupled technique was able to detect structural changes within the sample as variations in the peak amplitude of the through-transmitted signals.

4. Conclusions

A non-contact ultrasonic system has been developed, which can be used to measure properties of interest to the food industry. This was performed using two broadband electrostatic transducers together with a pulse compression signal processing technique. It has been shown that the system could detect physiochemical changes in food samples without the need to contact with the test sample, and can be used for either single-path measurements or the formation of images.

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