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Can airborne ultrasound monitor bubble size in chocolate?

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Abstract. Aerated chocolate products consist of solid chocolate with the inclusion of bubbles and are a popular consumer product in many countries. The volume fraction and size distribution of the bubbles has an effect on their sensory properties and manufacturing cost. For these reasons it is important to have an online real time process monitoring system capable of measuring their bubble size distribution. As these products are eaten by consumers it is desirable that the monitoring system is non contact to avoid food contaminations. In this work we assess the feasibility of using an airborne ultrasound system to monitor the bubble size distribution in aerated chocolate bars. The experimental results from the airborne acoustic experiments were compared with theoretical results for known bubble size distributions using COMSOL Multiphysics. This combined experimental and theoretical approach is used to develop a greater understanding of how ultrasound propagates through aerated chocolate and to assess the feasibility of using airborne ultrasound to monitor bubble size distribution in these systems. The results indicated that a smaller bubble size distribution would result in an increase in attenuation through the product.

1. Introduction

There are many different varieties of chocolate bars available to consumers with one of the most popular being aerated chocolate bars. Aerated chocolate bars consist of a solid bar with the inclusion of many bubbles. The gas in the bubbles is usually a carbon dioxide mix and is added to the bars whilst the chocolate is in a liquid state. Once the chocolate solidifies, the nitrous oxide disperses in the atmosphere to be replaced by atmospheric gases. An important property of aerated chocolate bars is the volume fraction of gas and the bubble size distribution. These features have a significant effect on the production cost, sensory attributes and consumer perception of the product, therefore the bubble size distribution is monitored during production. Current techniques to monitor bubble size in these products consist of removing samples from the production line, breaking the bar to expose the bubbles and making a visual observation of the bubble size distribution. This method is far from ideal as the classification of bubble size is subjective, and can often only identify undesirable bubble sizes in products long after the fault has occurred. There is an industry need for online real time techniques capable of monitoring the bubble size in these products to optimise the manufacturing process, ensure product consistency and minimise production waste. Acoustic and optical techniques do exist to

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measure bubbles sizes in systems such as the fermentation process [1] but the majority of these have only been utilised in liquid systems. Acoustic techniques are well developed and employed for measuring dispersed phase size of droplets in emulsions [2, 3] although it should be remembered that systems with bubbles are very different. Existing acoustic techniques comprise of either listening to the sound of moving or collapsing bubbles (in a liquid system) or transmitting ultrasound through the systems [4-7]. Most active transmission technique require multiple measurements on the system under investigation and can require complex data analysis rendering them unsuitable for an online measurement system on a fast moving production line due to the time required to make multiple measurements and process the data.

For process monitoring in the food industry there is a need for non contact and non invasive techniques as contact could risk contamination of the food and potentially impact the process. This would make most acoustic techniques unsuitable as the transducers are generally in contact with the object under inspection. One solution would be to use a non contact air coupled system. This technique works by transmitting an acoustic pressure wave from one transducer through air, the product under investigation and through air again before the wave is detected by the receiver. The properties of the tested food will affect the received signal so it is possible to infer information about this product from the characteristics of the received pulse. Airborne ultrasound systems have being used to detect foreign bodies in food products [8] but to the authors knowledge no studies have being performed using the technique to monitor bubble sizes in aerated chocolate products.

Computational modelling techniques exist to study how ultrasound will propagate through systems such as aerated chocolate bars and can be used to study the effects of varying experimental parameters such as transducer frequency and location. If a well validated model is constructed it can be used to optimise the design process of new instrument development by performing a large number of virtual experiments which would be costly both in time and monetary terms to perform with actual experiments.

The purpose of this work is to use a combined experimental and modelling approach to assess the feasibility of using airborne ultrasound to monitor bubble size distributions in aerated chocolate bars. This was achieved by constructing two model two dimensional aerated chocolate products from straws and comparing the acoustic results with those from a COMSOL model with the same geometry. Straws were chosen as they have the same cross sectional area across their length so a direct comparison can be made to the 2D computational model. Experimental measurements were then made on two aerated chocolate bars known to have different bubble size distributions. These results were compared with two dimensional simulation results in which the geometry is a cross sectional area with a bubble size distribution representative of the corresponding aerated bar. The representative cross sectional area was determined by slicing each of the aerated chocolate bars, photographing the exposed area and using image analysis to calculate the bubble size distribution. Since the surface topography and material property is known to affect airborne ultrasound propagation this was also investigated experimentally in order to understand ultrasound propagation in these systems and to determine if the variations in ultrasound results are dominated by the bubble size distribution or other properties of the aerated product. This information will help determine the feasibility of developing an airborne ultrasound system for online real time monitoring of bubble size distribution.

Ultimately this research will provide valuable information into the viability of using airborne ultrasound as a method to monitor bubble size distribution in aerated chocolate bars online in real time.

This paper will start with a description of the experimental system and how it was used followed by how the computational model was developed. Where possible the model was constructed to represent the experiment as closely as possible. The results and discussion will be combined into a single section. First the experiment and simulation results will be presented and compared for the straws. Next the experimental and simulation results will be presented and compared for the actual aerated chocolate. The final section of the results and discussion will experimentally study the affect of the topography and surface condition on aerated chocolate bars.

2. Experimental methods

2.1 Airborne ultrasound system

For all measurements a bespoke airborne ultrasound system was used. This system can be seen in Figure 1. The set up comprises of a pair of Ultran non contact transducers (1). Three different pairs of transducers were used. One with a central frequency of 50 KHz (NCG50-S25), one with a central frequency of 140 KHz (NCG140-S38) and one with a central frequency of 200 KHz (NCG200-S38). Each pair of transducers was separated by a distance of 76 mm as this is the focal distance of all transducers. The transducers were attached to a robotic stage so they could be automatically moved over the aerated chocolate or straws. The straws or aerated chocolate were place at the centre distance between the transducers using a mould with the bottom cut away (2). This was to ensure that the sound wave only travelled though air and the sample under inspection. Both transducers were attached to a handy scope HS3 USB oscilloscope (3). This was controlled by purpose built Labview software. The software was used to send and receive the ultrasound pulse and analyse the received signal. The software also controlled the robotic stage. As ultrasound is highly attenuated in air both the transmitted and received pulse were amplified using an A 303 high voltage amplifier and modulator (A A lab systems, Israel) (4) for the transmitted pulse and THS4022 board (Texas instruments, USA) (5) for the received signal.
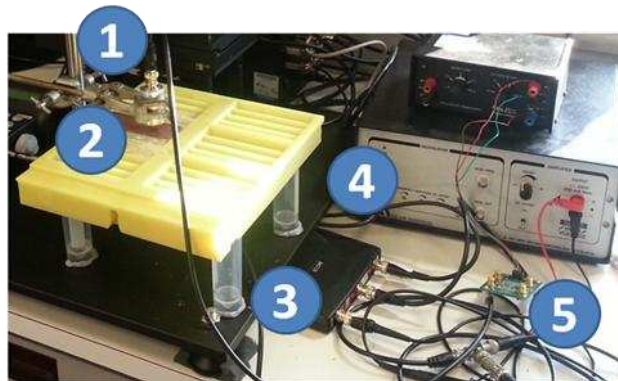

Figure 1. Airborne ultrasound system.

2.2 Experiments performed

Three sets of experiments were performed using the airborne ultrasound system:

1. Small and large straw configuration

2. Aerated chocolate bars with small and large bubble size distribution

3. B Scan along the length of an aerated bar with different surface conditions

Each set of experiments measurements were made with all three pairs of airborne ultrasound transducers. For each transducer the transmitting frequency was selected as the central frequency of the transducer pair (50, 140, 200 KHz). The transmitted pulse was 50 μs seconds long and had a sinusoidal shape function with a period twice that of the transmitted pulse duration. For all experiments only the attenuation of the ultrasound pulse was measured. Initially a measurement was made through air alone so that all the attenuation results could be presented relative to air. For this

calibration measurement the transmitted amplitude was set to 0.01 V. When the straws or aerated chocolate was placed between the transducers the transmitting amplitude was increased to 6V. Once the measurement was made through air the received pulse was saved in the software. The amplitude of all other received pulses from the experiments was increased so that they matched this reference amplitude and the attenuation could be calculated. For the final set of experiments the pair of airborne transducers was scanned along the length of an aerated chocolate bar using the bespoke robotic platform. The purpose of these experiments was to determine the effect that the shape of the chocolate would have on the ultrasound attenuation. This is important as few chocolate bars are flat so the effect the shape has on ultrasound attenuation must be studied. If the shape has more of an effect than the bubble size distribution it may make the development of a process monitoring system difficult. In addition to studying the effect of aerated chocolate bar topography the surface condition of the chocolate may affect the attenuation. This was studied by placing small chocolate crumbs or an oil layer on the top and bottom of the bar for a particular area and then scanning the airborne transducers over the length of the bar. For these experiments the transducers were positioned in the center width of the bar and scanned along the length by 80 mm. Figure 8 A and B show the region of the bar scanned. For each scan a measurement was made every 0.5 mm.

2.3 Result representation

There are many different methods used to analyse acoustic propagation through a system such as speed of sound or signal frequency content but it was decided to study only the attenuation through the straws or aerated system. This method was chosen as the ultimate aim is to develop an online real time system so we wanted to minimize the amount of signal analysis required. This was also the rationale as to why we only used the single central frequency for each transducer. Spectroscopy techniques are capable and successful at measuring bubble size distributions but they require algorithms to compute the band width and the dispersive effects of each transducer and would not be suitable using the current system and may not be suitable for a real-time system with temporal changes. For all results presented in this paper the peak amplitude of the received pulse was measured. This was then compared to the amplitude of the received pulse which had only travelled through air so that the attenuation (relative to air) could be measured for each of the experiments using the equation below.

$$Attenuation\ (dB) = 20log10(600 \times peak\ amplitude\ difference)$$

The 600 represents the voltage increase for the transmitted pulse (0.01 to 6) and the peak amplitude difference is the difference in amplitude between the received pulse which has travelled through air and the pulse which had travelled through the straws or aerated chocolate bar. When measuring the peak amplitude of the received pulse it was important that this was measured on the section of the received wave which had travelled through the straws or aerated chocolate bar. This was achieved by windowing the received signal. Ten measurements were made for each experiment and the average was recorded. For each measurement the aerated chocolate bar was removed and replaced so the error associated with repeated changes in location could be observed. For the experimental results the attenuation on the figures is the average of the ten measurements and the error bars represent the standard deviation.

2.4 Image analysis of aerated chocolate

The aerated chocolate was sliced so that the bubble size distribution was exposed. This was done for two aerated chocolate bars, one which was known to include abnormally large bubbles and one which was known to include abnormally small bubbles. The exposed cross section area was photographed using a Canon 500D digital Camera and subsequent image analysis was performed using ImageJ [9]. The image was cropped so that only the area containing the bubbles remained; this was then enhanced

and converted to a binary image. A water shedding function was employed so that the individual bubbles could be seen and the particle size function was used to calculate the average area of the bubbles and generate an outline of the bubbles which could be used in the COMSOL model. From the ImageJ results if we assume that the bubbles are spherical in size the average radius of the small bubble size distribution is 0.48 mm and the average radius of the large bubble size distribution is 0.56 mm.
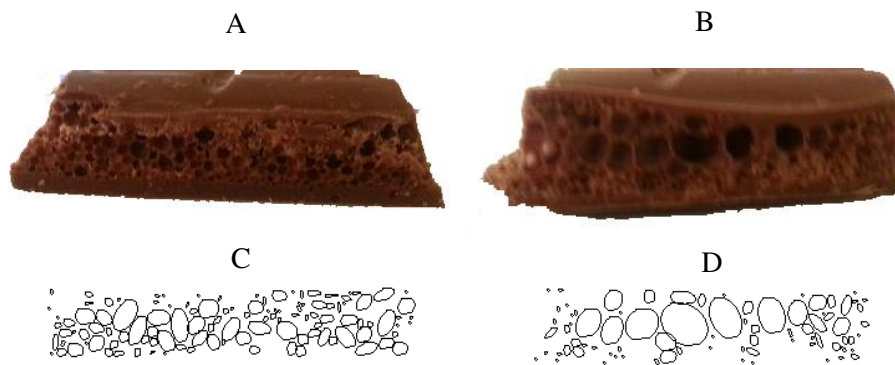
A   B

C   D

Figure 2. Aerated chocolate bar cross sections and representative bubble size distributions.

3. Computation modelling

3.1 Model definition
A computational model was created using COMSOL 4.3a to simulate how ultrasound propagates through aerated products. Four models were made, one for the small straws, one for the large straws, one for the aerated chocolate with a small bubble size distribution and one for the aerated chocolate with a large bubble size distribution. All models used the COMSOL transient pressure acoustics model and were created in two dimensions. Although the actual aerated chocolate bars would be more representative in a three dimensional model, the small element size and simulation time step required to accurately model the acoustic propagation in 3D would increase the simulation duration to an unacceptable time with the current computational setup.

3.2 Geometry
The Geometry of the COMSOL model can be seen in Figure 3 A, The horizontal line at the bottom represents the transmitting transducer and the horizontal line at the top represents the receiving transducer. Both of these lines have representative dimensions of the airborne ultrasound transducers used for the experiments. The arrow in this diagram represents the acoustic propagation path. The geometry of the straws can be seen in Figure 3 B and C. The size number and wall thickness of the straws was modelled with the dimensions used in the airborne experiments. The geometry for the aerated chocolate consisted of a rectangle with height 13 mm and width 44 mm (approximate dimensions of aerated chocolate bars used). The two dimensional images of the small and large bubble size distributions calculated from image analysis (Figure 2 C and 2 D) were placed in the centre of these rectangles. The two horizontal lines (representing transmitting and receiving transducers were separated by a distance of 76mm as was used in the experiment.
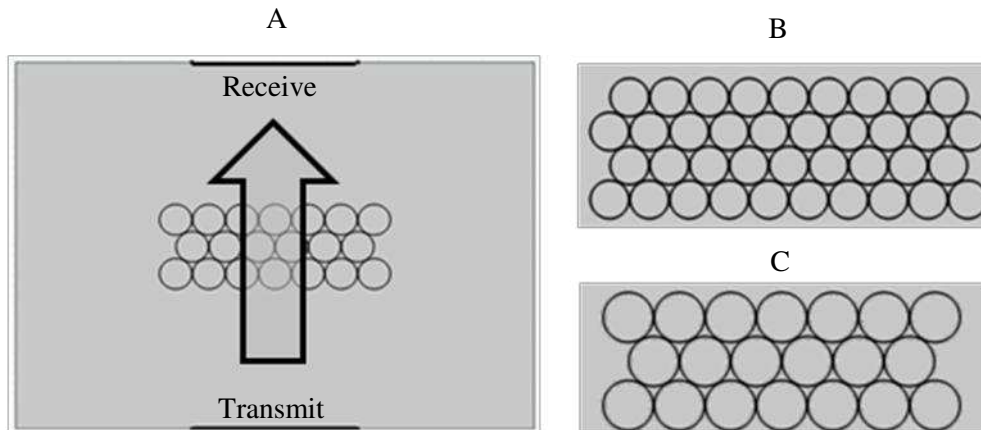
A   B

Receive

Transmit

C

Figure 3. Computational model geometry, A: Model domain with transducers straws and air. B: Geometry of small straws, C: Geometry of large straws.

3.3 Acoustic wave propagation
To simulate the ultrasound propagation the bottom horizontal line experienced a plane wave radiation. Three different frequencies of this pulse were simulated; these were 50, 140 and 200 KHz. These were the same frequencies used in the airborne experiments. Each transmitted pulse was given a duration and shape identical to the experiments. The ultrasound pressure wave propagated through the air and aerated chocolate in the model and was detected at the top horizontal line in Figure 3 A, this represented the receiver transducers. The pressure was integrated across this line as is the case in acoustic transducers.

3.4 Material properties
The three materials used in the simulations were air, chocolate and paper (for the straws). The important information for the ultrasound propagation was the longitudinal speed of sound and the material's density. Air is a well defined property within the software so already had the required values. For chocolate and paper these material properties can be seen in Table 1. For the speed of sound of the chocolate a non aerated bar of the same chocolate was produced and the speed of sound was measured experimentally using a contact ultrasound system. The density of the chocolate was calculated by weighing an amount of known volume. The speed of sound and density of the paper straws was measured using similar techniques.

Table 1. Simulation material properties

	Longitudinal Speed of sound (m/s)	Density (Kg/m^3)
Chocolate	1500	1325
Paper	1325	800

3.5 Finite element mesh
The geometry of the system was discretised using a finite element mesh. A free triangular mesh was used for all models. An important aspect is the size and number of mesh elements utilised as this governs the accuracy, precision and time duration of the simulation. A trade off always exists to this extent. Adopting the method of Mylavarapu and Boddapati [10] the maximum element size used was

the ultrasound pulse wavelength divided by ten. This results in ten elements for each cycle of the waveform. The wavelength was calculated from the speed of sound and the transmitted frequency used.

3.6 Solver configurations
All simulations used a single time dependent solver. The selection of the simulation time step is important as it controls the accuracy resolution and simulation duration. Mylavarapu and Boddapati [10] stated that the simulation time step should be less than ((wavelength/10)/speed of sound). This approach was used in this work. The longitudinal speed of sound used in this equation was chosen as the highest value for a given simulation (paper or chocolate) to give the smallest critical time step and ensure mathematical stability.

3.7 Data analysis
To ensure that the simulation results could be compared directly to the experiments the measurements were made in the same way. First a simulation was performed without the presence of the straws or aerated chocolate geometry and the maximum amplitude of the received pulse was recorded. For all subsequent simulations through the straws and the aerated chocolate the peak amplitude of the received pulse was recorded so that the attenuation is decibel relative to air could be calculated.

4. Results and discussion

4.1 Model 2D straw systems

Figure 4 display the results for attenuation through the small and large straw configurations at the three different frequencies. Generally the attenuation is greater at a higher frequency which is usual for acoustic results as attenuation increases with the propagating frequency squared. For all frequencies the attenuation was highest in the smaller straws. As the total height of the straws was the same the smaller straws consisted of more straws in the height of material. This resulted in an increased number of interfaces reflecting the sound and an overall increase in attenuation. The difference in attenuation between the small and large straws was not identical at all frequencies. At 50 KHz there was a difference of around 3 dB whereas at 140 and 200 KHz the differences were approximately 0.5 and 1 dB respectively. The results from the simulations with the straw geometries showed the same trends as from the experiment. The attenuation was found to increase with frequency and the small straws had the highest attenuation. Consistent with the experiments the difference in attenuation between the small and large straws was greatest for the 50 and 200 KHz transducers. It should be noted that the three different pairs of transducers used all had slightly different geometries which might influence some of the results. Quantitatively the attenuation was found to be higher in the experimental system and the attenuation difference between the small and large straw geometries were greater from the simulations.
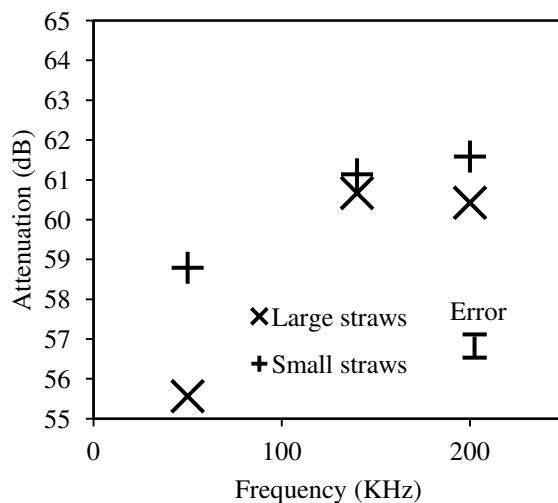
Figure 4. Airborne attenuation measurements on model systems of small and large straws.
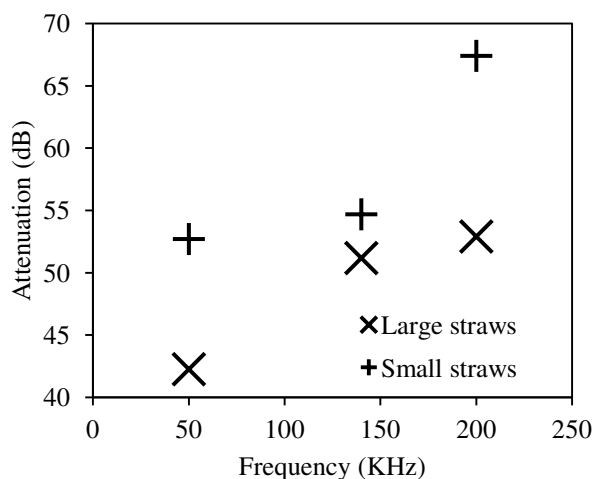

Figure 5. COMSOL attenuation simulations on model systems of small and large straws.

These results are very encouraging as they indicate that airborne ultrasound may distinguish between a small and large bubble size distribution in a model two dimensional system. Although inversion methods have not been used to calculate an actual bubble size distribution from the acoustic data the results do show that an indication of size can be taken from one simple ultrasound measurement. This would allow for quick online determination if a sudden change had occurred in the bubble size distribution. A system would require calibration with a known good bubble size distribution but calibration is common practice for online monitoring systems and the advantage of a processing monitoring system which can instantly identify a change in a product property such as bubble size has large commercial benefits. To understand how beneficial an airborne ultrasound system would be for monitoring bubble size distribution it is important to understand and investigate all factors of the product which will affect ultrasound propagation so that it can be determined how accurately can the system detect changes in the bubble size distribution. It should be noted that these experiments and

simulations were only performed at two representative size distributions; more sizes and distributions should be studied to fully determine the capability of such a system.

The computational model predicts the main features of the experiments. The use of computational models is becoming increasingly popular since they offer many benefits. Once a model is developed and validated with suitable experiments such as those describe here, it can then be used to aid the understanding of the science of the system under question as well as aid the development process of a process monitoring system. The model developed during this research could be used to simulate a wide range of frequencies and transducer geometries to find the most suitable one for studying the aerated product under inspection. The model can also be used to optimise parameters in the system such as pulse repetition frequency and precise transducer location. These simulation results could then be used to minimise the time and cost required to develop the process monitoring system and increase the possibility of producing a successful commercial system.

4.2 Chocolate with different bubble size distributions

Experimental results from the airborne experiments on aerated chocolate bars with a small and large bubble size distribution show that attenuation increases with frequency and is higher in the bar with the small bubble size distribution. These results are consistent with the measurements for the model straw system. The difference in attenuation between the small and large bubble size distributions was found to be larger for the lower frequencies, with a generally greater differential than for the straws experiments. Image analysis revealed that the small and large bubble sized aerated bars had approximately the same volume fraction of gas. For the small size distribution this would result in more scattering objects (bubbles) in the active acoustic area resulting in the observed increase in attenuation.
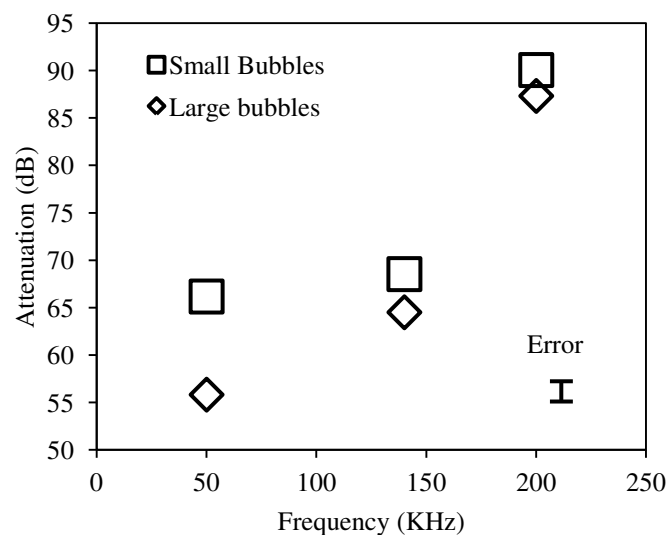

Figure 6. Experimental attenuation results from airborne ultrasound system using aerated chocolate bars with a small and large bubble size distribution.
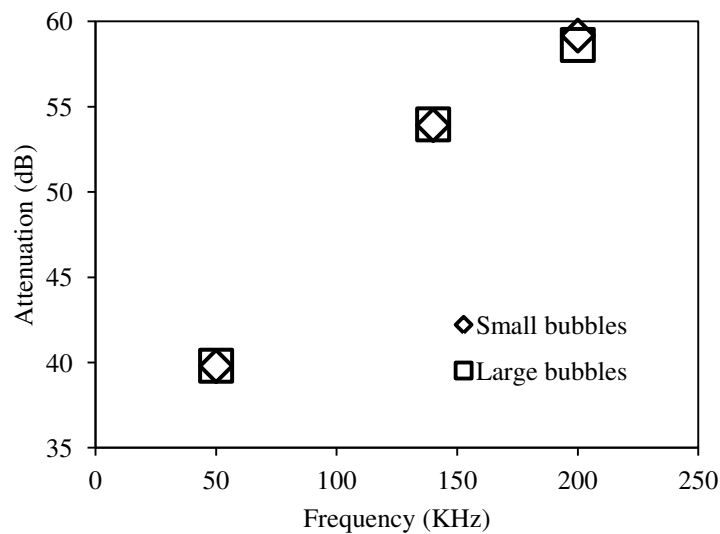
Figure 7. Simulation attenuation results from airborne ultrasound system using aerated chocolate bars with a small and large bubble size distribution.

Simulation results for models with representative small and large bubble size distributions (taken from image analysis of bars) indicate that attenuation increases with frequency although very little difference was observed for the two different bubble sizes. For all frequencies the attenuation was greater for the small bubble size distribution but this was only really noticeable for the simulations at 200 KHz. This difference was small compared with all other experimental and simulation results presented in this research.

The COMSOL model used was a two dimensional representation of the system and this could account for the difference between the experimental and simulations results. The straws experiment and models had almost identical geometry and comparable results. The geometry used in the models of the aerated chocolate bars were much simpler than the actual real life system as the image analysis only generated a representation of the bubble size distribution and contained far fewer bubbles than are known to exist in the actual products. The bubble area fraction from the image analysis was 35.5% for the small bubbles and 34% for the large bubbles. For the actual aerated products it is known that the aerated area size fraction is around 50%. This difference is accounted for by the lack of small bubbles detected by the image analysis technique and it may be that these small bubbles have the greatest effect on attenuation. With more accurate image recording and processing it will be possible to build more accurate models capable of predicting the experimental system.

4.3 Effect of chocolate surface condition

B scans along the length of the aerated chocolate bars were performed to study the effect of the topography of the products. The surface condition was also changed on certain sections of the bars by adding either chocolate crumbs or an oil layer. The initial results showed that the attenuation through the aerated bars is sensitive to the bubble size distribution but it is important to understand the effect that other product factor may have on these results. This is to determine whether the airborne ultrasound system is actually sensitive enough to monitor bubble size distribution. The application of chocolate crumb was used to represent what may happen in a manufacturing environment and the oil layer was used to represent a different surface condition. The results of the B scans (Figure 8) showed that the topography of the chocolate products has a large affect on the attenuation with a variation of

approximately 15 dB. The attenuation was greatest at the side of one of the domes in the bar, this is most likely due to the incident ultrasound wave contacting an angled surface and having a larger proportion reflected away from the receiver than transmitting through the bar. The area at the top of an individual domed section had the lowest attenuation even though this is the region with the most aerated chocolate that the ultrasound pulse must travel through. The crumb layer had very little effect on the overall attenuation (Figure 8 D) with only a small increase in attenuation in this region. The oil layers did cause an increase in attenuation but this was only small (Figure 8 E). The average attenuation was calculated from all points along the length scan and shown in Table 2. It can be seen here that the scans with the surface conditions had a slightly higher average attenuation but this was only approximately 3 dB.

Table 2. Average attenuation for different surface coatings

	Average attenuation (dB)	Standard deviation (dB)
None	72.3	0.5
Chocolate dust	75.2	1.2
Oil	75.4	1

The attenuation results for the aerated chocolate bars showed that at different frequencies the effect of the small and large bubble size distributions was between 3 and 12 dB. The topography of the bar affected the attenuation by a similar magnitude meaning that any online system would need to have an accurate way to know exactly where on the bar the acoustic measurement was made, and statistical techniques could also be used. Although this sounds challenging this is not as difficult as it appears. Possibilities include using a laser range finder device or using calibration and synchronization techniques with the current airborne ultrasound system. The results for varying surface conditions showed that these had a small effect on the attenuation but this was not as great as that caused by the topography or bubble size. These experiments actually had extreme versions of changes in surface properties so it is anticipated that the actual effect they would have on an industrial system would be less.
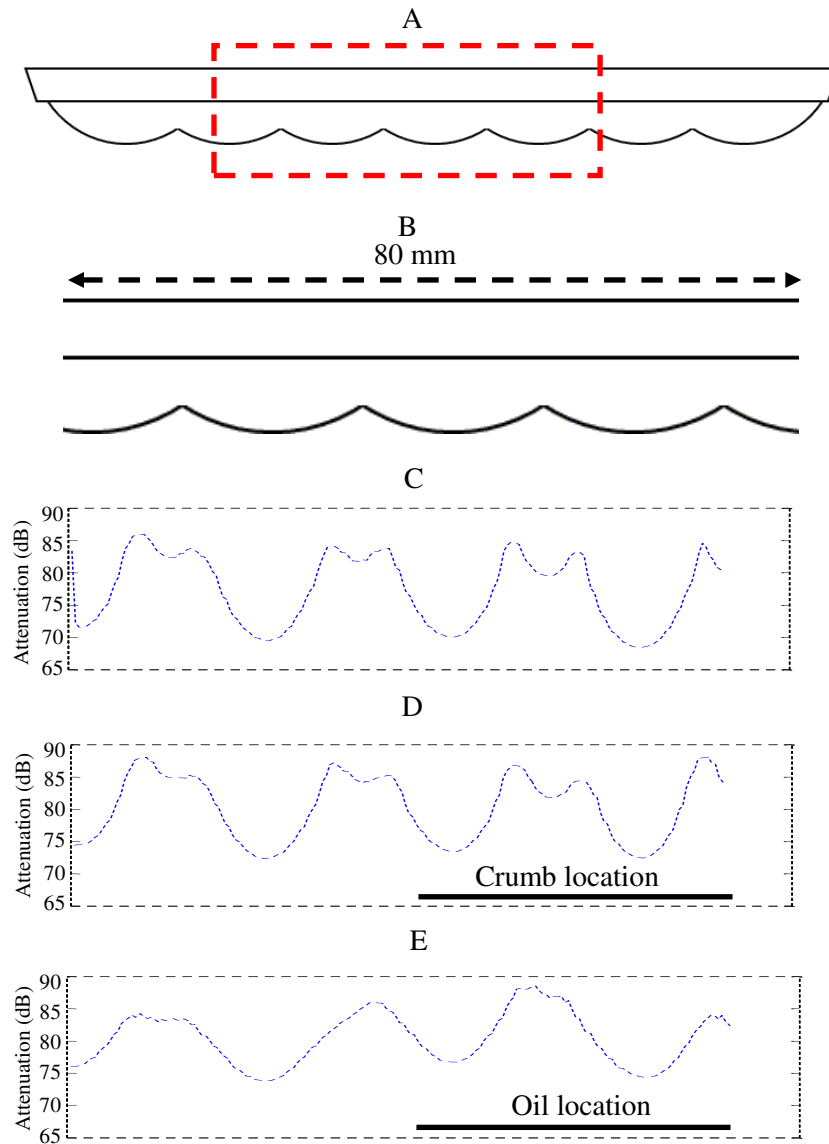
Figure 8. Airborne experiments and results along an aerated chocolate bar. A: the view of the side of the aerated bar. B: the actual length which was scanned. C: Attenuation results for an aerated bar as a function of length. D: Attenuation results for an aerated bar when chocolate crumbs were placed on the top and bottom of the bar at one end. E: Attenuation results for an aerated bar as a function of length when a thin oil layer was placed on the top and bottom of the bar at one end.

5. Conclusions

The purpose of this work was to determine the feasibility of using attenuation measurements by an airborne ultrasound system to monitor bubble sizes distribution in aerated chocolate bars. A computational model of the monitoring system and aerated chocolate was built to investigate whether the model could predict the experimental results and be used to optimise the design process. Experiments and simulations were performed on a 2D model system comprising of straws and aerated chocolate bars with a small and large bubble size distributions. The effect of the chocolate bars shape and surface properties on the ultrasound measurements was also investigated experimentally.

The results for the model two dimensional systems showed an increase in attenuation for the smaller straws and a good qualitative comparison between the experimental and simulation results. The results for the actual aerated chocolate bars also showed an increase in attenuation for the smaller bubble size. The simulations of the aerated bars did not show this affect. This was attributed to the model merely being a 2D representation of the experimental system whose image analysis may not fully represent the actual bubble size of the aerated chocolate product. The scans along the aerated bars showed that the shape of the bar had a great effect on the attenuation measurements but the surface condition (such as oil layer or chocolate crumbs) had little.

From this work it is concluded that airborne ultrasound could be used to monitor bubble size distribution in aerated chocolate products using attenuation measurements. More testing will be required to determine how accurately the system can detect small changes as the current work only studied two aerated products, one with a small and one with a large bubble size distribution. The results are encouraging as they indicate that the current technique would be capable of identifying an undesirable small or large bubble size distribution. The surface topography of the bars had a great effect on the attenuation measurements so the location of the measurement on the product must be known for meaningful interpretation of the results.

The computer simulations encouragingly recreated the experimental results for an identical geometry. With more precise modeling of the aerated chocolate products it will be possible to generate three dimensional models which could predict ultrasound propagation through the aerated bars and be used to aid the design process for an airborne ultrasound process monitoring system.

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