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Mini Review

Low intensity ultrasound applications on food systems

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Abstract

Ultrasound is composed of sound waves with frequency beyond the limit of human hearing. Ultrasound techniques are relatively cheap, simple and energy saving, and thus became an emerging technology to be used for food processing. Ultrasound technology used in food systems are divided as low and high intensity ultrasound applications. The changes to the physical properties of ultrasound, such as scattering, attenuation and acoustic velocity caused by food materials have been used in food quality assurance applications and will be discussed for selected food systems which are of importance to Australian export industry.

Introduction

Ultrasound is an oscillating sound pressure wave with a frequency greater than the upper limit of the human hearing range. Ultrasound ranges from 20 kHz to 10 MHz which is then subdivided into three main regions: low frequency, high power ultrasound (20–100 kHz); intermediate frequency, medium power ultrasound (100 kHz–1 MHz); and high frequency, low power ultrasound (1–10 MHz) (Ashokkumar and Mason, 2007). Typically, low power ultrasound uses intensities below 1 W/cm^2, which can be utilized for non-invasive analysis and monitoring of various food materials and foreign bodies during processing and storage to ensure high quality and safety (McClements, 1995; Mason and Luche, 1996). The present review summarises the low intensity ultrasound applications on quality control measures of some food systems which are primary export products of Australia.

Low intensity ultrasound

Sound propagates through a medium as mechanical waves causing alternating compressions and decompressions (Blitz, 1963). The interaction of sound waves with matter alters the velocity of the soundwaves via absorption and/or scattering mechanisms (McClements, 2005). The velocity of sound is the product of frequency and wavelength where high frequency sound waves have short wavelengths while low frequency waves have long wavelengths (McClements, 1995). Ultrasound velocity is very sensitive to molecular organizations and intermolecular interactions, which then suitable for determining composition, structure and physical state (Buckin *et al.*, 2002; 2003) and detection of foreign bodies and defects in processed and packaged food (Haeggstrom and Luukkala, 2001; Zhao *et al.*, 2009). The velocity of ultrasound in solids is usually greater than in liquids, which is in turn greater than in gases (Laugier and Hayat, 2011). The less dense a material is, the faster an ultrasonic wave propagates. However, differences in the moduli of materials are greater than those in density. So the ultrasonic velocity is determined more by the elastic moduli than by the density. Hence, the ultrasonic velocity in solids is greater than that in fluids, even though fluids are less dense than solids.

Other ultrasound parameters apart from ultrasonic velocity that correlate with many physico-chemical properties of materials are “attenuation coefficient” and “acoustic impedance”. Attenuation in ultrasound is the reduction in amplitude of the ultrasound beam as a function of distance through the medium (Buckingham, 1997). The absorption contribution of attenuation is associated with homogeneous materials whereas the scattering only exists in heterogeneous ones. Absorption in both homogeneous and heterogeneous materials is caused by molecular processes that convert some of the energy stored as ultrasound into other forms, and ultimately into heat. Scattering in heterogeneous materials occurs when an ultrasonic wave is incident on a discontinuity and is scattered in directions that are different from that of the incident wave. Unlike absorption, the energy is still stored as ultrasound, but

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the direction of propagation is altered so that the wave is not detected by a receiver in the forward direction (Pinton *et al*., 2012). Nevertheless, there is often absorption mechanisms associated with scattering in heterogeneous materials, and these can dominate the overall attenuation (Blackstock, 2000). Attenuation coefficients are used to quantify different media according to how strongly the transmitted ultrasound amplitude decreases as a function of frequency. A large attenuation coefficient means that the beam is quickly "attenuated" (weakened) as it passes through the medium, and a small attenuation coefficient means that the medium is relatively transparent to the beam (Oelze and O'Brien, 2002). Ultrasound attenuation measurement in heterogeneous systems yields information on particle size distribution (Dulkin *et al*., 2000; 2005).

Acoustic impedance is the product of density and sound velocity passing through the boundary of different materials, which affects the reflection coefficient. Acoustic impedance indicates how much sound pressure is generated by the vibration of molecules of a particular acoustic medium at a given frequency (McClements, 1995). Acoustic impedance is frequency dependent. The characteristic acoustic impedance of a medium is an inherent property of a medium. In a viscous medium, there will be a phase difference between the pressure and velocity, so the specific acoustic impedance will be different from the characteristic acoustic impedance (Cox and D'Antonio, 2009). Materials with different densities will have different acoustic impedances, which results in reflections from the boundary between two materials with different acoustic impedances. The acoustic impedance of a material is usually determined by measuring the fraction of an ultrasonic wave that is reflected from its surface (Hull, 1992).

Low intensity ultrasound applications in food processing

Quality assurance is crucial for monitoring food processes and evaluating the final food products to ensure they are safe for consumption and meet consumer expectations with regards to organoleptic attributes and consistent quality (Chandrapala *et al*., 2012). Low intensity, high frequency ultrasound is increasingly being used in the food industry where it can provide a rapid, accurate, inexpensive, simple and non-destructive method to assess and to monitor the properties of foods in-line during process operations (McClements, 1997; Awad *et al*., 2012). This application of ultrasound relies on there being a significant change in the acoustic properties such as velocity, attenuation and impedance of a food as its composition or structure varies (Awad *et al*., 2012). The larger the magnitude of the change, the more accurately the composition/structure can be determined. Foreign bodies (e.g. glass, metal, plastic), suspended particles (e.g. microorganisms) or internal structural defects (e.g. holes, cracks) in foods are a hazard and quality assurance issue for many food manufacturers. Typical foreign body detection methods used by the food industry include optical inspection, metal detection, and X-rays. Many of these techniques suffer from limitations in the range of foreign bodies that they can detect (Chandrapala *et al.*, 2012). Ultrasound is found to be a promising alternative, due to its ability to detect changes in acoustic impedance between different regions within a given volume. Selected uses of low intensity ultrasound for quality assurance purposes for Australian export food products will be discussed.

Fruits and vegetables

Increasing demand for improved quality of processed or unprocessed fruits and vegetables require the necessity for fast, accurate methods of detection for measuring the product quality (Awad *et al*., 2012). Ultrasound usage insitu has grabbed plenty of interests in quality control measures in fruits and vegetables on processed lines due to its large number of added benefits as previously mentioned. One of the principal factors restricting further expansion of the export market is fresh fruit quality at the point of sale (Henderson, 1989). The ability to grade fruit into ripeness classes and to predict the probable rate of ripening of fruit would be of benefit to the grower and to the retailer and hence the ability to assess the quality of fruits quicker without destructing the fruits led increasing demands for using ultrasound during pre and post harvesting periods. Many fruits and vegetables have very large attenuation coefficients which results in lower ultrasonic velocities similar to that of air. This is mainly due to the presence of intercellular air spaces that exhibit resonant behaviour over a wide range of ultrasonic frequencies (McClements and Gunasekaran, 1997), and thereby resulting lower penetration of ultrasound waves which is not ideal for analysis. Some researchers have tried to overcome this problem by using higher ultrasonic intensities, lower frequencies (<100kHz), and small slices of fruit rather than the whole fruit. However, high-intensity ultrasound can damage the plant tissues, using parts of the fruits to predict the whole fruit behaviour is inaccurate and surface irregularities makes interpretation of the data more complex. Despite these limitations, some researchers have worked on ultrasonic transmission measurements to follow the ripening and quality of apples, melons and avocados and to detect physiological defects of potatoes (Mizrach *et al*., 1989, 1991, 1992; Jivanuwong, 1998).

In order to avoid destructive analysis, Mizrach *et al*. (1996) patented a device for non-destructive determination of quality parameters of fruits. The device is represented in Figure 1. Initially, the sound produced by the transducer travel through the concentrator and fruit samples and will be received through the concentrator by the receiving transducer. The sound signal received by the transducer is then converted to an electrical signal and is applied to the pulse receiver. Then this signal is applied to a microprocessor controlled serial interface which allowed transfer of the digital read out of echo amplitude to an external computer where the computer analyses the signal and determine the wave velocity and signal attenuation. These parameters were further analysed in conjunction with the maturity of the fruit samples.

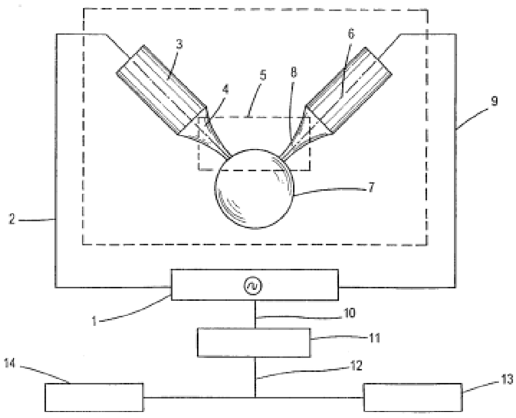

Figure 1. A schematic representation of the non-destructive ultrasonic device for measuring the quality of fruits patented by Mizrach et al 1996 : 1 – Pulse Receiver (which generates electrical pulse) ; 3 – Source Transducer; 4 - Energy Concentrator ; 5- Housing Unit ; 6 – Receiving Transducer ; 7 – Sample Position; 8 – Energy Concentrator; 11 – Microprocessor Controlled Serial Interface; 13 - Computer

Figure 2(a) and (b) represents the velocity and attenuation resulted from the patented device for avocados during their ripening period. It was shown that the velocity and attenuation decreased as the firmness of the fruit decreases (Mizrach *et al*., 1996). Similar method was adapted by Mizrach *et al*. (2004) for plum tissues where the differences in the acoustic signals transmitted through the tissues of fruits at different stages of maturity were measured. The measured attenuation decreased with maturity and was found a relationship between firmness versus attenuation (Mizrach *et al*., 2004). However, Mizrach

(a)

(b)

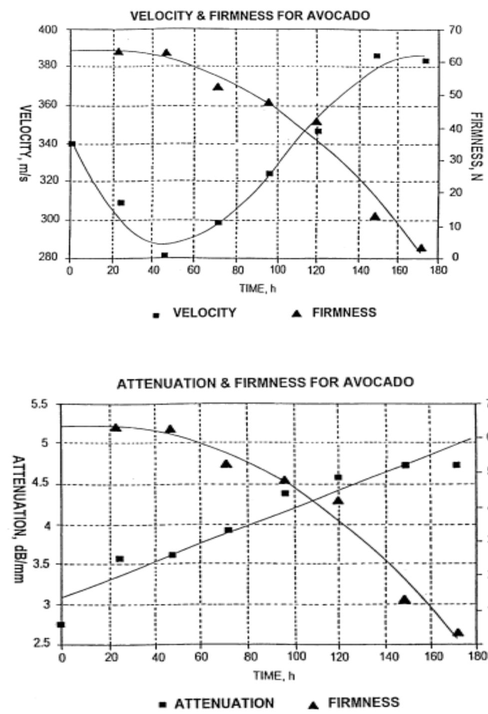

Figure 2. (a) Surface velocity and (b) apparent attenuation of the ultrasonic signal in the peel and the vicinity of the peel of a whole avocado fruit vs time. These graphs also represent the firmness of the fruits (Adapted from Mizrach *et al.,* 1996)

et al. (1999) found an increase in attenuation as the avocado gets ripens. These differences were attributed to the amount of oil present in different varieties even with the similar type of fruit. However, it was unexpectedly found that this method was successful in determining the oil content in avocado which is also a valuable method in determining the ripeness. The other key parameter for determining ripeness is the dry weight of a fruit. Furthermore, a relationship between the ultrasonic attenuation and dry weight of an avocado as it matures was found (Mizrach *et al*., 1999).

The most promising applications of ultrasound in the processed food lines is the in-line sensor that is used to measure the properties of fruits/vegetables during processing. By acquiring ultrasonic measurements in real time, composition can be adjusted, and/or process parameters modified, to optimize product quality. This in-line capability has been demonstrated, for example, by Choi *et al.* (2002), where ultrasonic doppler velocimetry (UDV) measurements (at 5 MHz) were successfully used to determine the flow rate of tomato juice and corn syrup in pipes. The ultrasonic Doppler velocimetry (UDV) technique, also called ultrasonic pulsed echo Doppler, was originally developed in the field of medicine (Jorgensen *et al.*, 1973). Later, this technique was extended to the flow measurements in physics and engineering (Takeda, 1986). Not only can the UDV technique measure flow, but combining a velocity profile obtained by the UDV technique with a simultaneous pressure drop measurement allows the evaluation of various rheological properties during viscometric pipe flow. As another example, ultrasonic pulsed echo Doppler-pressure differences (UVP-PD) (using four ultrasonic transducers, 2-4 MHz), in combination with in-line rheological measurements, was applied to successfully determine the concentration of solids in various highly concentrated, bimodal and polydisperse model and industrial food suspensions (tomato, vegetable and pasta sauces) (Wiklund and Stading, 2008).

Bread

The baking industry relies on the control of dough/batter properties to achieve food quality and consistency. Traditional methods use in dough testing are slow and off-line where it needs a development of fast and in-line instruments capable of providing relevant data for baking. Álava *et al*. (2007) showed that ultrasonic velocity and attenuation (at ~100 kHz) could be successfully used to assess flour quality where the ultrasound parameters correlated well with the rheological properties of dough traditionally measured prior. Furthermore, Letang *et al*. (2001) evaluated the physical properties of wheat flour: water systems using high frequency low power ultrasound with a reflectance technique measuring the acoustic impedance of dough. The velocities of propogation, attenuation and viscoelastic moduli has also been evaluated for both compressional and shear ultrasonic waves in the range of 2-10 MHz for differently hydrated dough (Letang *et al*., 2001). The acoustical properties of dough were found to be frequency dependant and sensitive to key technological parameters such as water content and mixing time.

Batters are air filled mixtures of high viscosity which do not support significant transmission of ultrasound (Elmehdi *et al*., 2003; Leroy *et al*., 2008) and hence the conventional ultrasonic density sensors for liquids are not suitable for this application. Due to these limitations a special transducer has been developed by Salzar *et al*. (2004). The sensor was constructed using a piezoelectric ceramic at the fundamental frequency of 1 MHz. The changes in compressibility in batters were monitored by measuring the acoustic impedance of the batter instead of measuring the density. Main advantage of this novel approach was that the changes in acoustic impedance are easier to detect than changes in density especially when air is incorporated. It was found that the attenuation coefficient and velocity data increased significantly as the void fraction lowered. However, this increase was not found to be due to the decreased number of gas bubbles alone. Hence, this technique was found not only to provide information about gas bubbles, but also points providing a means of probing changes in the intermolecular bonding in the dough matrix (Salzar *et al*., 2004). In complimentary, Gomez *et al.* (2008) also found that acoustic impedance of cake batter provided a direct measurement of the gas content in the batter.

Several researchers have shown the potential of ultrasonic techniques to characterize the structure of breadcrumb. By combining the results of both the attenuation and the velocity of the sound at 54 kHz, information on the porosity and the cell size and shape was obtained (Elmehdi *et al*., 2003). Since the gas cells determine the structural integrity of the bread crumbs, these effects can form the basis of methods for characterizing the mechanical and structural properties of bread crumbs and predicting loaf quality. To investigate the effects of anisotropy in the cell structure of bread crumbs, freshly baked samples were compressed uniaxially, thereby transforming the shape of the cells from approximately spherical to ellipsoidal (Elmehdi *et al.*, 2004). The density dependence of the velocity in the compressed samples was found to be opposite to that in the non-compressed samples, with velocity decreasing with increasing compression, more prominently along the direction parallel to the stress. Signal amplitude has also showed a slight increase. Their results demonstrated that the sensitivity of ultrasonic waves towards changes in the size and shape of crumb cells leads to potentially use ultrasound as a tool, and hence for measuring some of the determining factors of bread quality (Elmehdi *et al.*, 2004). Complementary information on bread crumb is provided by the attenuation of the ultrasonic waves, which is affected by absorption and scattering from heterogeneities in the crumb. In particular, the transmitted signal amplitude was found to increase as crumb cells became smaller, i.e., as the density increased, consistent with the simple physical picture that scattering and absorption is decreased when the sizes of the cells become smaller relative to the ultrasonic wavelength. Lagrain *et al.* (2006) employed non-contact ultrasonic techniques to characterize the porous structure of bread crumbs, and the phase velocity and attenuation measurements confirmed structural differences between two different bread types for a broad frequency range (40 kHz up to 1 MHz). Furthermore, non-contact ultrasound permitted estimation of flow resistance, open porosity and tortuosity of different crumb grain features.

Other workers used ultrasound to characterize the fermentation phase during bread making (Elmehdi *et al.*, 2003; Skaf *et al*., 2009). Fermentation of the sugars in bread dough produces carbon dioxide which diffuses through the dough matrix into the gas cell nuclei formed during dough mixing. As a result, the void fraction of the dough increases and dough density decreases. It was shown that low intensity ultrasound can be used to monitor changes in the void fraction of this opaque material, thus providing real-time information on changes in the structure of the dough during fermentation. As fermentation time increased (and gas cells expanded), the ultrasonic velocity decreased and the attenuation increased. At early fermentation times, a substantial drop in velocity was observed before the density changed appreciably, indicating that yeast activity has two independent effects on dough properties: modifying the elasticity of the dough matrix and expanding the gas cells (Elmehdi *et al.*, 2003).

Honey

Honey can be made poorer in quality by adding amounts of sucrose, commercial glucose, starch, chalk, gelatins, water and other substances. Honey has been a prime target for adulteration reasons of economic gain (El-Bialee *et al*., 2013). Honey adulteration discriminated by chemical analysis or sophisticated devices which consume time, effort and money. Detection of adulteration in honey is so difficult because of the large natural variability of honey, such as differences in species, maturity, environment, processing and storage technique (Cordella *et al*., 2003). Singh and Dwivedi (1995) reported changes in the physical properties of honey such as density, viscosity and homogeneity, which were accompanied by changes in ultrasound velocity due to adulteration. The ultrasonic velocity increased with the increase of honey component in the mixture. Though the flavour and taste did not change even up to the adulteration level of 50%, ultrasonic velocity was found to be affected by addition of sugar even in little amounts in honey (Singh and Dwivedi, 1995).

In a recent study, Camara and Laux (2010) showed that ultrasonic (at 10 MHz) shear reflectivity method could distinguish between two honeys with a moisture content difference of < 0.2% over the range 15-20% moisture. This technique also provided information on the honey microstructure as the temperature at which the vitreous plateau began could be related to relaxation times. The authors proposed the application of this technique for honey quality control. The advantage of this technique is that it is highly sensitive, non-destructive, requires little information about the honey and can potentially be applied directly to glass jars of honey with closed lids (Chandrapala *et al.*, 2012).

Fish and meat

Fish processing industry faces the problem of detecting and removing seal worms from fish musculature. The most common practice of deworming and trimming of fish fillets involve manual labor in fish processing lines and at the same time this removal is not a 100% success leading some go undetected to the consumer. Hofteinsson *et al.* (1989) employed ultrasonic wave to detect seal worms embedded deep in the fish musculature. Attenuation of ultrasound in the frequency range from 1 to 12.25 MHz and pulse echo technique at 10 MHz was studied in Atlantic cod. The seal worms were successfully detected in over 4 cm thick fish tissue provided the fish was fresh. Similarly, Ghaedian *et al.* (1998) measured the ultrasonic velocity (at 4 MHz) of Atlantic cod fillets having various moisture contents between 78-82%. The ultrasonic velocity decreased linearly over the range 1575-1595 m/s with increasing moisture content, estimated to ±1% weight. The same method was later used to determine the composition of chicken analogs and the solid fat content of chicken fat (Chanamai and McClements, 1999). Abdul *et al*. (2012) also showed that there is correlation between fat content and the measured ultrasound velocity travelled in the sample indicating that fat measurement using the ultrasound A-Mode scan technique can be used to determine fat content in fish, meat and chicken fillets with reasonable accuracy. A trend of decreasing ultrasound velocity with increasing fat content in the sample for chicken fillet and fish fillet was observed whereas the correlations between two variables were found to be moderate and weak for meat fillets. They suspected that it might due to in-homogeneities in sample thickness. The influence of frequency (1-6 MHz), temperature (5-25^{o}C) and composition on the ultrasonic velocity and attenuation coefficient of Atlantic mackerel *(Scomber scombrus)* was investigated by Sigfusson *et al.* (2001). There was good agreement between the fat, water and solids-non-fat content determined by ultrasonic velocity.

The variation in ultrasound velocity (at 1 MHz) with temperature was used by Benedito *et al.* (2001) in determining the chemical composition of fermented sausages containing various protein (2-21%), moisture (7-76%) and fat (2-90%) contents at two temperatures, 4 and 25^{o}C. A variance of 85.4% for protein, 98.7% for moisture and 99.6%

for fat was achieved. In another study, Niñoles *et al*. (2010) demonstrated the feasibility of using ultrasonic measurements (at 1 MHz) to characterize the melting behavior of fat in Iberian dry-cured hams, and subsequently their related sensory attributes. Ultrasonic velocity strongly correlated ($R^2 = 0.99$) with the percentage of melted fat, demonstrating an increase of 5.4 m/s for a 1% increase in melted fat (% melted fat > 60%).

Mőrlein *et al*. (2005) classified animal carcasses based on intramuscular fat content by spectral analysis of ultrasound echo signals (at ~3.5 MHz). In pigs, backfat thickness and longissimus muscle depth have been predicted using ultrasound scanning (at 3 MHz), as a prediction of meat yield (Cisneros *et al*., 1996). In poultry, breast muscle thickness, as determined by ultrasonography (at 7 MHz), was shown to be a reliable measurement of meatiness (Kleczek *et al*., 2009). Ultrasound images (at 3-7.5 MHz) and body measurements of live animals have been employed to predict carcass traits of sheep (Emenheiser *et al*., 2010) and cattle (Stelzleni *et al*., 2002)

Recently, other workers also used contact or non-contact ultrasound to detect defects and internal objects in and skinless poultry breast (Cho and Irudayaraj, 2003). Air instability compensation transducers were used to obtain non-contact ultrasound images of boneless chicken breast with metal fragments in poultry. It was expected a strong reflection and refraction at the interfaces of the host tissue and foreign object interface. Objects such as bone, metals, and glass have different physical properties compared with the medium, and as a result, changes in ultrasound time-of-flight and velocity are expected. To date, the conventional ultrasound measurement uses a coupling medium (oils or gels) between the transducer and test specimen to overcome the high attenuating power due to the large acoustic impedance mismatch between air and material. The coupling media being a chemical agent has the potential to contaminate or interact with the food sample. By using a novel non-contact ultrasound piezoelectric transducer (Bhardwaj, 2000) along with improved signal-processing capabilities, the ultrasound system exploring was worthwhile. Since non-contact ultrasound uses air as its medium, the transmitted signal may be highly dependent on the conditions of the air, such as temperature, humidity, and airflow and hence the instability of the air column may cause errors in the velocity and thickness measurements in an air-coupled ultrasound system. Cho and Irudayaraj *et al*. (2003) overcome this problem by using a fixed reference in front of the transducer and collecting the reflected signal with respect to the reference, where it was possible to obtain information of the air column between the transducer and the reference from the transmitted signals by examining the velocity and attenuation of the ultrasound waves with respect to the target reference placed in front of the transducer (Figure 3). From the known distance and time-of-flight between the transducer and the reference, the ultrasound velocity through air can be calculated in real time and used in the calculation of ultrasound velocity and thickness of the sample material. The minimum 3 X 3 mm^2 foreign fragments in poultry and 1.5 mm diameter cylindrical objects were successfully detected. However, they further argued that distinguishing foreign objects from food materials were difficult and predicted that a quantitative analysis needs to be performed by using absolute values of ultrasound parameters for food materials and foreign objects.

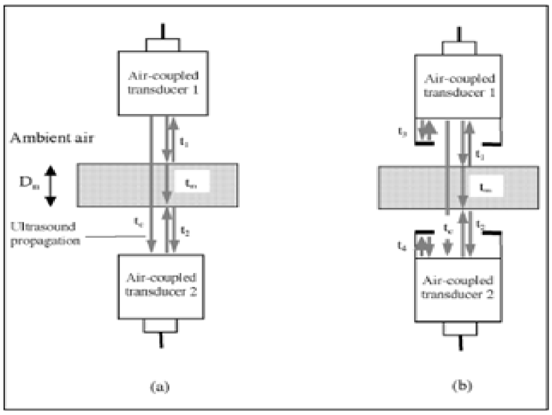

Figure 3. A schematic representation of the noncontact ultrasound measurements with (a) normal non-contact ultrasound transducer and with (b) non-contact air instability compensation transducers (Adapted from Cho and Irudayaraj, 2003)

Conclusion

Quality assurance is crucial for monitoring food processes and evaluating the final food products to ensure they are safe for consumption and meet consumer expectations with regards to organoleptic attributes and consistent quality. In addition, fast non-destructive monitoring of foreign bodies within a food processing line in a food manufacturing factory is essential. Scattered, transmitted and reflected acoustic pulses from low intensity ultrasound can be used as a viable technology in quality assurance purposes and food safety.

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