ULTRASONIC SENSORS FOR THE FOOD INDUSTRY

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I. INTRODUCTION

Sensing and measurement of food properties are crucial to improving the quality and profitability of food manufacturing operations. Instrumental measurements can reduce the dependence on time-consuming chemical and sensory analysis. The ideal would be to make an assessment of the food quality as close to the processing step as possible. The measurement should provide some information about the food (e.g. temperature, composition, structure, concentration) useful in controlling the final product quality. The response time is crucial, so while laboratory tests on finished product are valuable, measurements, made at-line or on-line of the freshly made or in-process food are better. On-line sensors in the food industry must also be adequately cheap and robust to survive in the frequently hot and wet environment of a food processing plant. They should also be both nondestructive of the food products and amenable to hygienic design principles (ideally noninvasive) and provide output usefully to an operator or automated control system.

Sensing modalities meeting some or all of these conditions have found specific applications in the food industry (e.g., microwaves for water content, thermocouples for temperature, nuclear magnetic resonance (NMR) for solid fat content, and infrared (IR) for composition). Ultrasound has also been used, but to a much lesser extent. The different physical principles sensed ultrasonically provide a unique set of advantages (and disadvantages) as a food sensor.

Ultrasound has become invaluable as a nondestructive sensor for materials as diverse and valuable as a human fetus and an aircraft wing. The same principles that enable us to "see" these structures with sound have also allowed researchers to attempt to characterize foods ultrasonically. In many ways food is a more difficult material for nondestructive evaluation as low unit costs and high production rates make it uneconomic to have a trained technician make a piece-by-piece evaluation, and the sensor must be directly incorporated into the process.

There have been some important practical successes (e.g. ultrasonic flowmeters, carcass evaluation, concentration sensing and particle size determination), but a far wider set of studies that have never progressed beyond a few academic publications. One crude distinction between the successes and failures is that the physics of sound–material interactions is frequently underexploited by food scientists; another is that the complexities of food manufacture are often underestimated by nondestructive evaluation specialists. One of the goals of this chapter is to clearly set out some of the underlying physical principles and then, in a review of some applications, stress how they can lead to useful measurement.

We start by discussing the physics of sound and the interactions of sound with matter. We then describe the practicalities of ultrasonic measurement, and finally review some applications of ultrasonic measurements to foods, grouping them by the type of parameter measured rather than by food group. The field of ultrasonic evaluation of foods has been previously reviewed elsewhere, and the works of Povey (1997; Povey and Mason, 1998), McClements (1997), Javanaud (1988) and Kress-Rogers (1993) are all recommended. The bibliography provided by Povey (1998a) is particularly comprehensive.

II. THEORY

A. ULTRASONIC WAVES

A wave is a collective phenomenon, implying coherent local variation of elements of the structure. In an acoustic wave, the variation is in the position of volume elements of the media through which the sound is passing, and so the acoustic properties of a material depend on both its density (the amount of material to be moved) and mechanical properties (how easy it is to move). The strains within the material caused by the passing sound wave are coupled with other parameters including local energy, pressure, density and temperature of the medium. The rate of the temperature fluctuations is usually more rapid than heat flux; therefore, most theories of sound rely on the adiabatic assumption (i.e. no heat flux) (Strutt, 1945; Wood, 1955).

Ultrasound is qualitatively similar to audible sound except that the vibrations occur at frequencies (> 20 kHz) too high to be detected by the human ear. Indeed, a sound wave is part of the whole spectrum of material periodic motion (not including translational motion) that at very high frequencies is seen as thermal waves. Just as classical electromagnetic spectroscopy can probe different structures in the same material by interaction with light of different frequencies, ultrasonic spectra can in principle reveal detail at different levels of material structure. A further interesting parallel between electromagnetic and mechanical waves is that very high frequency sound is better thought of as a particle – a phonon – and the paradoxes of wave–particle duality are relevant; see Povey (1997) for further discussion.

The material oscillations associated with an acoustic wave can occur both normal to and parallel with the direction of transmission. When ultrasonic waves are transmitted through an elastic, inert material, each element will experience forces due to the fluctuating pressure and will tend to move from its equilibrium position. For a sinusoidally varying pressure, the motion of the particle will also be sinusoidal and, depending on the balance of forces acting, will follow an elliptical path about its equilibrium position (Wood, 1955). The frequency of the motion is the same as the frequency of the sound and the amplitude of the motion is related to both the magnitude of the wave and the mechanical properties of the material. In most sensing applications, the acoustic power levels and hence the material movements are small and within the elastic limit of the material. It is therefore assumed that as the wave passes the material will return to its unperturbed state and will be physically and chemically unchanged (i.e. ultrasonic testing is nondestructive).

The displacement (ξ) of a particle in a periodic wave from its equilibrium position (x) with time (t) is given by:

$$\xi = a \sin 2\pi\left(\nu t - \frac{x}{\lambda}\right) \tag{1}$$

where ν is the frequency of the oscillation, and a and λ are the amplitude and wavelength of the sound. Eqn (1) can be formulated in terms of wave velocity ($c = \nu\lambda$) so the microscopic motion of volume elements of the material is described solely by the bulk properties of the wave.

Although sound can propagate by the oscillation of volume elements in three dimensions, ultrasonic measurements are often conducted using waves to induce motion in simpler paths. When an oscillating stress is applied perpendicular to the surface of a material, vibrations take place as a series of compressions and expansions in the direction of sound propagation (particles oscillate back and forth) and *longitudinal* or *compression* waves are generated. When the oscillating force is applied parallel to the surface of a material, the vibrations take place perpendicular to the direction of wave propagation and *shear* or *transverse* waves are generated (Figure 1). Shear waves can be generated by a shear transducer or by mode conversion of longitudinal waves at an interface (see below). The different types of wave are sensitive to different material properties but, as longitudinal waves have been predominantly used in food systems, we will, unless noted, restrict our discussion to this mode.

Longitudinal and shear waves are both bulk waves but it is also possible to generate waves trapped in a surface (which are often useful for detecting surface defects or composition). These waves are produced when longitudinal waves are directed at a critical angle (see section D below) so the refracted energy passes into the surface (Raichel, 2000). Two types of surface waves are Love waves, which are shear waves polarized in the plane of the surface, and Raleigh waves, which contain longitudinal and

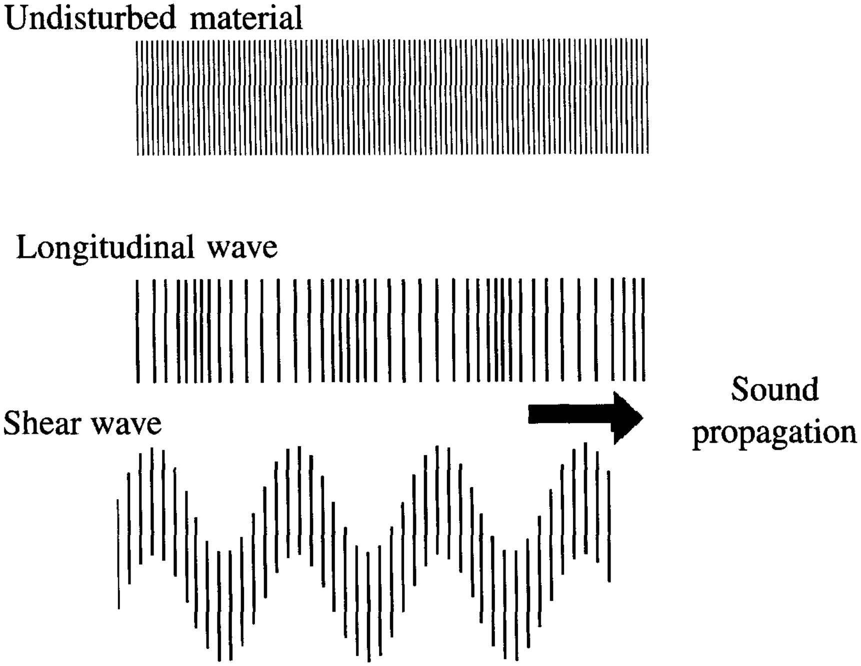


FIG. 1 Diagram illustrating the deformation of matter in a longitudinal or shear pressure wave. The parallel lines represent volume elements of the material that are deformed from their equilibrium either parallel or normal to the direction of sound propagation (i.e. longitudinal or shear waves).

shear components (Blitz, 1963). Surface waves can travel long distances and are sometimes used to detect flaws in pipes.

B. ULTRASONIC PROPAGATION IN HOMOGENEOUS MATERIALS

A material responds to the passing ultrasonic wave both elastically and viscously. These two phenomena can be expressed together as a complex wavenumber, k:

$$k = \omega/c + i\alpha \tag{2}$$

where ω is the angular frequency ($= 2\pi v$), α is the attenuation coefficient and i is $\sqrt{-1}$. Velocity is the distance traveled by the sound wave in unit time or the product of wavelength and frequency. Attenuation describes the logarithmic decrease in wave energy with distance (x), i.e.:

$$A = A_0 \exp(-\alpha x) \tag{3}$$

where A_0 and A are the amplitudes at distance 0 and x. The attenuation coefficient (α) is measured in Nepers (Np) or decibels (dB) per meter (1 Np = 8.686 dB).

The propagation of sound through a material depends on the physical properties of that material:

$$\left(\frac{k}{\omega}\right)^2 = \frac{\rho}{E} \tag{4}$$

where ρ is the density and E an appropriate elastic modulus. For materials where the attenuation is not large (i.e. $\alpha << \omega/c$), the imaginary component of the parameters described in Eqn (4) can be neglected and the expression can be rewritten as:

$$c^2 = \frac{E}{\rho} \tag{5}$$

The elastic modulus used here is distinct from the elastic modulus used in ordinary static measurements. In static measurements, deformation is slow and the material is at thermal equilibrium prior to measurement, so it is the isothermal elastic modulus that is measured. However, when ultrasonic waves travel through a material, the deformations are extremely rapid and the local temperature rises during the compression phase of the cycle and decreases during rarefactions. Since the rate of pressure change is rapid, no heat exchange occurs between the hot and cold regions and ultrasonic propagation is dependent on the *adiabatic* elastic modulus.

Frequently we shall be concerned with measurements of either the real (velocity) or imaginary (attenuation) part of the wavenumber, but Eqn (4) is a useful reminder that these are parts of a single phenomenon. Similarly the complex parts of the other measured parameters can give independent information on material properties. The ultrasonic properties of selected materials are listed in Table I.

1. Ultrasonic velocity

Gases are able to support only longitudinal waves and in practice even these can be hard to measure (see below). For ideal gases the appropriate adiabatic elastic modulus is the bulk elastic modulus (K), equal to the product of the hydrostatic pressure P and γ ($= C_p/C_v$, where C_p and C_v are the specific heats at constant pressure and volume). Depending on the

TABLE I

ULTRASONIC PROPERTIES OF SELECTED MATERIALS. UNLESS NOTED, MEASUREMENTS WERE CONDUCTED AT 20°C

Material	Frequency (MHz)	Ultrasonic velocity ($m\ s^{-1}$)		Ultrasonic impedance ($10^6\ kg\ m^2\ s^{-1}$)	Reference
		Longitudinal	Shear	Longitudinal	
Non-food materials					
Aluminum		6320	3130	17	Birks and Green (1991)
Brass		4400	2200	37	Birks and Green (1991)
Cast iron		3500–5800	2200–3200	25–42	Birks and Green (1991)
Epoxy resin		2400–2900	1100	2.7–3.6	Birks and Green (1991)
Gold		3240	1200	63	Birks and Green (1991)
Perspex		2730	1430	3.22	Birks and Green (1991)
Plexiglas		2670	1120	3.2	Birks and Green (1991)
Quartz glass		5570	3520	14.5	Birks and Green (1991)
Rubber (soft)		1480	–	1.4	Birks and Green (1991)
Steel		5900	3230	45	Birks and Green (1991)
Teflon		1350	550	3	Birks and Green (1991)
Air	0.4	330	–	4.3×10^{-4}	Blitz (1963)
Hydrogen	1	1300	–	1.1×10^{-4}	Blitz (1963)
Oxygen	1	310	–	4.5×10^{-4}	Blitz (1963)
Food materials					
Water		1482.3	–	1.48	DelGrosso and Mader (1972)
Ice		3840	1200	4	Povey (1989)
Sodium chloride solution (10 wt%)	2.25	1597	–	1.7	Saggin and Coupland (2001a)
Sucrose solution (10 wt%)	2.25	1511	–	1.57	Saggin and Coupland (2001a)
Glycerol (10 wt%)	2.25	1527	–	1.63	Saggin and Coupland (2001a)
Ketchup	2.25	1650	–	1.88	Saggin and Coupland (2001a)
Apple juice	2.25	1530	–		Zacharias and Parnell (1972)

TABLE I *(continued)*

ULTRASONIC PROPERTIES OF SELECTED MATERIALS. UNLESS NOTED, MEASUREMENTS WERE CONDUCTED AT 20°C.

Material	Frequency (MHz)	Ultrasonic velocity ($m\ s^{-1}$)		Ultrasonic impedance ($10^6\ kg\ m^2\ s^{-1}$)	Reference
		Longitudinal	Shear	Longitudinal	
Syrup (light and dark corn syrup and maple syrup)	2.25	1854–1900		1.9–2.3	Zacharias and Parnell (1972)
Olive oil	1.2	1465	–	1.35	McClements and Povey (1988)
Corn oil		1469	–	1.35	McClements and Povey (1988)
Palm oil		1459	–	1.35	McClements and Povey (1988)
Soybean oil		1470	–	1.35	McClements and Povey (1988)
Sunflower oil		1471	–	1.35	McClements and Povey (1988)
Solid animal fat (31°C)		2000–2070		2.0–2.1	McClements (1997)
Apple (golden delicious)	0.037	114	–	0.09	Liljedahl and Abbott (1994)
Avocado	0.05	274–283	–	–	Mizrach *et al.* (1989)
Papaya	0.12	160	–	0.16	Hayes and Chingon (1982)
Potato	0.5	700–850		0.7–0.85	Povey (1989)
Carrot	0.37	440	–	0.44	Nielsen and Martens (1997)
Unyeasted bread dough	0.5	114	–	141	Povey (1998b)
Milk chocolate (25°C)	0.5	1020–1740	–	–	Povey (1998b)
Aerated milk chocolate (25°C)	0.5	900–1000	–	–	Povey (1998b)
De-aerated milk chocolate (25°C)	0.8	2050	–	–	Povey (1998b)
Egg thin white	2.5	1560	–	1.6	Povey (1998b)
Egg yolk	2.1	1500	–	1.4	Javanaud (1988)
Muscle (39°C)	1	1590	–	1.65–1.74	Goss *et al.* (1978)
Cod fillet (30°C)	3.5	1572		55	Ghaedian *et al.* (1997)
Skim milk (28°C)	1	1522	–	1.5	McClements (1997)
Light cheddar cheese	1	1623	–	–	Saggin and Coupland (2001c)

gases present, K has a value between 1.3 and 1.7. Ultrasonic velocity in an ideal gas can also be calculated in terms of its molecular weight, M:

$$c^2 = \frac{\gamma RT}{M} \tag{6}$$

where R is the gas constant and T absolute temperature.

Liquids can readily support longitudinal waves but can only marginally support shear waves. In liquids the difference between adiabatic and isothermal elastic modulus is negligible and the modulus in Eqn (5) is equivalent to the bulk compressional modulus, K. Eqn (5) is often rewritten in terms of the compressibility $\kappa\,(= K^{-1})$, neglecting the imaginary (loss) part:

$$c^{-2} = \kappa\rho \tag{7}$$

In ideal cases the speed of sound in a mixture is given by the volume fraction weighted sum of the components in Eqn (7). When the beam of sound is narrower than the material through which it passes, there is some shearing at the beam edges, and therefore the modulus is equal to $K + (4/3)G$. However, since in fluids $K >> G$, it is often possible to neglect the shear modulus and measurements of longitudinal ultrasonic velocity have little direct value as a measurement of shear rheology.

The elements in a solid are more directly connected than in a fluid; therefore, solids are better capable of supporting both longitudinal and shear waves. When the sound wave passes through a narrow structure where the cross-sectional dimensions are small compared to the wavelength, the speed of longitudinal ultrasound is given by:

$$c^2 = \frac{Y}{\rho} \tag{8}$$

where Y is the Young modulus. However, when the longitudinal waves pass through a material in bulk form, some shearing motion occurs at the beam edges and the material shear modulus also affects the wave propagation and, as for liquids, the modulus is given by $K + (4/3)G$. For shear waves, the speed of sound in solids is equal to $(G/\rho)^{1/2}$ and is typically much slower than for longitudinal waves.

2. *Ultrasonic attenuation*

Any factors that cause sound energy to be either converted to other energy forms (usually heat) or directed into another direction so they are not detected will contribute to the attenuation. In practice the measured attenuation can be taken as an arithmetic sum of several contributing factors:

$$\alpha_{\text{measured}} = \alpha_{\text{classical}} + \alpha_{\text{resonance}} + \alpha_{\text{scattering}} + \alpha_{\text{other}} + \cdots \tag{9}$$

where the subscripts refer to the various mechanisms. Measuring attenuation as a function of frequency can help to differentiate between the loss mechanisms and to probe the structure and dynamics of the sample.

The heating and cooling due to the passing pressure wave is not completely efficient. Some energy is lost as heat (molecular friction), which contributes to measured attenuation. Classical attenuation accounts for only viscous and thermal losses:

$$\frac{\alpha_{\text{classical}}}{\nu^2} = \frac{4\pi^2}{\rho c}\left(\frac{4\eta}{3} + \frac{(1-\gamma)\tau}{C_{\text{p}}}\right) \tag{10}$$

where η is the viscosity and τ is the thermal conductivity. The first term of the equation describes the viscous losses due to intermolecular friction, while the second describes the thermal losses due to inefficient heat transfer. Except for the simplest fluids, other attenuation mechanisms will be much more significant than these, and Eqn (10) usually greatly underestimates the actual attenuation. Important other loss mechanisms include scattering and the disruption of certain chemical equilibria.

When a system is in equilibrium and the conditions change, the position of the equilibrium will also change. A passing ultrasonic wave creates periodic zones of high (and low) pressure and temperature that will tend to cause such a shift in the position of the equilibrium if it can respond rapidly enough. The rate of response of the system will depend on the kinetics of the processes, e.g. for a system at equilibrium between two states interconvertable by first-order processes with rate constants k_1 and k_{-1}, the relaxation time, t_{r} (i.e. the time to respond to a change) is $(k_1 + k_{-1})^{-1}$ (Dickinson and McClements, 1995). More complex expressions exist for more complex transitions. If the rate of change in temperature/pressure is high (high frequency) then the system has no time to respond and there is little additional energy lost, while at low frequency the rate of change in pressure/temperature is slow and the reaction can respond fast enough to remain in equilibrium throughout the passage of the wave. However, at intermediate frequencies the position of the equilibrium is constantly attempting to respond to the varying conditions. At the low and high frequency limits, the ultrasonic velocity is constant (and different) and the attenuation (due to this mechanism) is low. Over the intermediate region the velocity increases from the low to the high frequency limit and there

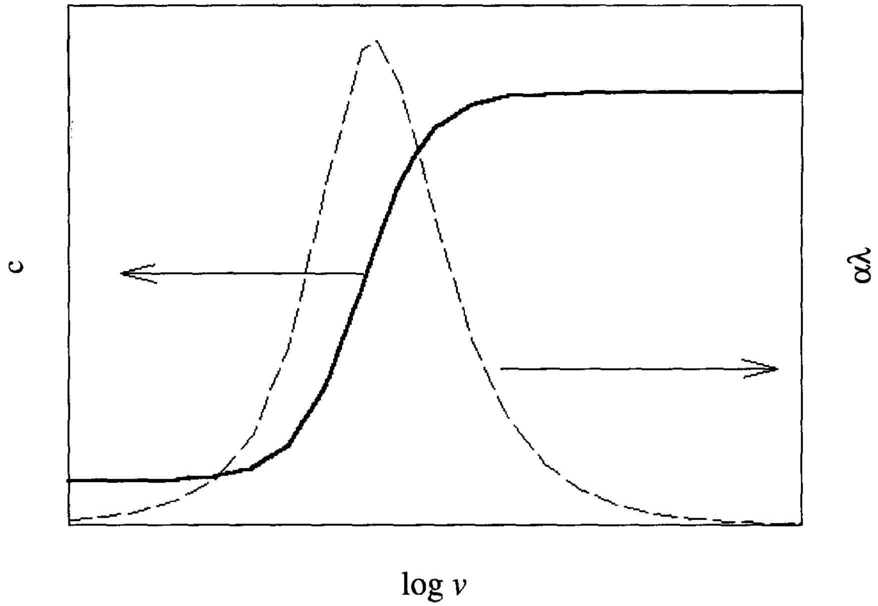


FIG. 2 Variation of velocity and attenuation across a resonance. The velocity increases from a low to a high frequency plateau while the attenuation per cycle shows a bell-shaped peak.

is a peak in the attenuation spectrum. This process is known as a relaxation. It is expressed mathematically as follows and is illustrated in Figure 2:

$$c = c_0 + \frac{(c_\infty - c_0)\,\nu^2}{\nu_r^2 + \nu^2} \tag{11}$$

$$\alpha_r = \frac{K_r\,\nu_r^2\,\nu^2}{\nu_r^2 + \nu^2} \tag{12}$$

In Eqns (11) and (12) c_0 and c_∞ are the ultrasonic velocities at zero and infinite frequency (the plateau values above and below the relaxation), ν_r is the frequency of the resonance, α_r is the attenuation due to the resonance and K_r is a constant describing its magnitude (Dickinson and McClements, 1995). Measuring the resonance frequency by ultrasonic spectroscopy can allow calculation of the relaxation times of the process and is extremely useful in probing the kinetics of fast chemical reactions ($t_r \sim$ 1 ns to 1 ms) (Slutsky, 1981; Bryant and McClements, 1999b).

C. ULTRASONIC PROPAGATION IN INHOMOGENEOUS MEDIA

All foods are heterogeneous over some length scales. Very small heterogeneities are not distinguishable by a sound wave and very large structures are best thought of as bulk phases (see sections describing reflection and imaging). Intermediate sized structures where a characteristic length scale is of similar magnitude to the wavelength of the sound can scatter the acoustic wave, leading to increased attenuation and changes in ultrasonic velocity. For longitudinal sound propagating in water, the wavelength of 1 MHz sound is about 1.5 mm, so many very small structures found in food can act as scatterers. The extent of scattering depends on the size, shape, composition and number of inhomogeneities, and so ultrasonic measurements can be used to characterize fine structure.

Mathematical descriptions of scattering interactions are often extremely complex and in many cases of only moderate complexity cannot be readily solved. One successful application of scattering theory is the ultrasonic characterization of emulsions. (Other, more complex, theories are available for nonspherical particles (Ahuja and Hendee, 1978).) Emulsion droplets are spherical and (usually) considerably smaller than the wavelength of sound. These two conditions make the problem much more approachable. The two stages to predicting the ultrasonic properties of a dispersion are: (1) calculate the scattering from an individual particle; and (2) calculate the interactions between the scattered and nonscattered waves from an ensemble of particles.

Because the particle is small compared to the wavelength of the sound, it experiences an effectively uniformly changing pressure. The pressure gradient induces fluid flow and both the particle and the surrounding medium will tend to move. However, because they have a different inertia, the droplet and continuous phase will move slightly out of phase and the particles will be seen to oscillate in the acoustic wave (Figure 3). The moving particle itself acts as a dipolar source, scattering sound mainly forwards and backwards. As well as moving in the pressure gradient, the particle and surrounding media will also be compressed. If the particle has a different compressibility to the surrounding fluid it will be differentially compressed and seen to pulsate. A pulsating droplet acts as a monopolar sound source scattering sound waves homogeneously in all directions (Figure 3).

In fact the actual amount of sound energy scattered by these mechanisms in the long wavelength regime is very small and the losses are dominated by the inefficiencies of the interactions. (Scattering becomes dominant as the particle radius approaches the ultrasonic wavelength.) The friction between the oscillating particle and the surrounding fluid converts sound

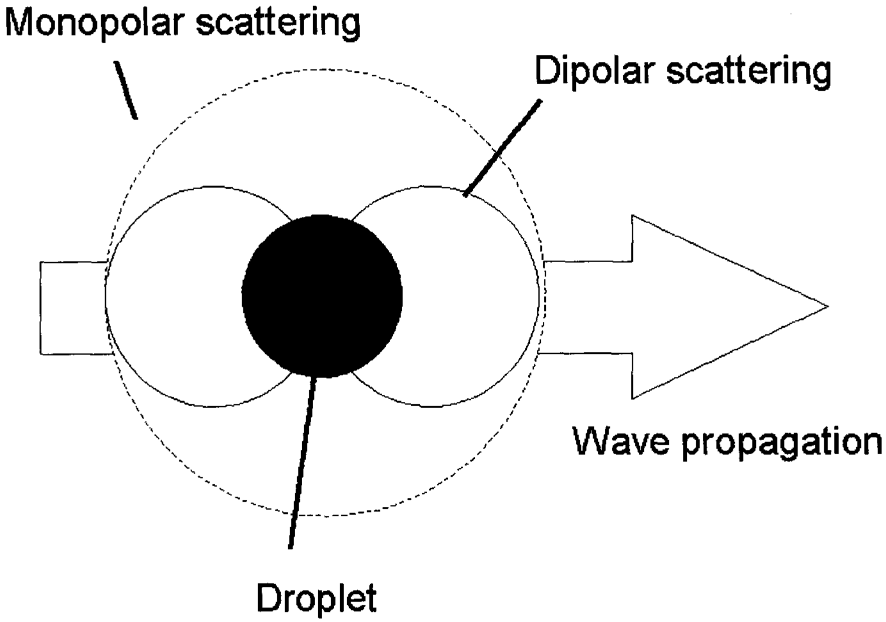


FIG. 3 Diagram illustrating viscoinertial and thermal scattering from an emulsion droplet in an ultrasonic wave. Viscoinertial scattering is due to the particle oscillating in the continuous phase as a result of the inertial mismatch and acting as a dipolar source. Thermal scattering is due to pulsations of the particle and scatters waves in all directions (i.e. monopolar).

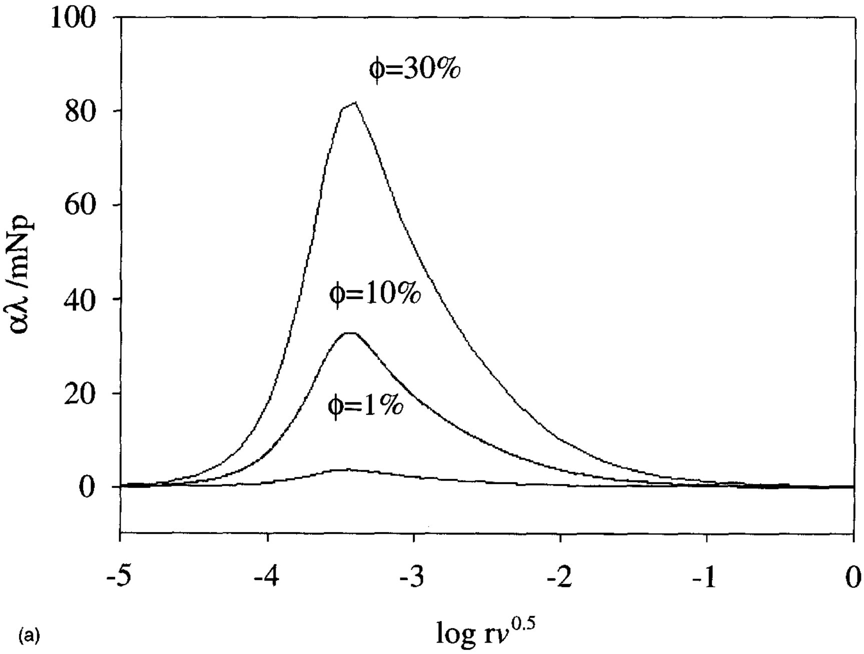
energy to heat (viscoinertial losses) and the compression of the particles causes a differential heating effect. Thermal diffusion is inefficient and energy is lost as heat.

Once the scattering from a single particle is understood, the next stage of the problem is to combine their effects to predict the ultrasonic properties of a reasonably concentrated ensemble of particles. The main approaches to this problem are the core–shell models and the use of multiple scattering theories. Both of these are well described in the literature (McClements, 1992; Hermar *et al.*, 1997) and only the former will be described further here.

Multiple scattering theory (Waterman and Truel, 1961) uses an arithmetic sum of terms to calculate the interactions between the primary acoustic wave and the waves scattered from other particles. Each of the terms can be calculated from a series of complex simultaneous equations (McClements and Povey, 1989) and complete solution of the problem can require the extremely laborious calculation of more than 20 of these. However, in the long wavelength limit for moderate concentrations of scatterers, adequate precision can be achieved by considering only the first- and second-order terms (McClements, 1996):

$$\left(\frac{K}{k_1}\right)^2 = 1 - \frac{i4\pi N(A_0 + 3A_1)}{k_1^3} - \frac{48\pi^2 A_0 A_1}{k_1^6} \qquad (13)$$

where k_1 is the complex wavenumber of the continuous phase, N is the number of droplets per unit volume ($= 3\phi/4\pi r^3$, ϕ is the volume fraction and r the droplet radius). The velocity and attenuation predicted from the theory are contained in the real and imaginary part of K, the complex wavenumber of the emulsion ($= \omega/c + i\alpha$). The terms A_0 and A_1 are analytical solutions to the scattering equations describing the thermal and visco-inertial losses. They are functions of the particle radius, wavenumber (i.e. velocity and attenuation), the physical properties (density, thermal conductivity, viscosity, cubic expansion coefficient and specific heat at constant pressure) of the component phases and the frequency of the sound (McClements, 1996). Using published values for the physical constants it is possible to use Eqn (13) to predict velocity and attenuation as a function of frequency and the concentration and size of the particles present. If necessary, the terms in radius can be replaced by a size distribution



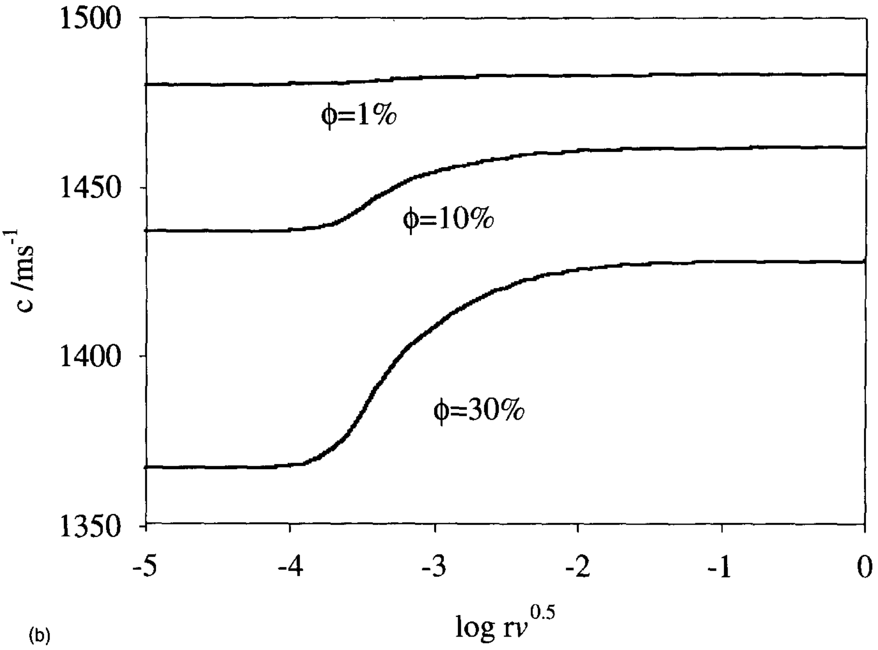


FIG. 4 Theoretical prediction of the ultrasonic (a) attenuation and (b) velocity spectra of a dispersion of corn oil droplets (ϕ = 1%, 10% and 30%) in distilled water. The calculations were performed using a simplification of multiple scattering theory as described in the text using literature data for the physical properties of the component phases. Note that the spectra are size dependent over a limited frequency range and concentration dependent over the whole range.

function – most commonly a log-normal function that only requires the introduction of polydispersity as an additional unknown. Theoretical predictions of the acoustic spectra for various concentrations of fine corn oil droplets in water are shown in Figure 4. (Note that in Figure 4 frequency and particle size are both contained in the x-axis and losses are expressed as attenuation per wavelength, $\alpha\lambda$.) At high and low frequencies the ultrasonic properties of a dispersion are independent of the size of the particles, but over a critical range velocity increases sigmoidally and there is a peak in attenuation. For micrometer-sized droplets this occurs in the range of 10^4–10^8 MHz and size measurements are possible from ultrasonic spectra made in this range. (More complete theories greatly extend this range.)

Particle sizing can then be achieved by measuring the ultrasonic properties of the emulsion over this region and iteratively finding the best value of radius (and perhaps also concentration and polydispersity) to fit the theory to the experimental data. Both velocity and attenuation can be used for particle sizing (Coupland and McClements, 2001b), although the latter is usually preferred as it is often less sensitive to temperature fluctuations (Chanamai *et al.*, 1998a). These calculations can be somewhat laborious with current computing power and simpler solutions are available under more limited circumstances (Wang and Povey, 1999).

As with any curve-fitting operation, the fewer adjustable parameters (i.e. size, volume fraction, polydispersity and physical constants), the more rapid and satisfactory the solution. Where possible the physical properties of the component phases should be measured independently for the system under investigation, but, failing that, literature values are available (Coupland and McClements, 1997). Babick *et al.* (2000) used numerical analyses to show the effects of uncertainty in material parameters on the results of a sizing operation. If possible, it is advantageous to determine the volume fraction of the emulsion from an independent chemical or density measurement, leaving only the hard-to-measure microstructural parameters unknown.

The simplification of multiple scattering theory described here has provided a reasonable description of experimental results up to moderate particle concentrations (McClements, 1992), but the full theory is required for concentrated (>~10%) particles or outside the long wavelength limit. More complex theory based around multiple scattering or core–shell theories have been shown to work over a wide range of particle sizes and concentrations (Chanamai *et al.*, 1999; Herrmann and McClements, 1999).

Recently, a theory has been developed to describe the ultrasonic properties of flocculated emulsions (McClements *et al.*, 1998). As we have seen, the compression of particles in a sonic field generates waves of heat that are inefficiently dispersed into the continuous phase. When the droplets are closely associated, for example in a floc, the thermal waves overlap and heat loss is reduced, leading to a decreased ultrasonic attenuation. This effect is treated theoretically by assuming the flocculated emulsion can be treated as a two-phase system, which consists of spherical "particles" (the flocs) dispersed in a continuous phase. The flocs are treated as an "effective medium" whose physical properties (e.g. density, viscosity) depend on the size, concentration and packing of the droplets within them. The ultrasonic properties of the flocculated emulsion can then be calculated by considering the interactions of sound with (a) a single particle within the effective medium of the floc and (b) the floc with the continuous phase. Sample calculations for flocculated emulsions are presented in Figure 5. In this figure the total oil–water ratio is held as a constant but the proportion of the (1 μm) droplets present in (10 μm) flocs is changed. This theory has been shown to give good agreement with experimental measurements of flocculated oil-in-water emulsions (Chanamai *et al.*, 1998b). At high frequencies the flocs scatter sound themselves and cause

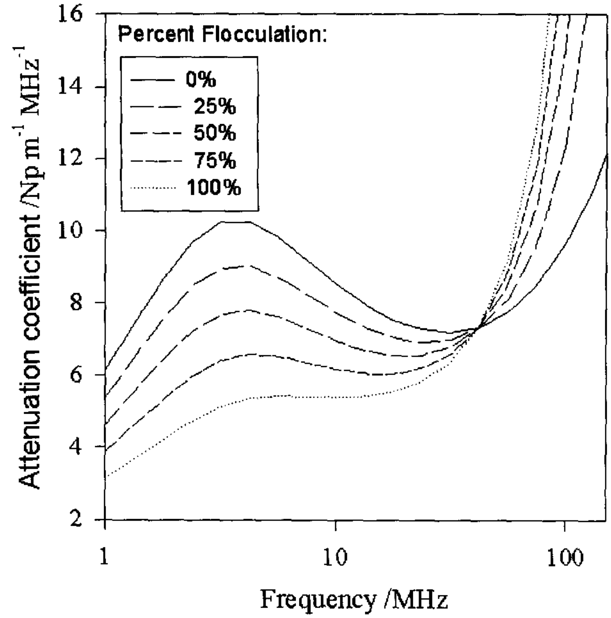


FIG. 5 Theoretical prediction of the attenuation of a fine (1 μm water emulsion with varying proportions of the droplets present in larger (10 μm diameter) flocs. The more flocculated droplets have a higher attenuation at high frequency and a lower attenuation at low frequency.

the additional attenuation observed. At low frequencies the thermal overlap effects discussed above are responsible for the reduced attenuation.

D. WAVES AT INTERFACES

Inevitably to make an ultrasonic measurement the wave must pass across an interface where it will be partly reflected (Figure 6). The proportion of transmission and reflectance at an interface is governed by the acoustic impedances of the component phases. The specific acoustic impedance, Z_a, is defined as:

$$Z_a = \frac{P}{\xi} = \frac{\omega\rho}{\kappa} = R_a + iX_a \tag{14}$$

where P is the acoustic pressure. (Note the shear impedance will be different to the longitudinal impedance.) As with all acoustic parameters characterizing both the elastic and inelastic parts of the wave, acoustic impedance is complex, expressed as the complex sum of R_a the resistive (real) and X_a the reactive (imaginary) part. In many cases, the attenuation is low and the reactive part of the impedance can be neglected, so it is possible to simplify Eqn (14) to $Z = \rho c$, where Z is the characteristic impedance. The characteristic impedances of some materials are provided in Table I.

The amount of energy reflected at a plane interface can be expressed in terms of the ratios of either the amplitude or the intensity of the reflected (subscript r) to the incident (subscript i) wave. (In fact it is possible to define the reflection in terms of almost any characteristic parameter, for example the local pressure maximum, particle velocity, particle acceleration.) As intensity (I) is proportional to the square of amplitude (a), this leads to two commonly used, and frequently confused, reflection coefficients (R):

$$R_a = \frac{a_r}{a_i} = \frac{Z_2 - Z_1}{Z_1 + Z_2} \tag{15}$$

$$R_I = \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \tag{16}$$

When sound that is traveling from a medium of low acoustic impedance encounters a boundary with a second medium of high acoustic impedance (e.g. traveling from air to a solid), the ultrasonic waves are almost entirely reflected (R tends to unity). When the boundary is between media of similar impedance, then R tends to zero and the materials are said to be acoustically matched, or ideally coupled.

By a similar analysis, the transmission coefficient (the ratio of the transmitted and incident waves) is:

$$T = \frac{I_t}{I_i} = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \tag{17}$$

The situation is more complex when the wave encounters an oblique interface and part of the sound is reflected and part of it is refracted, as illustrated in Figure 6(a). The (ultrasonic) refractive index (n) is given by Huygens' principle and Snell's law as:

$$n = \frac{\sin \theta_1}{\sin \theta_2} = \frac{c_1}{c_2} \tag{18}$$

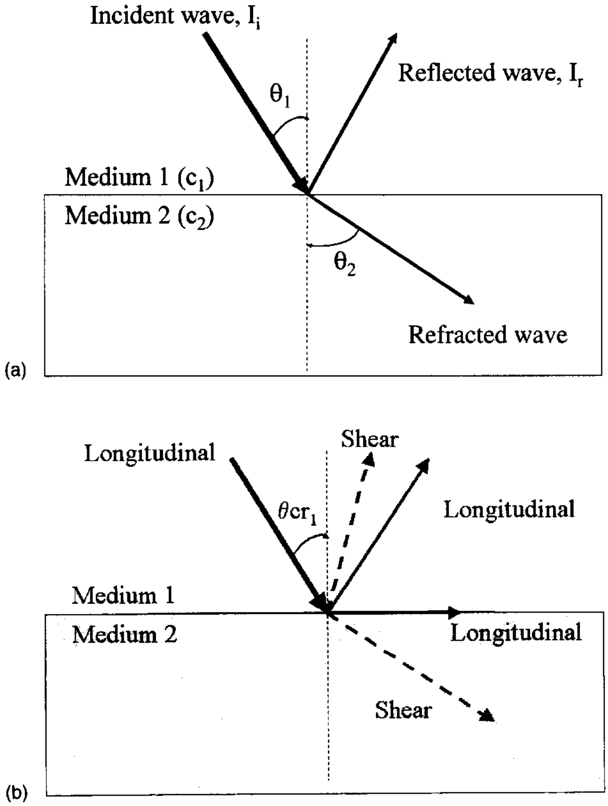
where c_1 and c_2 are, respectively, the velocity of waves in medium 1 and 2, θ_1 is both the angles of incidence and the angle of reflection, and θ_2 is the angle of refraction. The reflection and the transmittance coefficients are given by:

$$R = \left(\frac{Z_2 \cos \theta_1 - Z_1 \cos \theta_2}{Z_2 \cos \theta_1 - Z_1 \cos \theta_2}\right)^2 \tag{19}$$

$$T = \frac{4Z_1Z_2 \cos \theta_1\theta_2}{(Z_2 \cos \theta_1 + Z_1 \cos \theta_2)^2} \tag{20}$$

When θ_1 and θ_2 are both equal to 90°, i.e. normal incidence, $\cos \theta = 1$ and Eqns (19) and (20) reduce to Eqns (16) and (17).

When longitudinal waves reflect with a certain critical angles at a boundary, they are subjected to a mode conversion and they can generate different types of wave (Rose, 1999). For example, when the velocity of



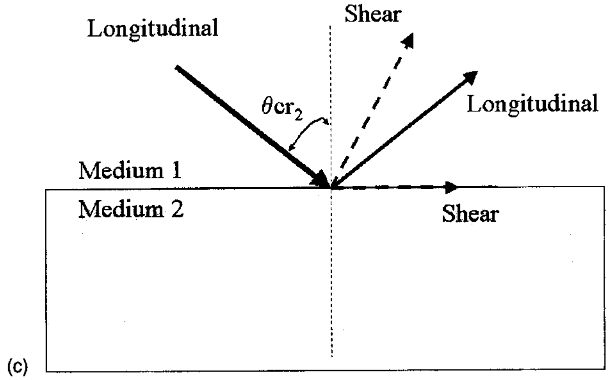


FIG. 6 Interaction of a wave with an interface. (a) Oblique incidence leads to partial reflection and partial transmission (refraction). Because the incident wave is oblique to the interface, shear and longitudinal components will be generated (not shown). (b) When the angle of incidence is equal to the first critical angle (ϕ_{cr1}), the longitudinal transmitted component is guided along the interface. (c) When the angle of incidence is equal to the second critical angle (ϕ_{cr2}), the shear transmitted component is guided along the interface.

sound in medium 2 is greater than in medium 1, the refracted longitudinal waves are deviated away from the normal. The first critical angle (θ_{cr1}, Figure 6(b)) occurs when the angle of normal wave refraction θ_2, is equal to 90° so that the transmitted longitudinal sound moves along the interface and the shear component continues into the second medium. The second critical angle (θ_{cr2}, Figure 6(c)) is when the shear component is refracted along the interface and the longitudinal component is completely reflected.

E. DIFFRACTION

Our discussion of sound propagation so far has treated the acoustic waves as a coherent beam, and it is possible to find analogous expressions for many of the equations used here in the field of laser optics. However, sound waves are not coherent and we must also account for diffraction. Diffraction is particularly important as beam spreading can mean the detector can receive only a portion of the sound energy produced and the apparent attenuation of the material is overestimated. An ultrasonic transducer can be considered as a piston source. A crystal vibrates under an applied voltage and the force wave propagates away from it as ultrasound. The area in front of the acoustic source is divided in two

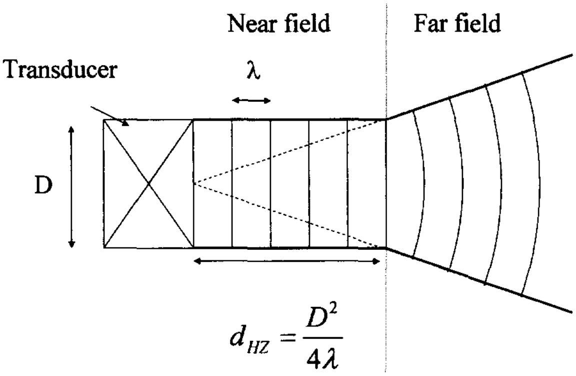


FIG. 7 Diagram showing the near- and far-field regions in an ultrasonic wave emitted from a plane source. In the near-field region the wavefronts are parallel to the source but the pressure fluctuates wildly with distance. In the far-field the pressure fluctuates sinusoidally with distance and the wave appears to diverge from the center of the source.

regions (Figure 7): the near and far fields. In the near zone, the beam of sound is parallel to the generating source, while in the far zone it diverges apparently from a point at the center of the source. The value of d_{nz}, i.e. the limit of the near zone, is calculated from the following equation:

$$d_{\mathrm{nz}} = \frac{D^2}{4\lambda} \tag{21}$$

where D is the circular source diameter. Measurements in the far-field region must account for the loss in signal either mathematically (Khimunin, 1972) or through appropriate calibration. Beam spreading can also lead to ultrasonic reflections from the container walls that can make accurate measurement more difficult, particularly as certain angles of incidence lead to mode conversion. In the near-field region the pressure fluctuates wildly with distance and it is extremely difficult to make an accurate measurement (Povey, 1997); it is almost always preferable to make measurements in the far field.

III. MEASUREMENT METHODS

In the theory section above we discussed the various ways that the ultrasonic and material properties of materials are linked. Later we will proceed to describe various applications of these relationships to food characterization, but we must first consider the practicalities of making ultrasonic measurements. In all cases we seek to define the principles and practicalities of the method as well as provide some suggestions for avoiding common errors. Several important elements of measurement system design are reviewed by McClements and Fairley (1991, 1992), Papadakis (1990a, 1990b), Crecraft (1983), and Sarvazyan (1982). In general, all the measurement systems share some common features:

(a) *Ultrasonic transducers.* Ultrasonic transducers convert an electrical to an ultrasonic signal and vice versa. There are various approaches to transducer design but most depend on the electrically induced vibration of a crystal, i.e. the piezoelectric effect. Cutting the crystal at different angles to the atomic structure can yield transducers with different modes of vibration. When an electrically insulating crystal is compressed it will experience a deformation and electric charges will be created on the surface, i.e. positive charge on one surface and negative on the other, generating an electrostatic field within the crystal. On the other hand, when a crystal is placed in an electric field, it experiences a deformation, i.e. transducers work both as transmitter and receiver. The back of the crystal is usually protected by an acoustically insulating backing material to absorb the energy released in that direction and the front by an acoustically conducting wear plate.

(b) *Signal generator.* A signal generator provides a controlled voltage to the transducer to generate the acoustic signal. The simplest measurements use a board-band electrical pulse to excite the transducer, i.e. an energy pulse containing a wide range of frequencies. This is analogous to striking a bell with a hammer; it is possible to make a loud noise but many frequencies of sound are generated simultaneously. More sophisticated signal generators can provide a burst of known energy composition and/or duration. Acoustic signal generators are frequently quite high voltage (~100 V) and provide a synchronization pulse to zero the time measurement apparatus.

(c) *Digitizer.* The acoustic signal captured and converted to an electrical signal by the transducer must be stored and analyzed. This is commonly achieved using a digital storage oscilloscope or an equivalent computer card. Whatever mode of data capture is selected, it is important to ensure that the resolution is sufficient to capture the high frequency detail in the signal – usually at least three times faster than the highest frequency of interest. The digitizer must also be able to store sufficient data points to capture all the signals of interest and should have a wide dynamic range to cope with highly attenuating samples. Modern oscilloscopes provide many other useful features such as

Fourier domain editing and arithmetic functions. A single ultrasonic measurement is often rapid (~ 20 μs) so a useful amount of signal averaging can be conducted in apparently "real-time" within the oscilloscope.

All of these items need to be connected with appropriate cabling. Unless very high frequency measurements are considered (> 10 MHz), conventional coaxial cabling is sufficient. The cabling should be kept as short as practically possible and should not be changed between calibration and when performing measurements. Defects in connections and cabling can cause errors in measurement often overlooked when troubleshooting a system.

A. PULSED MODES

A real-world application of a pulsed sonic measurement is shouting in a canyon and waiting for the echo to return. Using the wait time (t) and the speed of sound in air ($c \sim 330\,\mathrm{m\,s^{-1}}$), it is trivial to calculate the width of the canyon ($d/2$) from:

$$d = ct \tag{22}$$

Ultrasonic measurement methods seek to apply this principle in a systemized and controlled manner (McClements and Fairley, 1991). The measurement can be conducted in either one- or two-transducer mode, as illustrated in Figure 8. In one-transducer mode the signal reflects from a material interface and is detected by the original (speaker) transducer; in two-transducer mode the second transducer acts as a receiver. In both

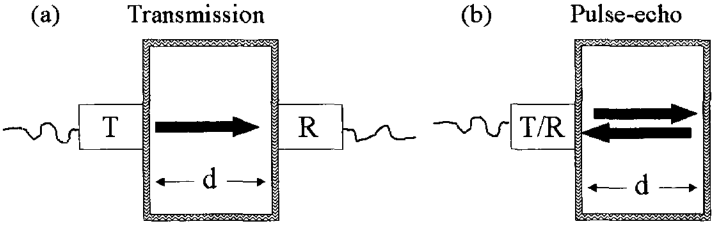


FIG. 8 Diagram illustrating pulsed mode measurements. Ultrasonic velocity is calculated from the time taken for the pulse to travel a known distance and attenuation is calculated from the energy loss. Measurements may either be made (a) through transmission mode, where a second transducer is required to detect the signal, or (b) in pulse-echo mode, where a single transducer is used to generate and detect the sound.

cases the ultrasonic velocity is calculated using Eqn (22) as $c = d/t$. The attenuation of the material can also be measured from the loss in signal amplitude with distance (Eqn (3)), but it is important to account for the nonattenuation losses due to diffraction and imperfect reflection. Frequency dependence of the acoustic parameters can be determined from a Fourier transformation of the various echoes (McClements and Fairley, 1992) or by a series of a few cycles of the pure frequency of interest (tone burst).

The time of flight of the pulse can be measured extremely precisely and so for precise velocity measurements a good measurement of pathlength is also required (see Eqn (23)). Conventional micrometers are not adequately precise so instead the sample cell is calibrated using a material of known ultrasonic velocity (i.e. water; DelGrosso and Mader, 1972). Calibration should be performed regularly and certainly whenever the temperature is changed or the transducers moved. For the most precise measurements it is good practice to check the calibration with another fluid of well-defined properties.

B. NONCONTACT MEASUREMENTS

A significant limitation of conventional ultrasonic measurements is the huge impedance mismatch between air and the transducer delay line. Indeed, until recently it was considered impossible to propagate high frequency (~MHz) ultrasound through air. However, a new transducer technology has been developed to overcome the air–transducer impedance barrier (Bhardwaj, 1986). In particular, so-called "quarter-wave matching layers" have been devised which gradually, i.e. layer-by-layer, adapt the traveling waves to lower and lower acoustic impedances until they match that of air and thus provide transmission into air with reasonable efficiency. This procedure has been so successful that it is now possible to transmit sound through air at frequencies of several MHz. The key feature in the transducer construction is the use of new materials, specifically the use of polymers filled with microballoons whose number and size can be adjusted to tailor the acoustic impedance. Ideally the acoustic impedance of the matching layer needs to be equal to the square root of the product of the two impedances to be matched. The thickness of the matching layer needs to be equal to one-fourth of the wavelength of the wave propagating through the layer (Tittmann *et al.*, 1998).

Clearly noncontact measurements are applicable to many sensing applications where direct contact with the food surface is impractical. A typical experimental setup is shown in Figure 9. The ultrasonic signal is passed to one of two ultrasonic transducers arranged a fixed distance

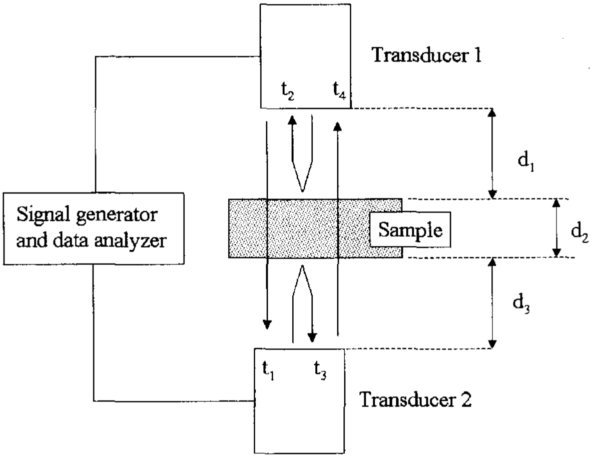


FIG. 9 Diagram showing the arrangement of transducers used in a noncontact measurement. By using each transducer to measure the time for a pulse of sound to echo from the sample surface and to transmit to the second transducer, it is possible to simultaneously measure the ultrasonic velocity in the sample and its thickness.

apart, in good alignment with each other. The ultrasonic transducer converts the electrical signal to sound that propagates through the air and is detected by the second transducer at a time t_1 later. If there is a sample between the transducers, part of the signal is reflected from the front face of the sample and the reflection detected by the first transducer after an elapsed time of t_2. The operation is then repeated in reverse, so measuring a transmitted time signal t_4 at the first transducer and, if there is a sample present, an echo at time t_3 at the second transducer. Measurements of t_1 and t_4 are recorded in the absence of a sample and t_{1-4} in the presence of a sample. The thickness (d) and speed of sound (c) of the sample can be calculated as follows (the superscripts a and s refer to the air and sample, respectively):

$$d_2^{\mathrm{s}} = c^{\mathrm{a}} t_1^{\mathrm{a}} - \frac{c^{\mathrm{a}}}{2} (t_2^{\mathrm{s}} + t_3^{\mathrm{s}}) \tag{23}$$

$$c^{\mathrm{s}} = \frac{-2d_2^{\mathrm{s}}}{(-2t_1^{\mathrm{s}} + t_3^{\mathrm{s}} + t_3^{\mathrm{s}})} \tag{24}$$

(Note that in Eqns (23) and (24), t_1 could be replaced by t_4 without changing the result.) Attenuation can be calculated from similar measurements of signal power.

Aside from the technological breakthroughs required in its development, noncontact ultrasonic measurements are a variation of the pulsed methods described above. A key advantage is that thickness is determined directly by the acoustic wave and not measured independently. Precise, contact-mode measurements are restricted to fluids confined in defined geometries and solids can only be measured by (imprecisely) measuring the thickness with calipers.

C. RESONANCE METHODS

Although pulsed modes are the most frequently used methods of ultrasonic food characterization, they have an important disadvantage of requiring a long pathlength to allow the signal to decay sufficiently for an attenuation measurement and for the arrival time to change enough to distinguish velocities. Consequently the sample volumes required are rather large and it can become difficult to maintain adequate temperature control for the highest precision measurements. An alternative approach is to exploit the resonance properties of a container holding the sample (Sarvazyan, 1982). A pair of aligned transducers is placed either directly in the fluid or around a container holding the fluid. One transducer generates a continuous pulse of pure varying frequency and the second acts as the detector. (A second, less common, type of resonator uses a fixed frequency and variable pathlength to generate the resonance peaks. Aside from this, the principles of measurement are similar.) The wave will echo backwards and forwards between the two transducers and when the wavepath is a whole number of half-wavelengths it will constructively interfere and appear as a peak in the frequency/amplitude plot, i.e. the condition for resonance is given by:

$$n \frac{\lambda}{2} = l \tag{25}$$

where n is the (integer) number of the resonance peak, λ is the wavelength, and l is the pathlength of the resonator. The wavelength is hard to measure independently, but can be calculated as $c\nu^{-1}$. Therefore the change in resonance frequency (dν) of a given peak can be related to a change in velocity:

$$\frac{\mathrm{d}c}{c} = \frac{\mathrm{d}\nu}{\nu} \tag{26}$$

Alternatively, the velocity can be calculated from measurements with a calibration liquid:

$$c = 2l(\nu_n - \nu_{n-1}) \tag{27}$$

where ν_n and ν_{n-1} are the resonance frequencies of adjacent peaks. This approach is somewhat simplistic since it neglects the effects of diffraction and nonideal reflection, but these factors can also be dealt with by additional calibration, often using sodium chloride solutions.

The losses of a filled resonance cell are often expressed as the Q-factor of the system (cell plus sample) calculated from the width of a resonance peak (Buckin and Smyth, 1999). The contribution of the cell to the Q-factor can be calculated from a suitable attenuation calibration (often magnesium or manganese sulfate solutions) to give the loss properties of the fluid. The Q-factor of the sample is a function of attenuation:

$$Q_{\text{sample}} = \pi / \alpha\lambda \tag{28}$$

The most precise ultrasonic characterization of fluids is by resonance methods; approaching $0.3 \times 10^{-4}\%$ for the best systems (Buckin and Smyth, 1999). Ultra-high precision requires optimization of all of the factors in the measurement system, importantly including temperature. Commercial water baths can easily control temperature to 0.01°C, but ultrasonic velocity precision of the type described above requires a two order of magnitude improvement over this. In practice, precision measurements are made using paired cells in differential mode – one cell measures temperature with a calibration fluid while the other makes high precision measurement of the fluid under consideration.

D. REFLECTANCE METHODS

The magnitude of an echo returning from an interface is related to both the ultrasonic properties* of the two phases (Eqn (16)) and the magnitude of the original pulse. If one of these materials is fixed, then the magnitude of the returning echo is solely dependent on the acoustic properties of the second material and on the magnitude of the incident pulse. This can be exploited as a sensing modality, as changes in the magnitude of an echo returning from the interface between the container and its contents will depend only on changes in the contents. Alternatively, a delay line can be coupled to the transducer and the reflection from the interface between the delay line and the sample surface measured.

In practice it is difficult to ensure that the performance of the transducer and signal generator is constant on a day-to-day basis, so it is better to

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*Specifically *impedance*; these techniques are also known as impedance methods.

normalize the reflection amplitude to that of a calibration material such as water. Alternatively it is possible to use a dual delay line made of two materials linked in series so there are echoes from the interface within the delay line and the delay line–sample interface. The two echoes can be used to solve the two unknowns in the measurements system (i.e. magnitude of the generated signal and ultrasonic properties of the unknown sample). When necessary, reflectance (R) can be calculated as a complex parameter from the magnitude (M) and phase (θ) of the reflected echo from the sample (subscript s) and calibrant (subscript c) obtained from a Fourier transformation (McClements and Fairley, 1992):

$$R_s = R_c \frac{M_s}{M_c} \exp\,[i(\theta_s - \theta_c)] \tag{29}$$

Reflectance measurements are often suitable for on-line sensing, as they do not require a fixed and invariant pathlength for the sound within the material of interest, which may not be available in some process equipment. However, reflectance is clearly only sensitive to the surface of material close to the container and may not be representative of the bulk. This may be a particular problem for foods in containers prone to surface fouling. Reflectance is the only effective way to characterize the shear ultrasonic properties of fluids, as shear waves cannot penetrate sufficient distances for transmission measurements.

Related to normal reflectance measurements are the so-called "guided wave" sensors where an acoustic wave is partly trapped inside a container or pipe wall and propagates a significant distance (several meters) along by multiple internal reflections. At each reflection a portion of the sound leaks into the surrounding material so the detected signal is sensitive to changes in composition. Guided wave sensors are particularly valuable in detecting fouling in pipes and hard to reach equipment (Rose, 1999).

E. LOVE WAVE SENSORS

Love waves are shear, horizontally polarized waves that propagate in a thin surface layer. There are some losses into the media surrounding the guiding layer and the wave properties are therefore sensitive to material properties. A major advantage of Love wave sensors is they can be manufactured very cheaply and compactly using printed circuit board technology onto silicon wafers of thickness in the order of 500–1000 μm. They can also be wirelessly interrogated and can operate in pulse echo, through transmission, or in resonance modes.

Curtin and coworkers (1998) developed a micromachined wet cell for Love wave measurements particularly suitable for foods and fluids characterization. A micromachined channel shields all but the wave path from the influence of the liquid and a heater controls the local temperature. A similar design, incorporating paired Love wave sensors, was used by Varadan and Gardner (1999) for a variety of sensing applications. In these cases, one of the sensors is shielded from the fluid and is thus only sensitive to temperature (or mechanical stress), while the other is exposed and responds to both temperature and fluid composition. With two such sensors it is possible to measure two unknowns simultaneously. Arrays of Love wave sensors are particularly exciting food sensors as controlling the masking layer can make them sensitive to different components. In the previous example a single mask allowed simultaneous temperature and fluid property measurement. Using selective masks, similar to those currently employed for ion selective electrodes, it would be possible to develop a genuinely multicomponent ultrasonic sensor.

IV. APPLICATIONS

Even good quality measurements of ultrasonic velocity and attenuation have little value in themselves, but only as they relate to properties determining food quality and to parameters useful for process control. Under certain circumstances the relationships used can be based directly on the underlying physics outlined in the theory section, but in most cases they are empirical. Empiricism should, as always, be treated with caution. Any established link is valid only for the sample set considered and apparently small variations outside this set may render the results meaningless (for example, a correlation between ripeness and ultrasonic velocity for one variety of apple may not hold for another variety). With a mechanistic relationship, it is explicit what is being measured and so wherever possible the physical principles should be at least applied qualitatively to justify an apparent correlation. As we introduce some applications, we shall attempt to stress their theoretical basis wherever possible.

A. LEVEL SENSORS

Perhaps the simplest ultrasonic measurement, one exploiting the gross differences between a fluid and a gas along with the useful ability of sound to make measurements through an opaque solid, is level sensing. Various modes of measurement are available:

(a) *Time-of-flight sensors.* An ultrasonic transducer is placed at the base of the tank and the time taken for a pulse passing up through the liquid and reflecting from the surface is used as a measure of depth. This is precise if the surface is flat and smooth enough to clearly detect a returning echo. This approach has been applied to controlling the filling operation for canned beverages using either a transducer mounted below the fluid (Ridgway *et al.*, 1999) or an air-coupled transducer mounted above (Griffin *et al.*, 2001).

(b) *Presence/absence sensors.* A series of pairs of ultrasonic transducers are aligned with each other at various heights in a column of liquid. The depth of the container is given by the highest pair that can transmit a signal (based on the principle that air cannot support ultrasound but the fluid can. The resolution of this method is limited by the spacing of the transducers.

(c) *Internal reflection sensors.* A pulse of sound is passed obliquely into a bar of solid immersed in the liquid. The sound echoes repeatedly within the solid waveguide and is detected either by a second transducer or in reflectance mode. Each echo depends on the material outside the bar at that point, i.e. either liquid or gas. In general more sound energy will be lost into the liquid so total attenuation of the signal can be related to the amount of the bar immersed in the liquid. Placing the bar appropriately inside a tank can provide a measure of depth.

B. FLUID FLOW

Another widely used group of methods determine the rate of flow of liquids from longitudinal ultrasonic velocity measurements. Again, there are three groups of methods (Lynnworth, 1989):

(a) *Transit-time mode* (Figure (10a)). Two transducers are clamped outside a pipe at a known distance from each and angled to the direction of flow either in V-mode (the transducers are mounted on the same side of the pipe; illustrated in Figure (10a)), W-mode (the sound traverses the pipe four times) or in Z-mode (the transducers are mounted on opposite sides of the pipe). By alternately using the paired transducers as transmitters and receivers, two times of flight are measured, with and against the direction of flow. The speed of sound measured with the flow (downstream) is greater than that measured upstream as the translational motion of the fluid supporting the wave adds to (and subtracts from) the movement of the ultrasonic wave. (If the fluid were not moving there would be no difference in measured ultrasonic

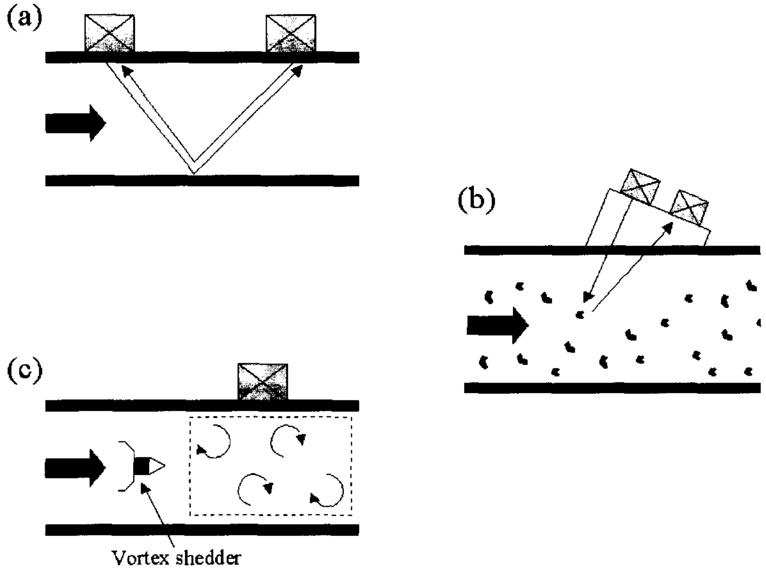

FIG. 10 Diagrams of various types of ultrasonic flowmeter. (a) Transit time mode: Paired transducers acting alternately as sources and detectors measure the time of flight of an acoustic pulse with and against the flow and use the difference to calculate the speed of flow. (b) Doppler flowmeters: Sound reflected from scattering particles entrained in the fluid is used to calculate flow rate. (c) Vortex shedding: Sound is scattered from vortices downstream from a strut introduced into the flow and related to flow rate.

velocity.) The liquid velocity (V) in the pipe can be calculated from the difference in time of flight (Δt) of the sound traveling downstream and upstream through the following equation:

$$V = BL\,\Delta t \tag{30}$$

where B is a constant and L is the distance between the two transducers. The constant B is usually either fixed empirically or calculated as a function of the Reynolds number. Commercial transit-time mode devices are available working in the temperature range −40 to 150°C, in pipe of diameter 1–500 cm, and typically perform best at high flow rates.

(b) *Doppler flowmeters* (Figure (10b)) are based on the principle that the frequency of ultrasonic waves reflected from suspended particles or gas bubbles (discontinuities) within the moving medium is shifted in proportion to the velocity of the moving discontinuities. Current technologies require for a 1 MHz transducer approximately 25 ppm of entrained particles in the liquids, and these inhomogeneities should be at least 30 μm in diameter to provide an adequate reflected signal. To obtain a good signal and high precision during measurement, some conditions need to be satisfied; specifically the pipe must be full and flowing above a certain minimum velocity. Also the scattering particles must be moving at the same rate as the liquid. In many cases turbulence is also required.

(c) *Vortex shedding* (Figure (10c)). A bluff body (the vortex shedder) is fixed to the wall of the pipe, forcing the liquid to flow turbulently around it, producing a series of downstream vortices known as the *von Kármán vortex street.* These vortices have a characteristic frequency that is proportional to the fluid velocity. Using an ultrasonic device either in transmission or in reflection mode, and knowing the geometry of the shedder and the Reynolds number, the velocity of a liquid can be measured with an accuracy of 1%. Vortex shedders are particularly vulnerable to fouling in fluid streams containing a large amount of suspended solids.

C. TEMPERATURE

In most media the speed of sound is a function of temperature (see Figure 11 for examples) and so measurements of ultrasonic velocity can be potentially used as a thermometer. For example, at room temperature the speed of sound increases approximately 3 $\mathrm{m\,s^{-1}}$ per degree Celsius. A typical pulse echo instrument is capable of measuring velocity to within 0.1 $\mathrm{m\,s^{-1}}$, implying a precision in temperature of 0.3°C. (Clearly the more precise resonance methods would be at least an order of magnitude better.) However, when Richardson and Povey (1990) used a tone-burst technique to measure the speed of sound of a fluid flowing in a pipe, they were only able to make measurements within confidence limits of ±1°C. The velocity–temperature function used as a calibration for this technique depends on composition and structure so any changes in the food caused by heating would make the temperature measurements unreliable.

Recently Sigfusson and coworkers (2001) measured the speed of sound in slabs of food undergoing unsteady state cooling. They calculated the theoretical speed of sound as a function of temperature in their food using composition-dependent equations developed by McClements and coworkers (Ghaedian *et al.*, 1998; Chanamai and McClements, 1999; Sigfusson *et al.*, 2001) and showed that the measured values were in good agreement with an integral of this function over the thickness of the slab calculated from the modeled thermal gradient. They further showed measured ultrasonic velocity is a product-specific linear function of core temperature and

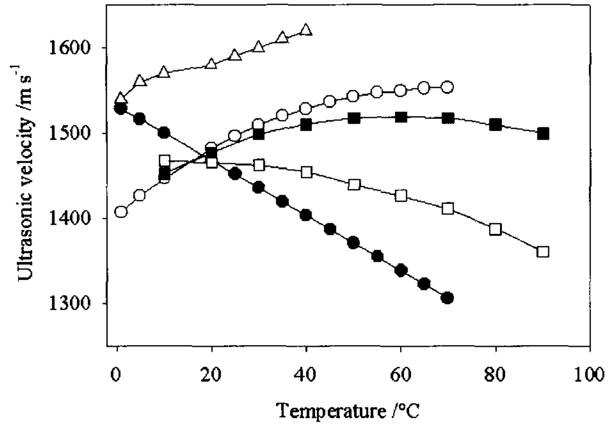

FIG. 11 Speed of sound (~1–2 MHz) as a function of temperature for (○) distilled water, (△) 20% sucrose solution, (●) corn oil, and a fine corn oil-in-water emulsion (■) $\phi = 10\%$, (□) $\phi = 50\%$. Note that while the speed of sound in water and aqueous solutions tends to increase (to a maximum at ~70°C) with temperature, it decreases in oils. The ultrasonic velocity in mixed oil–water systems shows a response to temperature somewhere between the constituents depending on their volume fraction. At the temperature where the speed of sound is similar in oil and water (~20°C), it is insensitive to their ratio in a mixed system. Data were either measured by the authors or taken from various literature sources.

therefore a good sensor for product chilling. In a somewhat similar study, Haeggstrom and Luukkala (2000) measured various ultrasonic properties of fried beef burgers during cooling (74–45°C) and found the best prediction of cooling from the attenuation of 300 kHz sound.

An alternative approach to ultrasonic thermometry is to place a rod in contact with the food. The rod expands with temperature and its length can be accurately measured by propagating an ultrasonic pulse along its length and measuring the reflection from the far (free) end. An advantage of this approach is that it does not need to be recalibrated for each food, but its important disadvantage is that it is invasive. Richardson and Povey (1990) evaluated several rod shapes and were able to achieve confidence limits to their measurements of 0.3°C using a tapered design.

D. COMPOSITION

Some of the most simple and most widely used ultrasonic applications are composition sensors. The speed of sound in many solutions increases nonlinearly with increasing concentration; several examples are shown in

TABLE II

REPORTED DETERMINATIONS OF COMPOSITION FROM ULTRASONIC MEASUREMENTS

Food	Ultrasonic parameters	Measurement conditions	Comments	Reference
Several simple sugars	Velocity (by resonance 1 MHz)	20–45°C	Study of hydration properties of sugars	Shiio (1957)
Alcohol and solids in wine	Velocity	30 and 65°C 12–20 vol% ethanol 2–14% wt% sucrose	Good correlation (r^2=0.99) with composition	Winder *et al.* (1970)
Yeast slurry and wort (°Plato) in brews	Velocity (3.6 MHz)	20°C 13–18% yeast 10.8–11.3°Plato	Calibration curve for wort and yeast and then measurements in brews	Feil and Zacharias, (1971)
Fruit and vegetable juices, oils, sauces, wines, syrups	Velocity	5–50°C	Effect of temperature, water content and alcohol content on ultrasonic velocity	Zacharias and Parnell (1972)
Sugar in solution and in juices	Velocity (0.1–10 MHz)	10–110°C 0–60 wt% sugar	Error ±0.25%	Fedotkin *et al.* (1981)
Aqueous solutions of starch and gelatin	Absorption (0.6–9 MHz)	30–60°C 0.1–0.6 wt%	Excess absorption was noted in starch solutions at various concentrations and temperatures	Reddy and Suryanarayana (1981)
Various monosaccharides	Velocity	20–80°C 0–1.2 M	Adiabatic compressibility was calculated from velocity and density.	Smith and Winder (1983)
Sucrose	Velocity and absorption (5–25 MHz)	20–40°C 0–5 mM		Berchiesi *et al.* (1987)
Monosaccharides, disaccharides, and methyl pyranosides	Velocity	5, 15, 25°C 0–50 mM	Molar compressibility and volume were calculated from velocity and density	Kaulgud and Dhondge (1988)

TABLE II *(continued)*

REPORTED DETERMINATIONS OF COMPOSITION FROM ULTRASONIC MEASUREMENTS

Food	Ultrasonic parameters	Measurement conditions	Comments	Reference
Nucleic bases	Velocity (7.1–7.4 MHz)	15–35°C 0.5–1.5 mg per g H_2O	Apparent molar adiabatic and isothermal compressibility were calculated for seven nucleic basis	Buckin (1988)
Sugar content in fruit juices and beverages	Velocity (2.5 MHz)	10–30°C	Ultrasonic measurements predicted sugar content to within 0.2% (pure sugar) or 0.5% (mixed sugars) and was sensitive to sugar type	Contreras *et al.* (1992)
Cod fillet	Velocity and attenuation (3.5 MHz)	5–35°C	Relation between moisture and speed of sound ($r^2 > 0.8$). No relation with attenuation	Ghaedian *et al.* (1997)
Catfish, cod, flounder, mackerel and salmon	Velocity and attenuation (3.5 MHz)	5–35°C	Measurement at different temperatures for multicomponent (fat, moisture, ash) analysis	Suvanich *et al.* (1998)
Fish analogs made from dried cod powder, sunflower oil and water	Velocity and attenuation (3.5 MHz)	5–35°C	Measurement at different temperatures for multicomponent (fat, moisture, ash) analysis	Ghaedian *et al.* (1998)
Atlantic mackerel	Velocity and attenuation (1–6 MHz)	5–25°C	Measurement at different temperatures for multicomponent (fat, moisture, ash) analysis. Attenuation was insensitive to food composition	Sigfusson *et al.* (2001)

TABLE II *(continued)*

REPORTED DETERMINATIONS OF COMPOSITION FROM ULTRASONIC MEASUREMENTS

Food	Ultrasonic parameters	Measurement conditions	Comments	Reference
Sausages	Velocity (1 MHz)	4–25°C	Explained variance 99.6% for fat, 98.7% for moisture and 85.4% for protein.	Benedito et al. (2001)
Glycerol, sucrose, sodium chloride, tomato ketchup solutions	Velocity and reflectance (2.25 MHz)	20°C	Both velocity and reflection coefficient could be used as concentration sensors with comparable precision.	Saggin and Coupland (2001b)

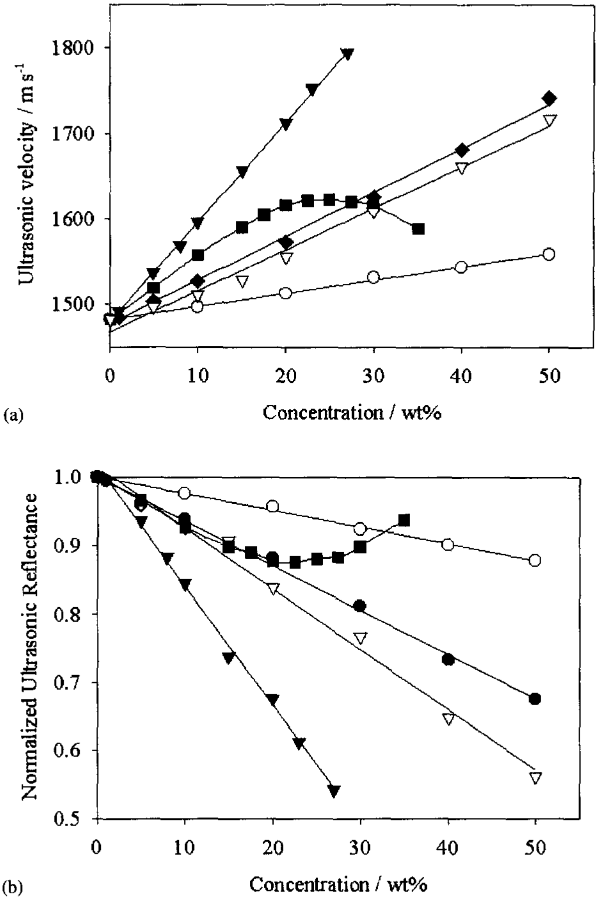

FIG. 12 Ultrasonic (a) velocity and (b) normalized reflection coefficient of solutions of various food samples (▼, sodium chloride; ■, ethanol; ●, glycerol; ▽, sucrose; and ○, tomato ketchup). Measurements were made using a pulse-echo device (2.25 MHz) at 25°C. Reflectance was measured from the interface between Plexiglas and the sample and was normalized to the signal from water.

Figure 12(a) and Table II. Clearly any of these correlations could be used, with caution, as a calibration curve for a concentration. The first major problem is that ultrasonic velocity is a function of overall composition as well as other factors, importantly including microstructure and temperature, and so concentration measurements require the other factors to remain unchanged. It is usually impossible to measure multiple components simultaneously. Ultrasound can, however, be combined as part of a measurement suite, for example for the simultaneous determination of alcohol and sugars in beverages from combined velocity and density measurements.

One way for making multicomponent measurements using ultrasound exploits the different temperature dependencies of the speed of sound in oil and water (Figure 11). At approximately 20°C, the speed of sound in an oil–water system is independent of the concentration of oil and so measurements at this temperature can be used to measure the composition of the aqueous phase (Chanamai *et al.*, 1998a). Moving away from this temperature the dependence on oil/water ratio increases and can be measured. This principle has been used in a dairy products analyzer developed in the United States by Winder and coworkers (1961) and the BIOTEST instrument developed in the Soviet Union (cited in Buckin and Smyth, 1999). It has also been used for the determination of fat and non-fat solids in various fish (Ghaedian *et al.*, 1997, 1998; Suvanich *et al.*, 1998; Sigfusson *et al.*, 2001) and meat products (Chanamai and McClements, 1999; Benedito *et al.*, 2001) and for the determination of alcohol in wine (Winder *et al.*, 1970).

Other ultrasonic parameters can also be used to measure concentration, but it should be stressed these often covary with ultrasonic velocity so may not be compatible as multicomponent sensors. Recently we have shown (Saggin and Coupland, 2001b) that the proportion of a longitudinal ultrasonic pulse that is reflected from the surface of a variety of foods depends on concentration (Figure 12) and that the precision available using a simple pulsed methodology was comparable to that for velocity-based measurements (for example, the amount of water added to a ketchup sample could be determined to within 2% from velocity measurements and within 1.5% from reflectance). Reflectance measurements can be a better technique for on-line analysis when the geometry of the system is not conducive to velocity measurements, but only in cases where the surface is representative of the bulk. Ultrasonic attenuation tends to increase only slightly with concentration for many food solutions and so is rarely used as a concentration sensor. However in some cases, particularly for some ionic solutions and for dispersions, attenuation has a useful dependency on concentration.

An especially important application of composition sensing is using ultrasonic measurements to predict the composition of animals and carcasses. One of the simplest versions of this is exploiting the correlation between backfat thickness (measurable ultrasonically) and bulk carcass composition (Fisher, 1997). Knowing the different speed of sound for lean and fat tissue, it is also possible to measure fat deposition in the carcass. However, ultrasonic velocity in muscle tissue is a function of both composition and microstructure (texture), so the results may be somewhat convoluted (Abouelkaram *et al.*, 2000).

E. PHASE TRANSITIONS

The speed of sound is typically much greater in a solid than in a liquid, and thus ultrasonic sensors are particularly applicable to monitoring phase transitions in both lipid- and water-based systems. There are two main groups of methods – isothermal and temperature scanning – although these are based on the same principle.

1. *Isothermal.*

Various authors (Miles *et al.*, 1985; McClements and Povey, 1987) have shown that the speed of sound in liquid oil increases by approximately 3 m s^{-1} per 1 wt% increase solid fat present and exploited this to measure fat crystallization (Coupland, 2001). If ultrasonic velocity can be measured to within 0.1 m s^{-1}, then this implies that a change of as little as 0.03% in solids content can be determined ultrasonically. Some theoretical justification for the observed data can be gained by extending Eqn (7) for a two-phase system by using volume fraction weighted averages of density and adiabatic compressibility: $\kappa = (1-\phi)\kappa_1 + \phi\kappa_2$ and $\rho = (1-\phi)\rho_1 + \phi\rho_2$ (subscripts 1 and 2 refer to the dispersed and continuous phases, respectively). The compressibility of each phase can be calculated from independent measurements of velocity and density and the solid fat content (SFC) as the positive solution of the quadratic equation:

$$\text{SFC} = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \tag{31}$$

where

$$A = c_1^2\left(1 - \frac{\rho_1}{\rho_2}\right) + c_2^2\left(1 - \frac{\rho_2}{\rho_1}\right)$$

$$B = c_2^2\left(\frac{\rho_2}{\rho_1} - 2\right) + c_1^2\,\frac{\rho_1}{\rho_2}$$

$$C = c_2^2\left(1 - \frac{c_1^2}{c^2}\right)$$

and c is the speed of sound in the semi-solid fat. This model is based on several at least partly unrealistic assumptions (i.e. small density difference between phases and solids fat particles much smaller than ultrasonic wavelength), yet gave a good prediction up to approximately 20% solids (McClements and Povey, 1987).

These workers also showed that this method of SFC determination was superior to NMR for low levels of solids (McClements and Povey, 1987). However, an important practical difficulty arises at higher solid fat content when the fat begins to scatter sound significantly, perhaps from voids within the structure (Cebula *et al.*, 1990) or from air entrained in the viscous mixture, and it becomes extremely hard to make a measurement. Another problem with many fats (particularly cocoa butter) is that the contraction of solidification is sufficient to pull the sample away from the wall of the container and form an air gap large enough to prevent ultrasonic propagation. Despite these difficulties, Garbolino *et al.* (2000) used an ultrasonic velocity meter as an on-line sensor to demonstrate the effect of applied shear on the onset of lipid crystallization.

Neither of these disadvantages arises when the oil is present as the dispersed phase of an emulsion, and some of the strongest applications of SFC determination have been made in dispersed systems. The relevant theory is largely similar and McClements (1988) showed that the ultrasonic velocity in a mixed alkane oil emulsion increases almost linearly with SFC. The technique has been used to track the crystallization kinetics of emulsified alkanes (Hindle *et al.*, 2000), palm oil (Hodate *et al.*, 1997; Kloek *et al.*, 2000) and cocoa butter (Hindle *et al.*, 2000). Most of the published work reported in this field suggests that the increase in ultrasonic velocity with solid fat is largely independent of solids composition (i.e., polymorphism), but Kloek and coworkers (2000) have suggested there may be some dependency on the polymorphic form of the fat. As polymorphic forms differ in density and crystal packing, it seems likely that there is at least some effect.

The same principles apply equally well for aqueous phase transitions, but have been applied less widely. Miles and Cutting (1974) showed that the speed of sound is much greater in frozen meat and thus the solid/liquid ratio (and thus enthalpy) of partly frozen product could be calculated from an ultrasonic velocity measurement.

2. *Temperature scanning measurements*

Changes in ultrasonic properties, usually velocity, measured as a function of temperature, can be used to identify phase transitions in lipid and aqueous systems. For example, the speed of sound in a lipid system is changed by temperature according to two factors: (1) the speed of sound in liquid oils decreases with temperature (Figure 11) and (2) the speed of sound in oils

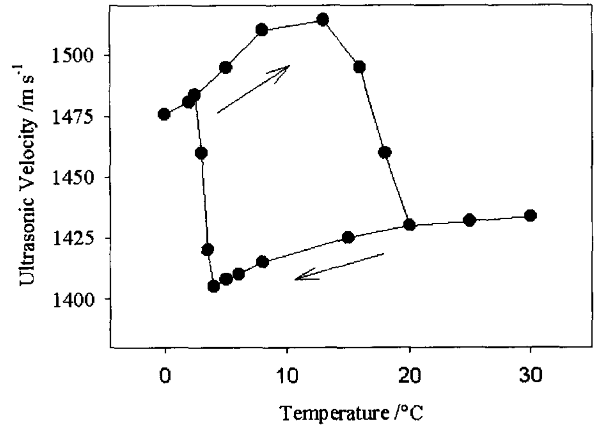

FIG. 13 Ultrasonic velocity in a fine, 20 wt% *n*-hexadecane-in-water emulsion stabilized with 2 wt% polyoxyethylene sorbitan monolaurate (d_{32} ~ 0.6 μm) as a function of temperature showing the hysteresis between cooling and heating cycles.

increases with SFC. These factors overlay to produce a typical sigmoidal function, as shown in Figure 13. The solid fat content can be measured by extrapolating the lines from the solid and liquid regions over the transition range then calculating SFC as:

$$\mathrm{SFC} = \frac{(1/c^2) - (1/c_1^2)}{(1/c_s^2) - (1/c_1^2)} \tag{32}$$

where c is the measured ultrasonic velocity and c_s (c_1) the velocity in pure solid fat (liquid oil) extrapolated to measurement temperature (Miles *et al.*, 1985). Eqn (32) has a similar theoretical basis as Eqn (31) and relies on similar, partially justified, assumptions. This approach is comparable to differential scanning calorimetry in that it assumes that the extrapolations drawn are from pure liquid or solid fat and suffers from similar limitations.

The temperature scanning approach has also been applied to emulsified oils and has identified transitions in alkanes (McClements *et al.*, 1993; Hindle *et al.*, 2000) and triglycerides (Hindle *et al.*, 2000; Kloek *et al.*, 2000). Although the changes in attenuation associated with dispersed phase transitions tend to be more modest than those seen in velocity measurements, and thus less widely reported, McClements *et al* (1993) noted an anomalously high attenuation as emulsified alkanes melted. The magnitude of this peak decreased with frequency (0.5–3.5 MHz). These workers postulated that the ultrasonic energy was absorbed by perturbing the $\text{fat}_{\text{crystal}} \rightleftharpoons \text{oil}_{\text{liquid}}$ equilibria and was thus related to the molecular dynamics of melting.

Other workers have used temperature scans of other ultrasonic properties to measure phase transitions. Recently Garbolino and coworkers (2000) showed that it is possible to measure the onset of lipid crystallization by the changing reflection coefficient of longitudinal ultrasonic waves. Shore and others (1986) that showed the attenuation coefficient was approximately four times larger in frozen beef than in unfrozen samples, but no attempt was made to measure percentage frozen from the data. Although not classically a phase transition, Mulet *et al.* (1999) showed the temperature dependency of the ultrasonic velocity in cheese changes as the cheese melts and were able to identify three distinct zones that could be related to thermal events in a thermogram.

F. RHEOLOGICAL PROPERTIES

There have been many efforts made to correlate the texture of foods, particularly fruits and vegetables, with ultrasonic properties; some of these investigations are summarized in Table III. The correlation coefficients reported are often quite low and probably fortuitous. The factors that allow sound to propagate through complex biological structures are poorly understood and there is no reason to assume they will correlate with the factors that determine bulk texture. This problem is compounded in most fruit and vegetables by the strong scattering of sound by intracellular air, which makes transmissions measurements at high frequencies extremely difficult. Lower frequency sound tends to be attenuated less and several of the publications listed in Table III use sonic resonance techniques, a related method based on measurements of the frequencies generated by the fruit when struck.

The limitations of some of these approaches arise from the lack of mechanistic basis for a relationship for the relationships sought. Longitudinal waves in fluids are only weakly related to changes in shear modulus and as $K \gg G$, longitudinal ultrasonic properties are effectively exclusively dependent on bulk modulus. Bulk modulus is rarely measured for foods as it is thought to have limited practical significance and it is unsurprising that attempts to correlate longitudinal ultrasonic parameters with shear viscous properties have met with only limited success. Another significant problem is that there is no reason to expect the ultrasonic properties of a food to be at all related to the large-deformation or failure properties of a food (e.g. fracture, chewability) and again the correlations seen are indirect, although frequently very useful. An example of this type of relation was

TABLE III

REPORTED DETERMINATIONS OF FOOD TEXTURE FROM SONIC MEASUREMENTS.

Food	Ultrasonic measurement	Texture property	Comments	Reference
Apples	Bar velocity, V_b; apparent wave propagation, V_{wt}; dilatation velocity, V_d	Poisson ratio (ν), density, Young modulus (E), shear modulus (G)	The velocity of propagation through the whole fruit is related to velocity through quarter sections	Garett and Furry (1972)
Apples	(a) Hitting sound wave and (b) power spectrum (20–1.25 kHz)	Mechanical firmness and sensory data	Best correlation, $r = 0.77$	Yamamoto *et al.* (1980)
Apples (red delicious)	Acoustic transmission profile (by sonic resonance) (5–10 000 Hz)	Firmness, soluble solids, and maturity	Single and multiple frequency models were developed to compare acoustic data with mechanical methods.	Affeldt and Abbott (1989)
Apples (golden delicious)	Amplitude resonance (0–2 kHz)	Puncture test	Resonance frequencies showed relationship to apple softening. Resonance method was more reproducible than puncture method	Liljedahl and Abbott (1994)
Watermelon	Amplitude resonance (0–2 kHz)	Puncture test	Best correlation, $r = 0.73$	Liljedahl and Abbott (1994)
Biscuits	Velocity, attenuation	Mechanical tests and sensory brittleness	Poor correlation with sensory data ($r = 0.13$) and only weak with mechanical data ($r > 0.5$)	Povey and Harden (1981)

TABLE III *(continued)*

REPORTED DETERMINATIONS OF FOOD TEXTURE FROM SONIC MEASUREMENTS.

Food	Ultrasonic measurement	Texture property	Comments	Reference
Oranges (skin texture)	Reflectance		Reflectance depends on skin roughness	Sarkar and Wolfe (1983)
Tomatoes (cracks)	Reflectance		Significantly more scattering in reflectance from cracked tomatoes, correlated ($r = 0.71$) with crack width	Sarkar and Wolfe (1983)
Potato, avocado, carrot	Velocity (50 kHz), attenuation (50 kHz), reflectance (500 kHz)		Large velocity difference between fresh and ripe avocado	Mizrach *et al.* (1989)
Winter-grown melons	Velocity, attenuation (50 kHz)	Modulus of elasticity, and tangent modulus	Poor correlation of velocity with internal properties of melons.	Mizrach *et al.* (1991)
Avocado	Velocity, attenuation	Firmness	Distinct minimum in velocity during ripening possibly related to changes in internal structure	Mizrach *et al.* (1996)
Avocado	Velocity, attenuation	Firmness	Correlation between firmness and attenuation related to cold-softening of avocado	Flitsanov *et al.* (2000)

TABLE III *(continued)*

REPORTED DETERMINATIONS OF FOOD TEXTURE FROM SONIC MEASUREMENTS.

Food	Ultrasonic measurement	Texture property	Comments	Reference
Avocado	Velocity, attenuation	Dry weight during ripening	Negative correlation between attenuation and dry weight	Mizrach *et al.* (1999)
Mango	Velocity, attenuation	Softness, acidity, and sugar content during ripening	Statistical model used to relate changes in ultrasonic signal to ripening in a packing house	Mizrach *et al.* (1997)
Cooked carrots	Velocity, attenuation (37 kHz)	Compressive Young modulus and strain at failure	Major changes in all properties in the first 25 min of cooking associated with changes in air and water content.	Nielsen and Martens (1997)
Mahon cheese	Velocity (1 MHz)	Texture profile analysis	Ultrasonic velocity decreases with curing time probably due to drying. The authors predicted a model (92% of variance) of the dependence of velocity on temperature and deformability modulus. Best measurement temperatures 0–17°C	Benedito *et al.* (2000c)
Cheddar cheese				Benedito *et al.* (2000b)

seen by Benedito *et al.* (2000a), who showed the speed of sound increased (approximately 1650–1720 m s^{-1}) in Mahon cheese during aging up to 1 year along with instrumental measures of large-deformation elasticity and yield values. Although the correlations were good (0.92 with modulus and 0.88 with the force maximum) the cheeses were also shown to lose about 30% of their water content over the aging period. These authors recognize that the value of ultrasound as a cheese texture sensor in this case is most likely due to both the speed of sound and texture varying with water content (Benedito *et al.*, 2000c) and showed similar results with Cheddar cheese (Benedito *et al.*, 2000b). A similar correlation-type approach was taken by Povey and Harden (1981) to relate the crispness of cookies to ultrasonic velocity.

An interesting way around both of these problems was taken by Faeth and Chem (1999), who used low frequency (0.1 MHz), noncontact ultrasonics to measure the position of the surface of baked goods as they were deformed by a jet of air. In this case ultrasound was simply being used as a strain gauge and the ultrasonic properties of the food were not measured. These workers were able to correlate the induced deformability of the bread with baking time ($r = -0.85$).

A more direct set of texture measurements is based on the direct relationship between shear acoustic properties and fluid viscosity. Viscous liquids are only marginally able to support shear waves and very strongly attenuate them. For low viscosity liquids (~1 cP), the shear velocity and attenuation coefficient are expressed as follows (Blitz, 1963):

$$c^2 = \frac{2\eta\omega}{\rho} \tag{33}$$

$$\alpha = \sqrt{\frac{\omega\rho}{2\eta}} \tag{34}$$

Both speed of sound and attenuation are frequency dependent and, while speed of sound increases with increasing viscosity, the attenuation decreases. For example, for water according to Eqns (33) and (34), 1 MHz shear waves would have a velocity of 3.5 m s^{-1} and an attenuation of 15 000 dB mm^{-1}, making it impossible to transmit waves over even a few micrometers. As the viscosity increases the characteristic time for the shear wave to collapse becomes less than the (reciprocal) frequency of the wave and propagation becomes more possible (Blitz, 1963).

One solution to this measurement problem is to generate a pulse of shear waves in a solid and measure the amount of this pulse reflected from an interface with water. Recently Kulmyrzaev and McClements (2000) and Saggin and Coupland (2001a) took this approach to measuring the viscosity of honey and oils, respectively. Both groups reported good correlations between ultrasonically and conventionally measured data and Kulmyrzaev and McClements noted the magnitudes of the viscosity measured by the two methods were significantly different – perhaps due to a relaxation over the wide span of frequencies separating the two methods. Buckin and coworkers (Buckin and Kudryashov, 2001; Kudryashov *et al.*, 2001) used a more sensitive shear wave resonator to track the sol–gel transition in milk during yogurt manufacture. The formation of a gel was monitored in time using high-frequency shear wave transducers (5–15 MHz) and dynamic rheology at a frequency of 0.1 Hz. Both methods monitored the same kinetics of formation of a gel network, which was accompanied by a significant increase of the elastic and storage modulus. However, the absolute values of G' and G'' of the casein gel at frequencies of 5 and 15 MHz were approximately 1000 times higher than the values at the low frequency (0.1 Hz). Furthermore, the measured viscosity at high frequencies was closer to the viscosity of liquid milk. The interpretation given by these workers was that at high frequencies (time scale 10^{-7}–10^{-8} s) the movements of the gel network are "frozen" and do not contribute to the viscous losses.

Lee and coworkers (1992) were, somewhat surprisingly, able to propagate shear waves over reasonable distances (1.1 cm) in bread dough and cheese. The shear wave measurements were used to calculate G' and G'' and there was reasonable qualitative agreement between the acoustic and conventional measures of material texture; however, the quantitative relationship was weak. More recently Letang and coworkers (Letang *et al.*, 2001) combined longitudinal velocity and shear wave resonance to study the effect of water content on complex shear and longitudinal moduli of bread dough and showed that the magnitude of the moduli increase with frequency.

Love waves are also shear ultrasound, and Varadan and Gardner (1999) noted a concentration and viscosity-dependent change in attenuation of 0.5 dB $\text{wt\%}^{-1}$ on inserting a micromachined liquid cell into glycerol solutions. A Love wave sensor is a surface measurement and again if the material close to the sensor is not representative of the bulk will not be reliable.

An interesting and novel approach to the ultrasonic characterization of fluid viscosity was recently taken by McCarthy and Choi (personal communication) based on the principle that the velocity profile across a fluid flowing in a pipe is dependent on both the rheological properties of the fluid and the pressure drop across the pipe. Pressure drop is easily measured by nonultrasonic methods and any method capable of measuring a flow profile could be used to calculate the rheological properties of interest.

There are two observations that are used to characterize fully developed, steady laminar flow in tomographic-based viscometry. First, independent of the constitutive equation for the material, the conservation of linear momentum demands that the shear stress, σ, depends upon the radial position in the tube, r:

$$\sigma(r) = -\frac{\Delta P}{2L} r \tag{35}$$

where $\Delta P/L$ is the pressure drop taken from the downstream direction of the flow over the tube length L. Second, the shear rate, $\dot{\gamma}$, is given by:

$$\dot{\gamma}(t) = \left|\frac{\mathrm{d}v(r)}{\mathrm{d}r}\right| \tag{36}$$

and is locally computed using a global curve fit to the tomographic velocity data. Using both Eqns (35) and (36) at each radial position yields the shear stress as a function of shear rate. Repeating this evaluation at all radial positions in a single image of velocity profile, the fluid viscosity can be characterized over a wide range of shear rates. Theoretically the shear rate ranges from zero at the tube center to a maximum at the tube wall. Then the shear viscosity, $\eta(\dot{\gamma})$, is given by:

$$\eta(\dot{\gamma}) = \frac{\sigma(\dot{\gamma})}{\dot{\gamma}} \tag{37}$$

A transducer is placed at an angle to the pipe wall and is used to transmit and receive pulsed ultrasound. The transducer used in this system operates at 5 MHz in a pulse mode. The time from transmission to reception yields the distance the pulse has traveled and the frequency shift of the wave yields the velocity of the particle reflecting the wave. The particles are assumed to move at the speed of the fluid and hence the measurement yields the velocity profile of the fluid. Ultrasonic Doppler velocimetry (UDV) measurements of the fluid velocity profile are in excellent agreement with simultaneous magnetic resonance imaging measurements of the velocity profile. Figure 14 demonstrates the UDV velocity image for tomato sauce and the extracted velocity profile.

G. DISPERSED SYSTEMS AND FOOD MICROSTRUCTURE

The ultrasonic properties of dispersed systems depend on the frequency of the sound and the size, shape and number of scattering particles (Figure 4).

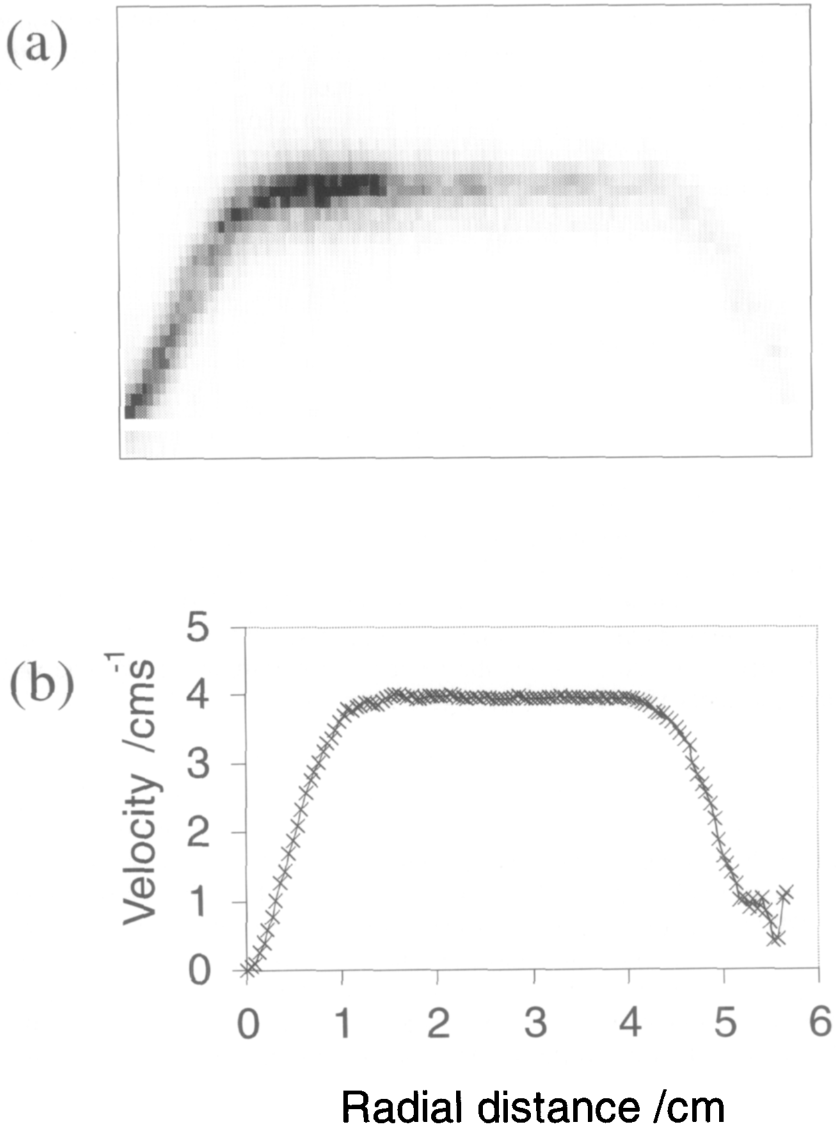

FIG. 14 Ultrasonic Doppler velocimetry of the flow pattern of tomato concentrate suspension (4.2° brix) and the calculated velocity profile. Note the decrease in signal intensity across the velocity image due to signal attenuation. Signal attenuation does not adversely affect the estimation of rheological parameters as long as the velocity profile can be extracted. (Figure courtesy of Dr M. McCarthy and Y.C. Choi, University of California, Davis, CA.)

In food emulsions the scattering theory has been developed to such an extent that good predictions can be made of the ultrasonic properties of a wide range of emulsion sizes and concentrations. These devices are particularly interesting as they remain the only practical technology for the rapid determination of the particle size of realistic concentrations of emulsions and are commercially available from a number of sources. Some examples of successful particle sizing include: emulsified vegetable oils (Coupland and McClements, 2001b), salad dressings (McClements *et al.*, 1990; Chanamai *et al.*, 2000), milk fat globules (Miles *et al.*, 1990), and parenatal fat emulsions (Kippax *et al.*, 1999). Similar methods have also been used to measure the size of casein micelles (Povey, 1997; Povey *et al.*, 1999).

A number of experimental studies have shown that droplet flocculation causes an alteration in the ultrasonic properties of emulsions (McClements, 1994; Hermar *et al.*, 1997; Hibberd *et al.*, 1997). This theory has been applied to the study of droplet aggregation in protein-stabilized emulsions in which flocculation was induced by decreasing the electrostatic repulsion between droplets (Demetriades and McClements, 1999) or by adding a nonabsorbing biopolymer to the continuous phase (Chanamai *et al.*, 1998c; Chanamai and McClements, 2001). These studies have shown that ultrasound is sensitive to the spatial distribution of the droplets within an emulsion. The same ultrasonic spectroscopy technique has been used to study the disruption of flocs in a shear field (Chanamai *et al.*, 1998c). As the emulsions are exposed to higher shear rates the flocs become disrupted and their attenuation spectra becomes closer to that of nonflocculated droplets.

An interesting modification of the scattering theories introduced above allows the calculation of the emulsion ζ-potential. Briefly, the acoustic wave causes a charged particle to oscillate within its associated ionic environment. At certain frequencies the ions cannot realign rapidly enough to keep pace with the moving particle and the ionic friction generates a voltage and causes additional ultrasonic losses, i.e. the electroacoustic effect (Dukhin *et al.*, 2000). Instrumentation can be based on this principle by either measuring the current generated from the particles in an applied ultrasonic wave or the ultrasound generated by the particles in an oscillating electrical field. The latter method is believed to be the most practical as the ultrasound generated by the particles is directly proportional to their electrophoretic mobility. Electroacoustic techniques have been applied to the determination of ζ-potential in concentrated suspensions including oil-in-water emulsions (Kong *et al.*, 2001), casein micelles (Wade *et al.*, 1996) and dairy emulsions (Wade and Beattie, 1997).

Bubbles and concentrated foams are important structures common to many foods. In many cases the foam is an integral and valued feature (e.g.

bread, ice cream, beer) but in other cases excessive foaming is a problem during processing (e.g. in bioreactors). Foams are transient and fragile and thus very difficult to characterize. Gravimetric analysis can usually provide a good estimate of volume fraction, but size analysis usually requires optical microscopy or other imaging techniques. Ultrasound is extremely sensitive to both the volume fraction and size of air bubbles and is a promising analytical approach. However, the extremely high attenuation means it is practically impossible to transmit high-frequency sound through an appropriate thickness of foam. Reflectance is a promising alternative and Kulmyrazaev *et al.* (2000) measured the reflectance spectra (1–7 MHz) from a series of model food foams and noted clear spectral differences between the foams (different sizes and concentrations), but only qualitative agreement with theoretical calculations.

Foreign bodies, such as glass, steel, plastic, wood or stones, can be hard to detect in the finished product and may injure consumers. However, their significant acoustic mismatch with most other food materials makes them relatively easy to detect ultrasonically. Haeggstrom and Luukkala (2001) used ultrasonic signal analysis to detect small pieces of each of these materials at a depth of 20–75 mm in homogeneous materials (margarine, smooth cheese) but to lesser depths (50 mm) in coarser materials (marmalade). In some samples these workers were able to distinguish between the materials based on the ultrasonic echo pattern.

H. POLYMERIC SYSTEMS

The adiabatic compressibility of a solution can be calculated from measurements of its ultrasonic velocity and density (Eqn (7)). The compressibility of a solute is usually taken as the molecular increment of solution compressibility measurements made at very low concentrations. The extremely dilute (~1 mg ml^{-1}) solutions used in these measurements are extremely advantageous for high value or hard to obtain materials but also require extremely sensitive measurement apparatus. Precise density measurements can be made with a vibrating U-tube densitometer and ultrasonic velocity measurements with a precision resonator. Apenten and coworkers (2000) recently showed that the compressibility of proteins can be measured at relatively high concentrations (>10 mg ml^{-1}) if thermal scattering effects are accounted for. High concentrations means that less-precise pulse echo methodologies may be used.

Compressibility measurements are a useful way to probe polymer, particularly protein, hydration. The measured value is taken to be the sum of contributions from the hydration layer and the intrinsic compressibility of the polymer. Compressibility measurements have been used to reveal protein hydrophobicity, polar/nonpolar residues, and aspects of secondary structure (Gekko and Hasegawa, 1986) as well as changes associated with protein denaturation (Kamiyama and Gekko, 1997) and ligand binding (Gekko and Yamagami, 1998). Protein–solvent interactions are believed to be important determinants of functionality, and compressibility is unsurprisingly correlated to protease susceptibility, foaming capacity, and free energy of unfolding of a number of proteins (Gekko and Yamagami, 1991).

Gelation and melting of polymer systems has proved a more difficult process to probe ultrasonically. This may be because longitudinal ultrasound is sensitive to the bulk modulus and gelation usually involves changes to the shear modulus. However, in some cases attenuation has proved sensitive to polymer aggregation phenomena, perhaps due to the scattering by aggregates. Gunasekaran and Ay (1994, 1996) used a through-transmission pulsed method to measure the ultrasonic properties (velocity and attenuation) of milk after renneting. They showed that while the changes in ultrasonic velocity were small, the attenuation decreased, perhaps due to the same thermal overlap effects thought to be responsible for the attenuation decrease when an emulsion flocculates. Similar studies on the isoelectric precipitation of other proteins have also revealed a change in attenuation as the proteins aggregated (Pavlovskaya *et al.*, 1992; Bryant and McClements, 1999b). Buckin and Smyth (1999) were concerned with the tendency of calcium-fortified milk to aggregate and gel or precipitate on heating and used a high-precision resonator method to detect the onset of aggregation of their samples. Audebrand and coworkers (1995) demonstrated an increase in attenuation (greater at higher frequencies) as alginate gels. Shore and coworkers (Shore *et al.*, 1986; Shore and Miles, 1988b, 1988c) saw a peak in some muscle preparations (but not in liver or kidney) at pH 5 corresponding to a maximum shortening and density and minimum water-holding capacity of the meat. By suspending the myofibrils in solutions of different density and viscosity they were able to show that viscous scattering was not a significant contributor (~20%) to the total measured attenuation losses (Shore and Miles, 1988a), but they were not able to identify the dominant mechanism. Bryant and McClements used scattering theory to interpret the attenuation spectra of aggregating whey protein in terms of the sizes of structures present (Bryant and McClements, 1999a, 1999b).

Various investigators have seen an ultrasonic attenuation maxima at pH ~ 11 for solutions of amino acids, polypeptides (Appelgate *et al.*, 1968; Saravazyan and Kharakoz, 1979) and proteins (Kanda *et al.*, 1972; O'Brien and Dunn, 1972) owing to the excess absorption caused by the resonance of the protonation equilibrium at amine groups. Miles and others observed a similar attenuation peak at pH~11 in homogenates (Shore and Miles, 1988c) and suspensions (Shore and Miles, 1988b) of bovine skeletal muscle as well as other beef tissues (liver and kidney). By repeated fractionation of the protein components, they ascertained that this was largely due to a molecular relaxation process rather than to any scattering phenomena. Bryant and McClements (1999b) measured a similar pH-dependent peak in solutions of whey protein isolate and used ultrasonic spectroscopy to estimate the relaxation time of the process ($\sim 10^{-8}$ s)

I. MISCELLANEOUS APPLICATIONS

Varadan and Gardner (1999) reported on the use of a Love wave-based smart tongue and nose. Love wave resonance (108.7 MHz) depended on the properties of the materials in contact with the sensor (air, water, orange juice, deicer). Using similar sensors and interpreting the data using principle component analysis, Varadan (personal communication, 2000) was able to distinguish fruit juices (prune, grapefruit, grape, apple, orange) by type.

Vegetable oils deteriorate during frying, breaking down to form off-flavor volatiles and polymerizing to produce a dark brown color and an increase in viscosity. Lacey and Payne (1994) showed that the ultrasonic properties of oil also change with aging, but the correlations are probably too weak to detect spoilage before it becomes obvious.

Withers (1996) considered methods to evaluate pipe fouling and showed that ultrasound can quantify films of thickness between 0.5 and 6 mm (the lower limit being set by the wavelength of the ultrasound). A disadvantage of this method is that it is a single-point inspection and may not be representative of an entire piece of equipment. In non-food applications, Rose (1999) has pioneered the use of guided waves for fouling detection and has shown that a single transducer can inspect several meters of pipe (or kilometers of railroad track).

J. IMAGING

By making several measurements at different positions throughout the food it is possible to construct an image either of the fundamental ultrasonic properties or, by using several of the methods set out above, code the image to composition, temperature, etc. As with all ultrasonic measurements, it is important to remember that the measurements are a function of the composition, microstructure and physicochemical properties of the sample, and converting a time-of-flight into another variable for imaging purposes is not trivial. Pinfield and coworkers (1994, 1996) provide a good example of this problem, demonstrating that the microstructure of a creaming emulsion as well as the local oil concentration can have an effect on the measured velocity profile.

A single ultrasonic measurement is analogous to drawing a line (of finite width) through the body under consideration. The detected signal will contain information, in terms of echo times and amplitude, about the structures in its path. By taking many measurements at different positions on (or angles through) the body, it is possible to provide information about all the detectable internal structures. The process of reconstructing an image of these structures from a set of one-dimensional signals is known as tomography, and while the theory is well understood (Hoyle, 1998) and commonly exploited in medical (Shung, 1990) and materials imaging, it has not been adopted in its full form in foods. It is worth remembering that imaging is a way of generating two-dimensional data from a much richer data set and is therefore a data reduction operation. The full set of measurements is an A-scan, the image generated from selecting the amplitude at a set time is a B-scan, and that generated from the amplitude of a selected signal feature is a C-scan. It is important to bear in mind that both B-scans and C-scans are data reduction tools and there is often some valuable information lost in generating an image (Coupland and McClements, 2001a).

Perhaps the most sophisticated imaging regularly used in foods is in the field of carcass grading. Images can be generated based on a number of ultrasonic principles and used to estimate the texture and composition of carcasses, as well as quality attributes such as marbling and defects (Griffin *et al.*, 1999; Brethour, 2000). An interesting extension to conventional imaging is the use of elastography, where an image coded to elastic modulus is generated by measuring the movement of an ultrasonic signal reflected from the internal structures in a carcass on gentle bulk compression (Ophir *et al.*, 1994).

Ahvenainen *et al.* (1989) and Wirtanen *et al.* (1992) used ultrasonic imaging to measure the spoilage of milk in cartons (presumably through the formation of gas bubbles by the active microorganisms present). Acton *et al.* (1986) used a medical imaging system to generate some images of gels. Other workers have simplified the geometry of their system to allow only one-dimensional changes and recorded images of emulsion creaming (Howe et al., 1986; Gunning *et al.*, 1989; Dickinson *et al.*, 1994; Basaran *et al.*, 1998b) and the diffusion of small molecules in gels (Basaran *et al.*, 1998a) and emulsions (Basaran and McClements, 1999).

Ozguler *et al.* (1998) measured reflected (backscattered) ultrasonic energy (17.4 MHz) and used the signal to detect leaks (air- or water-filled channels and food inclusions) in laminated foil or plastic retortable pouches. The defects that could be detected were in the order of tens of micrometers. Frazier *et al.* (2000) used a modification of this approach to increase the resolution of the structures imaged.

An important limitation with acoustic imaging is that the sample under investigation must be placed in a tank of water to allow good acoustic propagation from the transducer to and through the food. The measurements are also quite slow and limited by the speed of the robot arm used to position the transducer. (Simultaneous measurements with arrays of transducers can greatly increase the speed of imaging.) These limitations are acceptable for certain high-value items, for example in the aerospace and materials science industries, but it is clearly unacceptable for the routine inspection of foods. However, the use of noncontact, air-coupled transducers offers a way to extend imaging to practical food characterization. Saggin and Coupland (2001c) have shown that noncontact ultrasonic velocity measurements can provide a good description of the size of various food items. For the various soft solids used in this study the ultrasonic measurement of thickness was superior to measurements taken with calipers. A particularly important aspect of the noncontact methodology to size measurement is that the ultrasonic properties of the material are measured simultaneously and do not need to be known *a priori*. A more sophisticated image based on noncontact ultrasonic velocimetry is reported in Figure 15. Noncontact imaging is potentially competitive with NMR imaging currently used in medical diagnostics and, just as NMR imaging has proved invaluable in various types of food characterization, we expect that it will also see wide applications in the food industry.

FIG. 15 Image of a coin generated from the sound reflected from the surface in air-coupled (noncontact) mode. The image was produced using an NCA-1000 (SecondWave Systems, Boalsburg) and an NCT230-R6 (3 MHz, 6.4 mm diameter and 6.4 mm focal length) transducer. (Image courtesy of Dr M. Bhardwaj.)

Scanning acoustic microscopy (SAM) is a useful nondestructive evaluation (NDE) method often applied to the measurement of micro-cracks or other defects in ceramics, composite materials and electronic materials. An important advantage of ultrasonic microscopy over other imaging techniques is in the detection of defects inside opaque materials without requiring sectioning or other destructive operation. Conventionally SAM works in contact mode, detecting reflections of high frequency (tone bursts at 5–230 MHz) sound from the microstructures of interest. The reflected signal is converted to an image dependent on the thickness of the layers and their impedance mismatch. Because of the low impedance of air, delaminations, bubbles and other voids are most easily imaged by this method (Adams, 2000). Aside from the differences in transducer size and frequency, ultrasonic microscopy is similar to other imaging methods and suffers from similar limitations. A couplant material (often water), located between the acoustic lens and the specimen, is usually necessary to allow the propagation of ultrasound into the sample; therefore, the samples are generally immersed in a water tank and repositioned using a stepper motor. Ultrasonic microscopy has been used to detect sealworms (a parasite) in fish fillets (Hafsteinsson and Rivzi, 1984), but other workers have generated SAM images of biological systems, particularly for medical applications (Kent and Lee, 1997; Kinoshita *et al.*, 1998; Karl and Bereiter-Hahn, 1999).

The resolution of ultrasonic imaging is limited because of the long wavelength of low-frequency ultrasound and the large size of the transducers used. It is possible to modify both of these in a technique known as acoustic microscopy to achieve resolutions approaching an optical microscope. An estimate of the minimum resolvable distance (Δr) is as follows:

$$\Delta r = F\lambda = F\frac{c_c}{v} \tag{38}$$

where F is a constant related to the ultrasonic lens geometry and c_c is the velocity of sound in the coupling medium. Therefore increasing the frequency of sound would decrease the resolution of the instrument (for example if 5 MHz sound could resolve points 0.1 mm apart, than 230 MHz sound could resolve points 2 μm apart). An intriguing alternative method to improve resolution is to use a coupling material with a lower ultrasonic velocity and hence shorter wavelength (for example, if a system could resolve points 0.1 mm apart through a water couplant, then it could distinguish points 0.02 mm apart in an air-coupled system). The air-coupled transducers discussed previously are therefore interesting candidates for high-resolution ultrasonic imaging (Bhardwaj *et al.*, 2000a, 2000b), particularly as the alternatives (liquid nitrogen or helium) are particularly disruptive of delicate structures (Briggs, 1992). It is also important to remember that attenuation increases with frequency so the penetration depth available at high resolution may be limited.

Some recent advances on this technique make use of shear wave lens and noncontact mode, as proposed by Miyasaka and Tittmann (2000). Shear waves offer some great potential, such as a better resolution than longitudinal waves, i.e. they have a shorter wavelength, less sensitivity to surface roughness and lower spherical aberration caused by reflection.

V. CONCLUSIONS

Ultrasound becomes attractive as a sensor in the food industry when it has a unique capability to make a measurement or can otherwise outperform other technologies. Many of the strongest applications gain their advantage from the capacity of ultrasound to propagate through many optically opaque materials, particularly container and piping walls, to make measurements on-line.

The significant disadvantages of ultrasound often center around the fact that propagation depends on a complex set of variables – compositional, structural and dynamic – within the sample and it becomes hard to deconvolute the parameter of interest. Practically, the most significant complicating factors tend to be fluctuations in temperature and/or the presence of air in the sample. The ultrasonic properties of food are strongly temperature dependent and even a 1°C deviation from the calibration conditions can obscure other important changes. The large acoustic mismatch between air and food means that even a tiny amount of entrained gas will dominate the signal or attenuate it to a such a degree as to make measurement impossible. Furthermore, the difficulty of transmitting ultrasound through air limits its application as an on-line sensor for discrete food items.

Another disadvantage is that ultrasonic measurements are often poor multicomponent sensors. Acoustic spectra can be used to identify multiple effects simultaneously but the various relaxations responsible for the changing signal are broad, complex and highly overlapping, so can be difficult to exploit in practice. Velocity and attenuation respond to different properties of the system so are sometimes useful in combination. As a rule of thumb: velocity tends to be more sensitive to composition and temperature while attenuation is more sensitive to structure.

Weighing the advantages and disadvantages, we can see why some ultrasonic applications have seen such a wide application. For example, the use of ultrasonic attenuation spectra for emulsion characterization allows measurement of a parameter not otherwise accessible (size of concentrated dispersions) under conditions where the other variables (importantly temperature) can be controlled. In cases when the conditions are less well satisfied, the acceptance of ultrasonics is also less, e.g. ultrasonic velocity can be easily used to measure the concentration of sugar syrup in a pipe, but on-line refractive index sensors offer similar functionality and compete for this market. In cases where ultrasound substantially fails to meet the conditions set out above, e.g. multicomponent compositional analysis based upon a temperature scan, we expect limited application.

The successful technologies will be improved and refined through applications by food scientists, but it is also interesting to speculate how this set may be extended by some of the recent innovations discussed in this chapter. Noncontact transducers are particularly interesting as they allow practical application of ultrasonic methods in cases where an air gap between the food and sensor is unavoidable. The use of printed circuit boards to make Love wave sensors that can be wirelessly interrogated has the potential to completely change the economics of sensing. If a fully functional sensor can be made for a few cents, one could be incorporated into each package of food. The use of selective masks for the sensor could allow the detection of spoilage compounds or the metabolic products of microbial growth. Building a reader into domestic refrigerators or cooking equipment could "ask" each piece if it were fresh, safe, or adequately cooked.

No single sensor will meet all the needs of the food industry but, through a critical understanding of both the strengths and weaknesses of ultrasonics, we expect the number of practical applications to grow.

ACKNOWLEDGEMENTS

We are grateful to Dr Mike McCarthy and Y. J. Choi (UC Davies), Dr Mahesh Bhardwaj (Ultran Laboratories/SecondWave Systems, Boalsburg, PA), and Julian McClements (University of Massachusetts) for contributing unpublished data, figures and valuable discussion to this paper, and to Melissa Goff for technical assistance in preparing the manuscript. This work was partly supported by a grant from the Center for Food Manufacturing (Penn State).

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