REVIEW

Probing the Properties of Dough with Low-Intensity Ultrasound

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ABSTRACT

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Ultrasonic assessments of the properties of dough have been used over the past 15–20 years to complement studies of dough properties that use other physical testing techniques. After the principles and techniques of low-intensity ultrasound are introduced, its use as a tool for investigating the rheology and structure of dough is reviewed. One important outcome from ultrasonic assessments of dough properties is an understanding of how bubbles alter dough rheology.

As summarized by Muller in *Cereal Chemistry*'s special issue on the rheology of wheat products, evaluation of the physical properties of dough is a longstanding scientific research challenge (Muller 1975). The deformation and flow of dough is a topic of such substantive importance to cereal science that it warrants its own division within AACC International, the Rheology Division. This division provides a forum for sharing knowledge on the fundamentals and application of the subject to better understand breadmaking and cereal product textures. As stated by Bloksma (1990), the interest in dough rheology stems from "the thesis that the rheological properties of dough form a link between the composition and structure of its raw materials and the functionality of the dough in the bakery." Determining the mechanism(s) of this link is still a work in progress, challenging the talents of a global research community.

The scope of this review is somewhat less ambitious and is focused on an understanding of dough rheology that has been acquired in the last 15–20 years through the use of a low-strain mechanical testing technique: low-intensity ultrasound. The technique has been particularly useful for probing the properties and structure of dough at short timescales because it operates at higher frequencies than those employed in standard rheological tests. In addition to the direct relevance of this information for optimizing high strain rate processes, such as sheeting, extrusion, and mixing, new insights at short timescales can also be used to further the development of comprehensive constitutive models for the complex multiphase viscoelastic material that is the heart of cereal science.

PRINCIPLES OF ULTRASOUND PROPAGATION IN DOUGH

The propagation of ultrasound through soft materials such as dough occurs when microscopic regions of the dough are displaced from their equilibrium position in a periodic manner. As with many natural phenomena, this periodic displacement from equilibrium is best described in terms of wave properties.

To generate ultrasonic waves in a material, an external excitation is typically applied to the surface of the material, and this excitation is passed successively on to neighboring regions away from the surface. Depending on the properties of the material and the frequency and manner of the excitation at the surface, a wavetrain of small displacements will propagate from the surface to pass through the material. The left-hand end (x = 0) in Figure 1 is the surface where the excitation is applied, and the x axis represents increasing distance into the dough. The y axis represents the displacements from the equilibrium position (y = 0), which can be either positive or negative (representing displacements in one or the opposite direction from the equilibrium position). The wave illustrated by the lines is in a transverse (shear) mode, so that the wave propagates at right angles to the displacements that the microregions undergo. This situation is similar to the creation of a wave train in a rope brought about by moving one end of the rope up and down.

The nature of the external excitation defines two features of the wave in the material. First, from Figure 1 it can be seen that the amplitude (how far an individual microregion is displaced from its equilibrium position) is governed by the magnitude of the excitation applied at the surface. For a perfectly elastic material, all peaks and troughs of the wave would have a height of $\pm y_{max}$ (the maximum displacement engendered in the material by the external excitation). For real materials such as dough, the amplitude decreases as the waves propagate further into the material owing to the dough's viscoelastic and heterogeneous nature.

It is important to recognize that the solid line in Figure 1 is a snapshot of how far the microregions of the dough are displaced at one given instant of time. The two dashed lines represent displacements in the dough at two later times when the external excitation has brought the region adjacent to the surface of the dough back to its initial position, and then later again, when the region has been maximally displaced but in the opposite direction. The faster this is done, the faster a given region of the dough oscillates back and forth. Thus, the second feature characterizing the wave that is governed by the imposed external excitation is the length of time taken for the external excitation to move back and forth. The time taken to complete one cycle, that is, for the surface displacement to go from $+y_{max}$ to $-y_{max}$ and back to $+y_{max}$, is the period. A more common means of defining this periodicity is through the reciprocal of the period, or the frequency (f) of the excitation. Because the mechanical response of a viscoelastic material is dependent on how fast it is excited, frequency must be defined in any ultrasonic analysis of dough properties. Thus, frequency is a key control parameter in ultrasonic testing, just as it is in shear rheology (Hibberd and Parker 1978; Dreese et al. 1988; Keentok et al. 2002; Newberry et al. 2002) and in compressive dynamic mechanical analyses (Weipert 1997).

Although the external excitation defines how far and how fast a given microregion is displaced at the surface of the dough sample, a third parameter is shown in Figure 1. This parameter, the wavelength (λ), is determined by the properties of the material itself as it responds to the "rate" of the external excitations. The wavelength is

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inversely proportional to the frequency with the constant of proportionality being the phase velocity (v_p) at which the waves propagate through the dough:

$$\lambda = v_p / f \quad (1)$$

As will be discussed later, the ultrasonic phase velocity is an important material parameter that characterizes the properties of the dough.

A second material parameter that can be derived from Figure 1 is related to the amplitude decay as the wave propagates into the sample. The initial amplitude, y_{max}, decreases in an exponential manner with propagation distance. The dough's attenuation coefficient, α, characterizes the extent of the wave intensity's decay with distance (where the intensity is proportional to amplitude squared):

$$y = y_{max} \exp(-\alpha x/2) \quad (2)$$

Displacements of microregions of the dough as defined in Figure 1 are transverse: the regions move up and down while the wave propagates from left to right. A more common mode of displacement in ultrasonic tests is longitudinal displacement, in which the external excitation compresses a region of the dough adjacent to the surface. The compressed region in turn compresses the adjoining region to its right, and the external excitation source starts pulling the surface microregion back from its equilibrium position (as displacement becomes "negative"). In this excitation mode, the oscillating excitations applied to the surface of the dough create regions of compression and rarefaction that map onto the peaks and troughs of Figure 1. The oscillatory displacements of the microregions for this excitation mode run parallel to the direction in which the wave propagates. It is these longitudinal displacements, giving rise to longitudinal waves, that are the basis for sound propagation in fluid materials. Although more complex wave types can be produced, this review is restricted to discussion of wave propagation by these two predominant types: transverse and longitudinal polarizations.

One additional point that perhaps needs highlighting is that in using ultrasound to interrogate the rheology and structure of dough, the maximum amplitude ($\pm y_{max}$) is small. Therefore, all displacements of microregions from their equilibrium position are small. Ultrasound as a low-intensity technique is thus distinct from high-intensity ultrasound (sonication), which has been routinely used to solubilize high-molecular-weight gluten proteins (Stevenson and Preston 1996; Ammar et al. 2000; Singh and MacRitchie 2001). As such, low-intensity ultrasound is a materials characterization tool

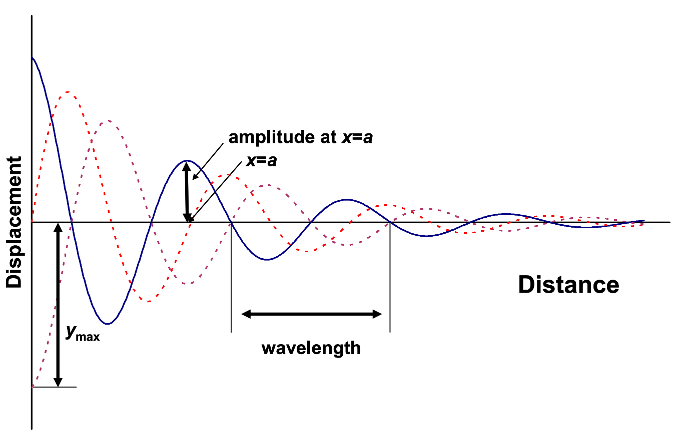

Fig. 1. Transverse (shear) waves propagating from periodic initiation at a surface deeper into a piece of dough. Lines represent displacements of regions of the dough at three different times.

that imposes small strains, of the order of 10^{-6} according to Povey (1997), so that rheological assessments are performed in the linear viscoelastic regime, and dough structure is characterized in its native undisturbed state.

In the last 20 years, there has also been interest in the analysis of the rheology of viscoelastic materials outside of the linear viscoelastic regime (Hyun et al. 2011). Such analyses have been useful for better understanding the constitutive properties of various materials, including those of gluten gels (Ng et al. 2011) and dough (Tanner et al. 2011). Although we are not aware of the use of nonlinear ultrasonic techniques for analysis of dough properties, nonlinear ultrasonic characterization is a vibrant research area, with applications in composites, structural materials, and biomedical materials (Lewin 2004; Jhang 2009).

TECHNIQUES

Signal Generation. For highly viscous materials that readily absorb ultrasound, such as dough, two options are available for creating the external excitation that allows an ultrasonic wave to propagate through the material. Either one transducer is used, and it emits and receives the ultrasonic signal, or two transducers are used, so that one transducer emits the signal and the second receives. A potential third option is the use of quartz resonance cells, in which standing waves are set up in the liquid within the cell (Coupland 2004). Quartz resonance cells have been used to examine the properties of solutions of gliadins in different solvents (Zhang and Scanlon 2011a, 2011b), but they are unlikely to be useful in studies of dough properties, in which high viscosity and a high concentration of bubbles frustrate the establishment of standing waves within the dough. One manufacturer of ultrasonic quartz resonance instruments does sell a cell suitable for analysis of semisolid materials, but we are not aware of the cell being used to investigate dough properties.

Typically the external excitation is created by a piezoelectric transducer, often composed of a face (wear) plate attached to a well-backed piezoelectric crystal or composite (Akdogan et al. 2005). An electrical signal causes the crystal to vibrate in a specific fashion, and the mechanical excitation of the crystal is transferred to the face plate that is in contact with the dough sample or a buffer rod (more details later). Intimate contact between the transducer face plate and the dough or buffer rod is aided by application of a coupling agent, for example, gels used for obstetric ultrasonic imaging.

In addition, with the more widespread use of air-coupled transducer technologies (Pallav et al. 2009; Pierre et al. 2013), noncontact ultrasonic interrogation of material properties through longitudinally polarized ultrasound is a possibility, and with it the option of on-line ultrasound control of specific dough process operations. An example that is currently being developed is in a dough noodle sheeting operation. In such a proposed setup, the properties of the dough sheet emerging from a set of rolls are measured, and a control loop uses these properties to alter roll gap settings to refine the work input into the dough so that noodle textural quality is optimized (Hatcher et al. *in press*).

Signal Types. The nature of the external excitation also requires some elaboration. As drawn in Figure 1, a continuous wave is being propagated into the sample. However, a more common means of propagating ultrasound into materials is through pulsed techniques (Povey 1997). Although not elaborated upon here, a pulse may be viewed as the superposition of a continuous spectrum of waves spanning a range of different frequencies. The pulse created in this manner is emitted by the transducer over a finite time (the pulse width, determined by the frequencies employed) and the pulses are repeated periodically in such a way that there is good separation between them. A typical reference pulse and its modified shape after propagation through a dough sample are shown in Figure 2.

Pulsed techniques have a number of advantages over continuous waves, particularly in regard to accurate measurements of the time it takes for the pulse to propagate through a given distance (thickness of sample). Extraction of parameters that characterize the properties of the dough (v_p and α) can be achieved by time domain (Elmehdi et al. 2004; Mehta et al. 2009) or frequency domain (Cobus et al. 2007; Leroy et al. 2008b) techniques.

Ultrasonic Setup. In using one transducer, two potential modes of interrogation of dough properties are available. The first is a reflection technique; here the difference in properties of the dough and the material with which it is in contact allows the dough properties to be determined from the signal reflected back from the surface of the dough. This technique has been advocated as a useful determinant of the properties of materials that strongly absorb ultrasound (Kulmyrzaev et al. 2000). It has been used to evaluate differences in doughs made with various ingredients (Braunstein et al. 2012), made with variation of water content (Létang et al. 2001), and dough dynamics as a function of aging time (dough made without yeast) and proofing time (dough with yeast) (Strybulevych et al. 2012).

The second single transducer mode is a transmission technique known as pitch and catch in which the ultrasonic signal propagates through a given thickness of dough and is then reflected off a cell wall (or steel plate), propagating back through the same thickness, and then received by the emitting transducer for signal analysis (Coupland 2004). This technique is most suitable for low attenuating materials and (to the authors' best knowledge) has not been used for ultrasonic analyses of dough properties.

To date, the most common method of acquiring information on dough properties is to use two transducers in transmission mode. From a precise knowledge of sample thickness, transit times of the pulses between emitter and receiver allow accurate determination of the ultrasonic velocity in the dough. Acquisition of a reference signal is an important element in ensuring accuracy of pulse transit times. A reference material of known properties can be inserted between the transducers or the two transducers can be placed in direct contact (typically with a very thin layer of coupling agent). By running experiments on samples of various thicknesses, it is possible to factor out signal losses that occur at the transducer–sample interface (more details later), and thus the attenuation coefficient can be accurately determined (Elmehdi et al. 2004; Mehta et al. 2009). With appropriate experimental design, it is also possible to calculate the interfacial losses and, hence, perform accurate measurements with a single sample thickness (Leroy et al. 2008b; Fan et al. 2013).

Sometimes a buffer rod material of known acoustic properties is employed between the transducer and the dough sample. This method affords two advantages over direct contact methods for both reflection and transmission. The extra path length taken by the sound pulses separates the pulses from electromagnetic pickup from the initial voltage pulse delivered to the transducer, and having a buffer material of known acoustic impedance allows accurate determination of the extent to which ultrasonic power is transmitted or reflected from the sample–rod interface (about which more later). An additional benefit for potential on-line exploitation is that buffer materials compatible with the hygiene and durability standards of the breadmaking industry are available for specific ultrasonic applications (García-Álvarez et al. 2013).

ULTRASOUND AS A RHEOLOGICAL TOOL

Ultrasonic Shear Wave Analyses. The frequency-dependent complex shear modulus for dough, $G^*(\omega)$, cannot only be determined from a harmonic steady-state analysis on a rheometer but also from experiments with transversely polarized ultrasonic pulses. A significant difference, though, is that shear modulus values measured by ultrasound will be at substantially higher frequencies than those acquired with rheometry. The magnitude of the strain also differs, generally being much less in the low-intensity ultrasonic techniques used for materials characterization. Although a material property, such as $G^*(\omega)$, does not depend on testing mode, rheometric and ultrasonic evaluations of the shear modulus differ in two principal respects.

First, to determine the shear modulus, modern rheometers typically rotate the dough specimen (constrained in a narrow gap between two circular parallel plates). Measurement may be achieved by applying a sinusoidal rotational displacement to one end of the specimen and measuring the torque at the other end (Weipert 1990; Amemiya and Menjivar 1992; Weegels et al. 1995; Edwards et al. 1996) or by applying the torque and measuring the resulting displacement of the specimen (Berland and Launay 1995; Létang et al. 1999; Leroy et al. 2010). Determination of the shear modulus by ultrasonic techniques typically makes use of ultrasonic transverse displacements resulting from the imposition of a simple shear stress (Longin et al. 1998; Leroy et al. 2010), as in Figure 1. (It is worth remarking that rheometric evaluation of dough properties has been previously conducted in simple shear mode [Hibberd and Parker 1978].)

Second, the ratio of sample thickness, h, to the shear wavelength (λ) differs considerably between ultrasound and rheometry. In rheometry, the ratio h/λ should be small (1/40 or less) to ensure that the effect of sample inertia is negligible (Ferry 1970; Klemuk and Titze 2009). For a high-viscosity material such as dough, a low ratio is invariably the case, for example, 10^{-4} at 1 Hz (Létang et al. 1999) or 0.02 at the higher frequency of 50 Hz when using a thicker sample (Leroy et al. 2010). In an ultrasonic test, h/λ is large, so that samples are usually many wavelengths thick. As a result, the test is not measuring stress–strain relations directly; instead, the velocity and attenuation coefficient are measured to permit a determination of the complex modulus of the sample if its density is known. Thus, independent measurements of dough density, ρ, are needed to determine the complex shear modulus from ultrasonic experiments.

In the case of a nondissipative material, the shear modulus is given by the following equation:

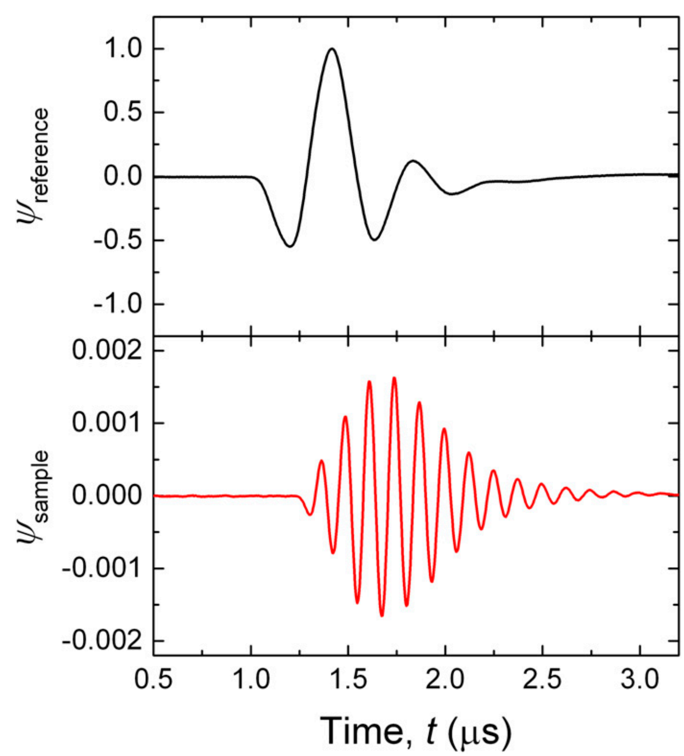

Fig. 2. Broadband ultrasonic longitudinally polarized reference pulse (top) and the pulse after having propagated through a dough sample of 0.52 mm thickness (bottom), both shown as a function of time (t). The amplitude scale has been normalized so that the peak of the reference pulse is 1.

$$G = \rho v_p^2 \quad (3)$$

where v_p is the phase velocity of a shear wave propagating in the material. For viscoelastic materials such as dough, use of equation 3 to derive the dough's shear modulus from independent measurements of ultrasonic velocity and dough density is not applicable owing to damping of the shear displacements. A frequently used parameter to characterize the extent to which ultrasonic waves of a given angular frequency, ω (= 2πf), are damped is the reduced excess attenuation, $\alpha^2 v_p^2/\omega^2$. The storage, $G'(\omega)$, and loss, $G''(\omega)$, shear modulus of the dough both depend on the magnitude of the reduced excess attenuation and are evaluated as follows:

$$G'(\omega) = \frac{\rho v_p^2 \left[1 - \frac{\alpha^2 v_p^2}{\omega^2}\right]}{\left[1 + \frac{\alpha^2 v_p^2}{\omega^2}\right]^2} \quad (4)$$

$$G''(\omega) = \frac{2\rho v_p^2 \left[\frac{\alpha v_p}{\omega}\right]}{\left[1 + \frac{\alpha^2 v_p^2}{\omega^2}\right]^2} \quad (5)$$

It can be seen that when $\alpha^2 v_p^2/\omega^2 << 1$, the shear loss modulus is negligible and $G' \sim G$, as defined in equation 3.

To date, two determinations of the shear modulus of dough through ultrasonic techniques have been reported (Létang et al. 2001; Leroy et al. 2010). The strong attenuation of shear waves in lossy materials such as dough has restricted the number of measurements conducted to date. The frequency dependence of the complex shear modulus of dough made from a hard wheat flour reported by Leroy et al. (2010) is reproduced in Figure 3. In it, the ultrasonic shear wave measurements demonstrate that the power-law gel behavior of dough (Gabriele et al. 2001; Ng et al. 2006) observed in rheometry extends upward to frequencies of hundreds of kilohertz (Leroy et al. 2010). Extending the power law of Figure 3 to angular frequencies of 20 × 10^6 rad/s (corresponding to the 2–4 MHz reported in the shear wave measurements of Létang et al. [2001]), values for the storage and loss parts of the shear modulus would be 750 and 310 kPa, respectively. These values are not dissimilar to those reported by Létang et al. (2001) for a soft wheat flour dough at its optimal water absorption, implying that dough's power-law gel behavior extends well over eight decades of frequency. The gigapascal shear modulus for dough at 1 MHz that was reported by Lee et al. (1992) is unrealistic (Létang et al. 2001; Leroy et al. 2010) and is likely because of the transducer eliciting a longitudinal wave response as well as the desired transverse displacements.

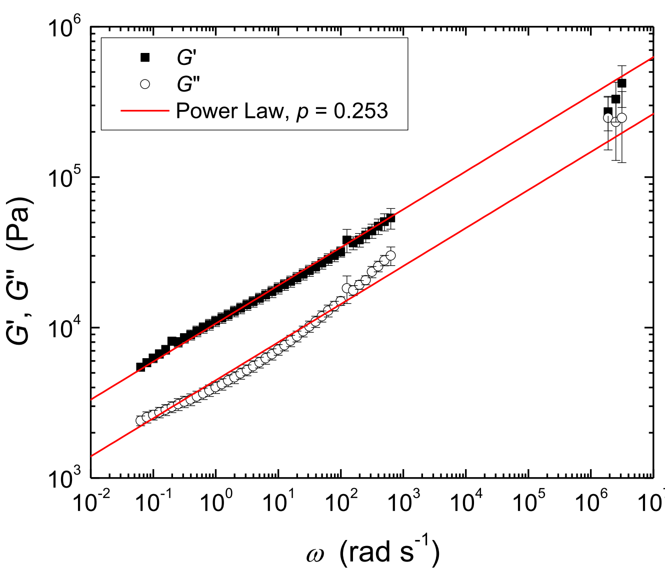

Fig. 3. Storage (G') and loss (G'') parts of the complex shear modulus of dough as a function of angular frequency (ω) determined by rheometry and ultrasound (adapted from Leroy et al. [2010], with permission from Elsevier). Solid lines are fits assuming dough behaves as a power-law gel material.

Ultrasonic Longitudinal Wave Analyses. Most investigations of dough properties at ultrasonic frequencies have been performed with longitudinal ultrasonic polarization. In this mode, the external excitation imparted by the transducer displaces regions of the dough backward (rarefying) and forward (compressing) in the same direction as the wave is propagating. It is the compressive nature of the longitudinally polarized ultrasound pulses that sensitizes them to bubbles in the dough, the compressibility and density of the dough matrix contrasting markedly with those of the gas in the dough's bubbles (Elmehdi et al. 2004; Scanlon et al. 2008). Because bubbles exert a profound effect on the quality of many cereal products (Shah et al. 1998; Cauvain et al. 1999; Babin et al. 2006; Cauvain 2007), a technique that is sensitive to the presence of bubbles would appear to be a promising technique for evaluation of the quality of aerated wheat products (Campbell et al. 1998).

Treating dough as a Maxwell liquid as a first approximation, ultrasonic pulses propagate as pressure (p) waves. The equation describing the propagation of the pressure pulses is as follows:

$$p = p_0 \exp\left[i\omega\left(x/v_p - t\right)\right]\exp\left[-\alpha x/2\right] \quad (6)$$

where p_0 is the maximum pressure experienced by the dough at its surface adjacent to the transducer or buffer rod, x is the distance at which the pressure is determined at a given time (t), and ω is the angular frequency.

Alternatively, equation 6 can be expressed as follows:

$$p = p_0 \exp\left[i\omega(k^* x - \omega t)\right] \quad (7)$$

where k^* is the complex wave vector, which can be expressed in its expanded form as follows:

$$k^* = k' + ik'' \quad (8)$$

with $k' = \omega/v_p$ and $k'' = \alpha/2$.

Expressing wave propagation characteristics by using the wave vector is useful for viscoelastic materials such as dough, especially in regard to evaluating how much of the external excitation is actually transmitted into the dough (see the following section on impedance).

The phase velocity of the longitudinal ultrasonic pulses is related to a modulus, just as the phase velocity of the transverse polarizations was related to the shear modulus of the dough. In this case, β is the longitudinal modulus:

$$\beta = \rho v_p^2 \quad (9)$$

For simple liquids, the longitudinal modulus is equivalent to the bulk modulus (B) because the shear modulus is zero, so that β is inversely related to the liquid's compressibility (κ). For soft viscoelastic materials such as dough, the longitudinal modulus has a small shear modulus component:

$$\beta^* = B^* + 4G^*/3 \quad (10)$$

The relative magnitude of the two moduli in equation 10 can be gleaned from the results of Létang et al. (2001), in which B^* was some three orders of magnitude greater than G^* in a dough with optimal water absorption, emphasizing the small shear stiffness of soft power-law gel materials such as dough (McClements 1997; Gabriele et al. 2001). As the dough's water content increases, this effect is even more pronounced, with Létang et al. (2001) observing that shear wave velocity (and hence shear modulus) approached zero when a soft wheat flour's water absorption attained 100% (flour weight basis).

Impedance. As remarked earlier, not all of the strain energy of the external excitation that is induced by the transducer is transferred into the dough; an acoustic impedance mismatch between the dough and the face-plate of the transducer or the buffer rod limits energy transfer into the dough. The acoustic impedance of a material is defined by the following equation:

$$Z^* = \frac{\rho\omega}{k^*} \tag{11}$$

which, when expressed in the measured parameters of phase velocity and attenuation coefficient, is as follows:

$$Z^* = \frac{\rho v}{1 + i\dfrac{\alpha v}{2\omega}} \tag{12}$$

For the case of a dough sample (material 2) in direct contact with a buffer rod (material 1), the impedance mismatch between the two materials determines how much of the energy passed through to the buffer rod is reflected back (R) and how much is transmitted (T) into the dough:

$$R = \frac{Z_2^* - Z_1^*}{Z_2^* + Z_1^*} \tag{13}$$

$$T = \frac{2Z_2^*}{Z_2^* + Z_1^*} \tag{14}$$

It can be seen from these equations that when materials 1 and 2 are identical, there is no mismatch, so that all of the energy is transmitted from the buffer rod to the dough, and none is reflected back. Although analysis is more complicated in the case of a transducer that is in direct contact with a dough specimen, one can use equations 13 and 14 to correct for impedance mismatch losses. For the case in which the reference signal has been measured after propagation through a buffer rod made of polycarbonate, the correction would account for the fact that about 92% of the power transferred into the buffer rod is actually transmitted into the dough. This number is based on a typical impedance for polycarbonate of 2.7 $MNsm^{-3}$ and for dough at high frequency of 2.3 $MNsm^{-3}$.

ULTRASOUND AS A STRUCTURE ELUCIDATION TOOL

Length Scales in Dough. Acoustic analyses at different frequencies can be used to better understand dough structure just as electromagnetic radiation of different frequencies has had a long tradition of elucidating the structure of various components in cereal science. Two examples for starch, a major component of dough, illustrate this concept. When electromagnetic radiation at a frequency of ~600 THz is used to examine amylopectin molecules eluted from field flow or chromatography columns, molecular size can be deduced from how that radiation is scattered (Millard et al. 1997; Chen and Wyatt 1999; Stevenson et al. 2003). Much higher frequencies (~300 EHz) are useful for probing starch structure at a smaller length scale, at which small-angle X-ray scattering experiments will quantify the intramolecular structure of the amylopectin molecules (Waigh et al. 2000). Acoustically, similar analogies occur, with low-frequency ultrasound probing properties at large length scales, whereas high-frequency ultrasound is useful for investigating small structural features.

Consideration of the structural features that act as scatterers in the dough rests on the acoustic impedance of the structural feature compared with that of the dough matrix as a whole. Components that have a large acoustic impedance mismatch will scatter ultrasound more effectively than those that are well matched (Povey 1997). A number of potential scattering components are present in dough, such as hydrated protein bodies (Don et al. 2003), remnants of endosperm cell walls (Toole et al. 2013), various bran particles (Campbell et al. 2012), starch granules (Amend et al. 1991), and air bubbles (Chamberlain and Collins 1979; Campbell et al. 1998). Precise information on the ultrasonic velocity (even at one frequency) of most of these components is lacking, so that it is difficult to accurately assess acoustic impedances to determine whether any of these components can be readily discriminated by ultrasound. However, a considerable amount of research has been performed on ultrasonic investigations of scattering from bubbles in liquids (Leighton 1994; Leroy et al. 2002, 2008b, 2009b; Tatibouet et al. 2002), from bubbles in soft solids (Meyer et al. 1958; Strybulevych et al. 2007; Leroy et al. 2009a, 2011), and from bubbles in dough (Elmehdi et al. 2005; Leroy et al. 2008a; Scanlon et al. 2008). The large acoustic impedance mismatch between the dough matrix and the bubbles it contains ($Z_{\text{bubble}} \sim 0.0004Z_{\text{doughmatrix}}$) means that ultrasound is effectively scattered by bubbles within the dough. Given that dough in its undiluted state is highly opaque to electromagnetic radiation in the visible region, there is the potential to exploit this scattering sensitization of ultrasound to ascertain bubble sizes in dough (Leroy et al. 2008a). As described later, longitudinally polarized ultrasound is so sensitive to gas bubbles that the acoustic spectrum of dough at frequencies below about 6–8 MHz is actually dominated by ultrasound's interaction with the bubbles within the dough. This sensitivity to the presence of bubbles results in part from strong scattering resonances, motivating the use of ultrasonic resonance spectroscopy rather than small-angle scattering techniques for investigations of bubble sizes.

Previous Ultrasonic Studies of Dough Properties. As mentioned earlier, only two studies on dough that used transversely polarized ultrasound appear to have been conducted. Accordingly, this section focuses on studies performed with longitudinal ultrasonic pulses. Because of the importance of bubbles to dough acoustic properties, a demarcation of the studies is performed according to the acoustic spectrum; research published in the book *Bubbles in Food 2* justifies this approach (Fig. 4).

From Figure 4 it is clear that dough with bubbles has acoustic properties that are distinct from dough mixed under vacuum (in which very few bubbles are entrained into the dough [Baker and Mize 1941]). It is also clear that for "normal" doughs, that is, those mixed in air, values for the phase velocity and attenuation coefficient depend markedly on the frequency chosen to report the results. Although the peaks are centered at different frequencies, the similarity between the theoretical curves for bubbles in water and the experimental ones for dough intimates that it is the presence of a bubble resonance within the dough that is responsible for the peaks in velocity and attenuation. Accordingly, this review's reporting of the different studies on dough that have been performed will be split into three regions of the acoustic spectrum: the very long wavelength regime (in which $\omega \ll$ bubble resonance frequencies), the bubble resonance region, and the high-frequency (short wavelength) region.

Low-Frequency Region. In the low-frequency region (very long wavelengths), the dough behaves as an effective medium, with ultrasound being sensitive to the composite properties of the dough matrix and the bubbles within the matrix. It can be seen from Figure 4 that in this region ($f < 0.1$ MHz for this dough) pulse amplitude is only moderately attenuated (Elmehdi et al. 2004) for air-mixed doughs, and the pulses propagate with very low velocity (~150 m/s). The velocity of sound in air and water at 25°C is 347 and 1,496 m/s, respectively. A value for ultrasonic phase velocity in dough that is less than two of its key constituents can be understood from evaluation of dough as a two-phase material, that is, a composite material with a highly compressible phase (air) and a phase that is almost incompressible (dough matrix). The compressibility of the dough as a whole (κ_{dough}) depends on these two compressibilities weighted according to their respective volume fractions, with ϕ representing the volume fraction of the air bubbles:

$$\kappa_{dough} = \kappa_{air}\phi + \kappa_{doughmatrix}(1-\phi) \quad (15)$$

For dough mixed without yeast, the volume fraction of gas in the dough can be determined from measurements of the density (ρ_{dough}) mixed at different headspace pressures (Campbell et al. 1993; Elmehdi et al. 2004). Extrapolation to zero pressure permits the gas-free dough density ($\rho_{doughmatrix}$) and the volume fraction of bubbles to be determined:

$$\phi = 1 - \frac{\rho_{dough}}{\rho_{doughmatrix}} \quad (16)$$

An important approximation for sound velocity in a bubbly liquid can be derived from equation 15 by recognizing that bubbles are highly compressible and of low density compared with the dough matrix (i.e., $\kappa_{doughmatrix} << \kappa_{air}$ and $\rho_{doughmatrix} >> \rho_{air}$). From equation 9, $1/\kappa = \rho v_p^2$, so that from equation 15 the following simple expression for the velocity of sound in the dough (v_{dough}) can be derived for $\phi > 0.001$:

$$v_{dough} \cong v_{air}\sqrt{\frac{\rho_{air}}{\rho_{dough}\phi}} \quad (17)$$

where ρ_{dough} can be taken as the volume-fraction-weighted average density of the bubbles and matrix, $\rho_{dough} = \rho_{air}\phi + \rho_{doughmatrix}(1-\phi)$. Equation 15, which leads to the prediction of remarkably slow sound velocities in bubbly liquids at low frequencies (equation 17), is usually referred to as Wood's approximation (Wood 1941).

With a volume fraction of bubbles in the dough of 10%, Wood's approximation predicts a velocity of about 40 m/s. Although somewhat on the low side compared with reported low-frequency results of the velocities of sound in dough (see later), the low velocity compared with ultrasonic velocities in water and air indicates that dough behaves similarly to other two-phase fluid systems such as bubbles in water (Povey 1997). The underestimation of dough's velocity from Wood's approximation (equation 17) is due to the neglect of the shear modulus of the dough matrix in the model (i.e., the dough has some solid character that contributes to the velocity [Elmehdi et al. 2004]); the shear rigidity of the dough matrix will increase the velocity, as can be appreciated from the additive nature of equation 10.

Because both bubbles and dough matrix affect the "composite" properties of the dough at low frequencies, this review of the literature separates the ultrasonic studies into examinations of the effects of the two components.

Low-Frequency Region: Bubble Effects. As would be expected from equation 17 and inspection of Figure 4, the measured ultrasonic velocity in the dough will be affected by changes in bubble concentration. For a given mixer and formulation, more bubbles are entrained into the dough by mixing at higher headspace pressures (Campbell et al. 1998) or by mixing for longer times (Baker and Mize 1937). A good illustration of the approximate equivalency of these actions on dough properties when probed by ultrasound is seen in Figure 5. This figure is derived from the measurements of Elmehdi et al. (2004) and Mehta et al. (2009), who created doughs from hard red spring wheat flour at optimal and close to optimal water absorption, respectively. It can be seen that a change in volume fraction of gas in the dough by either method (headspace pressure manipulation or mixing time) changes the ultrasonic velocity. The inset expands the velocity scale at larger values of the gas volume fraction so that the changes in velocity with ϕ are observable.

Low-Frequency Region: Effects of Growth of the Bubbles. In normal breadmaking situations, dough does not lack the yeast that generates its highly aerated structure during the proofing process. Accordingly, the bubbles incorporated during mixing grow with time, and at a certain volume fraction (Babin et al. 2006), they begin to coalesce. Two research groups have conducted low-frequency investigations of bubble growth and coalescence.

The experimental approach taken by Elmehdi et al. (2003a) and Scanlon et al. (2002) was to monitor ultrasonic velocity and relative attenuation of the fermenting dough with two large 50 kHz transducers attached on either side of a pair of Plexiglas plates separated by a precisely known thickness. In such a setup, the smooth-walled cavity allowed the dough to expand perpendicularly to the axis in which ultrasound pulses propagated through the dough. Thus, the dough sample was monitored nondestructively as a function of time throughout the fermentation process. They found that after the initial 5 min of fermentation, velocity decreased precipitously with time, and the relative attenuation increased in proportion to the

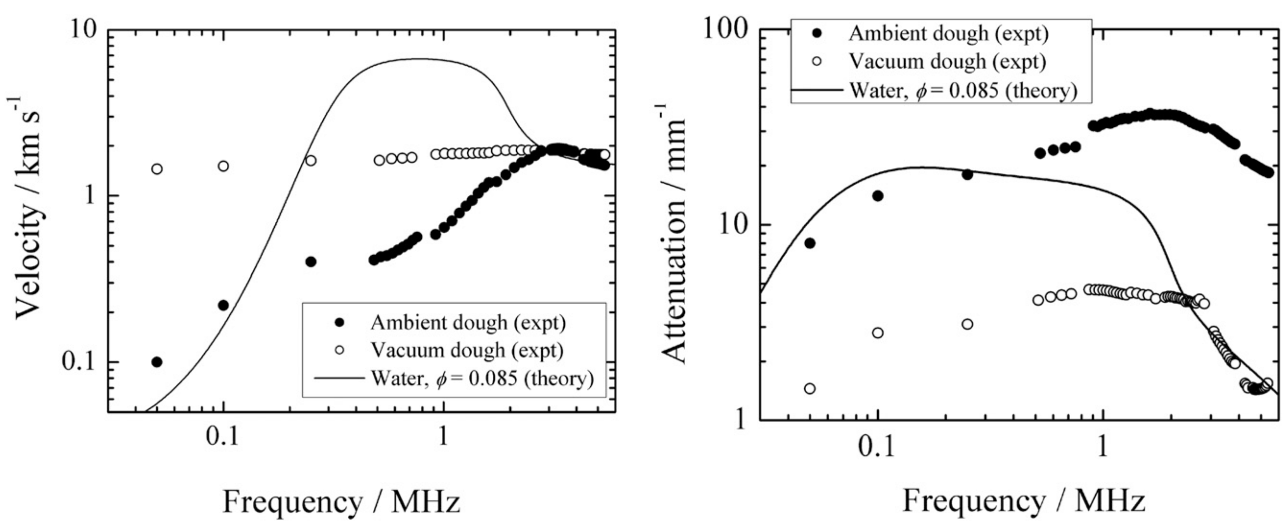

Fig. 4. The frequency-dependent response for the ultrasonic velocity (left) and the attenuation coefficient (right) of dough mixed at atmospheric (ambient) pressure (closed circles) or under vacuum (open circles). Solid line is the theoretical curve for bubbly water with the same volume fraction of bubbles as the ambient dough (reproduced from Scanlon et al. [2008]).

increase in void fraction. Thus, both velocity and attenuation are sensitive to the expansion of the bubbles in dough during fermentation. However, by 40 min of fermentation (at a gas volume fraction of approximately 0.5), the multiple scattering and associated thermal losses (Leighton 1994; Povey 1997) reduced signal intensity to such an extent that attenuation could no longer be measured confidently in their experiments (Elmehdi et al. 2003a).

Skaf et al. (2009) used a different transmission setup composed of a piezoelectric disc within a metallic ring to examine the ultrasonic signal propagating through an expanding dough during fermentation. The justification for this setup was that low frequencies were needed for monitoring of the whole of the fermentation process (compare with Figure 4, in which attenuation is low at low frequencies). However, low-frequency transducers are large (wavelength increases as frequency falls [equation 1]), and to obviate this limitation, Skaf et al. (2009) induced resonance in the ring and transducer structure so that low frequencies could be generated from a smaller dough monitoring setup. Velocities and attenuation coefficients of the fermenting dough were not reported, but the evolution of dough properties during fermentation was captured by the relative delay time of the ultrasonic signal and its relative amplitude (normalized relative to values at the start of fermentation). Using these parameters, Skaf et al. (2009) demonstrated clear differences associated with the progress of fermentation in doughs of various flour strengths that could be attributed to differences in gas-holding capacity at different proofing temperatures and to variation in the amount of yeast.

In regard to the yeast loading, Skaf et al. (2009) observed that in the initial stages of fermentation, the signal's relative delay time decreased when dough was made with only one quarter of the normal amount of yeast (i.e., with less yeast, ultrasonic propagation was faster through the dough). This observation led the authors to deduce that "another phenomenon, other than gas production, has an influence on the evolution of the delay such as the change in the elasticity of the dough matrix." A similar conclusion had been reached by Scanlon et al. (2002) on the basis of changes in the ultrasonic velocity during the initial stages of fermentation for doughs that had been mixed under vacuum. However, we postulate that the results reported by Skaf et al. (2009) for low-yeast-loaded doughs are actually evidence of the facultative respiratory capacity of yeast (Elmehdi 2001).

When the dough is initially mixed, the yeast respires by consuming any dissolved oxygen in the dough matrix and producing carbon dioxide and water (Briggs et al. 2004). The depletion of dissolved oxygen in the matrix sets up a concentration gradient so that gaseous oxygen from the bubbles dissolves into the dough matrix in response to this gradient. As a result, the gas bubbles shrink, and as shown earlier (Fig. 5 inset), small changes in bubble volume bring about an appreciable change in the ultrasonic velocity. With time, all the oxygen in the bubbles is depleted and yeast begins to respire anaerobically, producing carbon dioxide and ethanol (i.e., there is a change from respiration to fermentation [Chamberlain and Collins 1979]). The carbon dioxide generated from the yeast by either process eventually diffuses to the bubbles, again in response to a concentration gradient (Shah et al. 1998), this time inflating the bubbles, and their growth reduces the ultrasonic velocity (see equation 17). In doughs made with conventional amounts of yeast, oxygen depletion (and thus bubble shrinkage) and bubble inflation from carbon dioxide occur rapidly so that only reductions in ultrasonic velocity with time are observed. In the low yeast content situation, processes occur slowly, and so the effects of both bubble shrinkage and bubble inflation can be observed.

Low-Frequency Region: Dough Matrix Effects. A large number of factors can alter the mechanical properties of the dough matrix. Probably the preeminent topic in cereal chemistry is the extent to which intrinsic differences in breadmaking quality are attributable

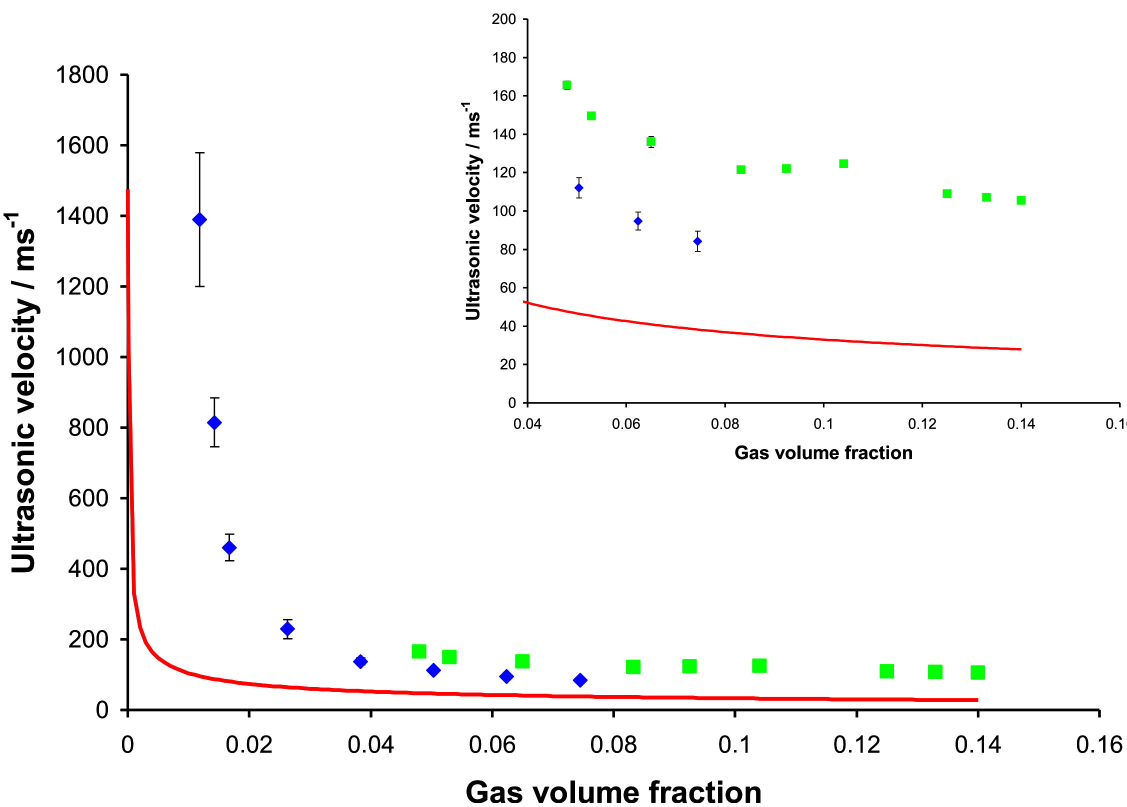

Fig. 5. Change in ultrasonic velocity of dough made from a strong breadmaking flour with change in amount of air entrained during mixing from two different studies: diamond symbols represent dough prepared at different headspace pressures (Elmehdi et al. 2004); squares represent dough prepared by mixing for different times (Mehta et al. 2009). Solid line represents Wood's approximation (equation 17). Inset figure expands the region in which gas content in the dough is 4–14% by volume.

to differences in the source of the wheat flour (Bushuk et al. 1969; Tipples 1975; Hoseney 1986; Goesaert et al. 2005).

Transducers operating at 50 kHz have been a popular means of identifying intrinsic differences in wheat quality by ultrasound. Probably the earliest such study was a preliminary investigation by Rubena Moorjani in Malcolm Povey's lab in Leeds (Moorjani 1983). A more comprehensive assessment was undertaken by Kidmose et al. (2001) nearly 20 years later. They found a high correlation between dough water absorption and ultrasonic velocity for doughs made from wheat flours covering a range of breadmaking quality.

Given the potential of ultrasound to serve as a means of determining dough strength and its ability to acquire information from dough or gluten samples as small as 4–7 g (Elmehdi 2001; Elmehdi et al. 2003b, 2013) or even 2 g (Alava et al. 2007), ultrasonic technologies have obvious applications as wheat quality screening tools in the early stages of wheat-breeding programs. One group that has significantly advanced the technology's commercial exploitation in this regard is the Sensor Systems Group at the Universitat Politècnica de Catalunya in Barcelona. This group led a European consortium of academic and industrial partners in developing an ultrasonic sensor for nondestructive assessments of dough quality as part of their Rheodough project. A Spanish patent from the group (García Hernández et al. 2003) described how valid measurements of ultrasonic velocity and attenuation could be acquired from a single dough subsample by automatically measuring the ultrasonic signal sequentially at three different thicknesses.

The Catalunya Sensor Systems Group showed that a parameter incorporating ultrasonic velocity and attenuation was able to discriminate flours of different breadmaking strength evaluated by using a constant water absorption procedure (Alava et al. 2007; García-Álvarez et al. 2011). Similar evaluations were being conducted concurrently at the University of Manitoba in support of a patent application striving to meet the same objective (Page et al. 2002, 2003). The relation between two conventional dough strength indices and ultrasonic velocity for doughs made from flours ranging from very good to poor breadmaking quality is shown in Figure 6 (Scanlon et al. 2011b). This figure shows that the correlations between ultrasonic velocity and these indices are fairly strong and are comparable to the correlation between these conventional indicators of dough strength. Although a commercial instrument has been, or is being, developed from the Rheodough project (McQueen Cairns Technology, Brentford, England), Alava et al. (2007) concluded that research on mechanisms affecting the ultrasonic signal in dough is required for a confident determination of flour quality by the technique. Certainly, one question worthy of investigation, given the result of Figure 5, is how does a correlation between air entrainment capacity and dough strength (Baker and Mize 1946; Campbell et al. 1993; Chin et al. 2005; Peighambardoust et al. 2010; Koksel and Scanlon 2012) affect ultrasonic assessment of dough strength?

After flour, the next most prominent ingredient in the dough matrix is water. Water profoundly affects conventional rheological parameters of dough such as the shear modulus (Hibberd 1970; Navickis et al. 1982; Berland and Launay 1995; Dreese et al. 1988), and so it is not a surprise that it also strongly influences ultrasonic properties (Kidmose et al. 2001; Alava et al. 2007; Nassar et al. 2012). This relationship is seen in Figure 7 from the work of Alava et al. (2007), in which ultrasonic velocity increased and attenuation decreased as the amount of water in the dough was reduced. Just as bubble entrainment and dough strength both alter the values of ultrasonic parameters, an outstanding question with respect to the result of Figure 7 is, how much of the changes are brought about by water's effect on the dough matrix per se, or by the effects of the altered dough matrix rheology on bubble entrainment? That the apparent viscosity of dough is altered by its water content (Skeggs and Kingswood 1981; Yener 2008), thereby altering how bubbles are entrained during mixing (Chin et al. 2005; Peighambardoust et al. 2010; Koksel and Scanlon 2012), means that both bubbles and dough matrix affect the reported ultrasonic results at the frequencies used by Alava et al. (2007) and in the on-line acoustic assessments of the mixing process by Nassar et al. (2012).

Few studies appear to have been conducted investigating the effect of other ingredients on dough ultrasonic properties at low frequencies. Shortening altered dough ultrasonic properties in much the same way as water did, that is, it appeared to exert its effect on the dough by plasticizing it (Mehta et al. 2009). This effect has also been observed by using conventional shear rheometry (Fu et al. 1997). Mehta et al. (2009) confirmed that this effect arose from the shortening's effect on the dough matrix by conducting separate experiments on shortening-enriched doughs that had been mixed under vacuum (so doughs were devoid of bubbles). In vacuum-mixed doughs, increasing attenuation and decreasing velocity with

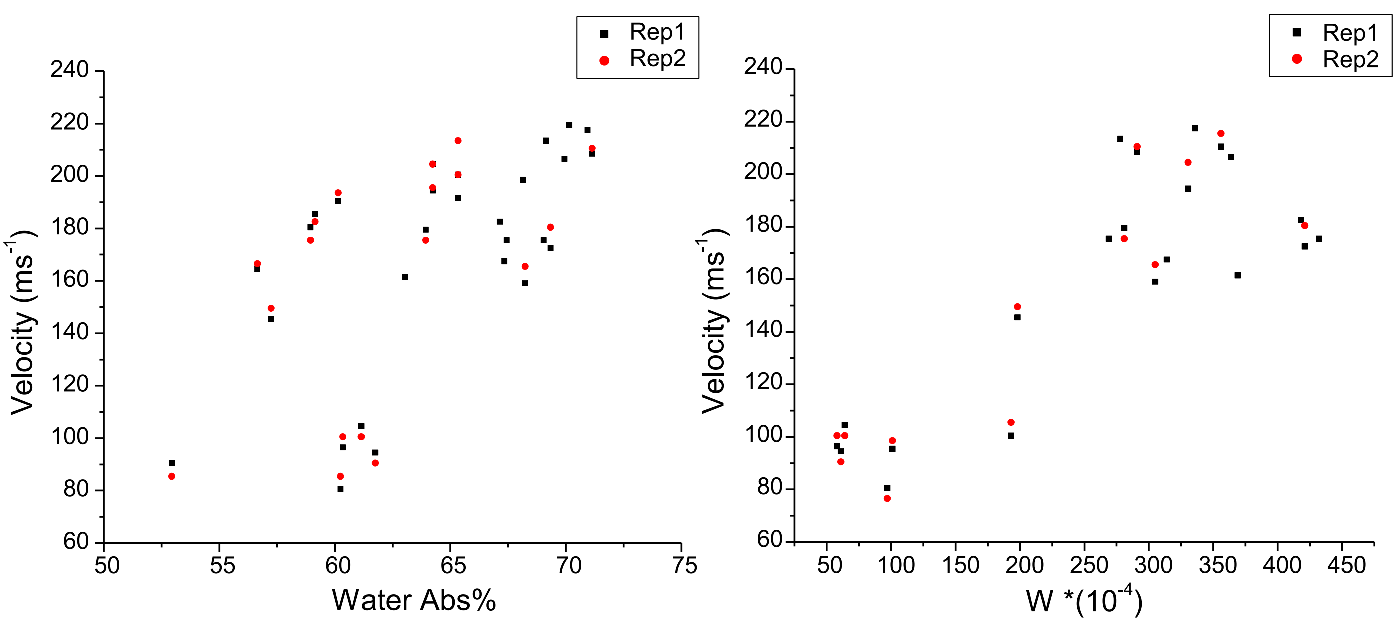

Fig. 6. Relationships between ultrasonic velocity and farinograph water absorption (left) and alveograph *W* parameter (right) for doughs made from flours with a range in breadmaking quality (from Scanlon et al. [2011b], with permission from AGROBIOS International).

greater amounts of shortening were observed: the same effects seen for doughs mixed at atmospheric pressure.

Low MHz Frequency Region. As will be appreciated from the attenuation results of Figure 4, the order of magnitude increase in the dough's ultrasonic attenuation as frequency increases presents considerable experimental difficulties to attaining accurate and precise velocity and attenuation measurements in the low MHz frequency region. Nevertheless, a number of studies within this frequency regime have been reported (Létang 1997; Létang et al. 2001; Lee et al. 2004; Ross et al. 2004; Fan 2007; Leroy et al. 2008a; Scanlon et al. 2011a), including two rather extensive analyses in which ultrasonic parameters were shown to be especially sensitive to bubble size in this frequency range (Létang 1997; Fan 2007).

The studies of Létang et al. (2001) were primarily conducted with reflectance techniques to cope with the difficulties of high attenuation (Kulmyrzaev et al. 2000). They found that increasing the water content of the dough decreased velocity, as found at lower frequencies, but in contrast to low-frequency measurements, increasing water content decreased attenuation.

Given the importance of mixing time to the development of a dough matrix with optimal gas-holding characteristics (Campbell and Shah 1999; Campbell and Martin 2012; Cauvain 2012), both Létang et al. (2001) and Ross et al. (2004) evaluated how ultrasonic parameters were affected by mixing time. Not surprisingly (based on air-entrainment expectations from low-frequency measurements discussed earlier), both studies showed that changes in velocity, and particularly changes in attenuation coefficient, were dependent on mixing time. It is likely that such effects arise from entrainment of air bubbles rather than changes in the dough matrix engendered by work input. Evidence supporting this assessment of these studies comes from Létang et al. (2001), who found that at frequencies greater than about 5 MHz, essentially no changes in velocity or the longitudinal loss modulus were observed with increase in mixing time. As can be seen in Figure 4, over the frequency range of approximately 2–8 MHz, both phase velocity and attenuation coefficient decrease with increasing frequency as the energy-absorbing effects of the resonance peak fall off away from its central frequency (Leroy et al. 2008a). Therefore, mixing time effects in the low MHz frequency range are highly unlikely to be independent of mixing time effects on bubble entrainment.

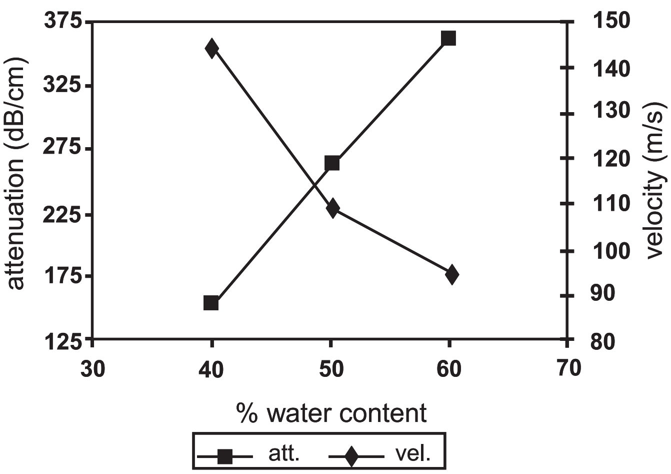

Fig. 7. Influence of water content on ultrasonic attenuation (att.) and velocity (vel.) in dough (reproduced from Alava et al. [2007], with permission from Elsevier).

Because of the importance of bubbles to ultrasonic properties in the low MHz frequency region, research at the University of Manitoba has focused on the effects of bubbles in the frequency range from 500 kHz to 5 MHz rather than on the effects of dough matrix properties (Scanlon et al. 2011a). The primary motivation has been to use a model describing the effects of the resonance peak on ultrasonic parameters to determine the bubble size distribution in the dough (Leroy et al. 2008a, 2008b, 2009b). An algorithm to extract the mean and variance of the bubble size distribution has been shown to work well with aerated complex fluids and viscoelastic solids (Strybulevych et al. 2007; Leroy et al. 2008b, 2009b). The principles of this back calculation of the bubble size distribution from the ultrasonic signal are illustrated in Figure 8 (Leroy et al. 2008a). In Figure 8A and B the model fits match the experimental profiles well (constrained by the necessity to find parameters that simultaneously fit both phase velocity and attenuation coefficient as a function of frequency). The size distribution determined by using the same ultrasonic resonance model was compared with the reported size distribution of bubbles in dough from X-ray tomography (Bellido et al. 2006), but the bubble distributions were seen to differ (Fig. 8C). Investigations are currently underway to determine whether effects resulting from multiple scattering from coupled resonating bubbles (Leroy et al. 2009a) or complications from local matrix stiffening arising from starch granule displacements require refinement to the model. In addition, higher resolution X-ray tomography measurements with synchrotron radiation are being conducted to ensure small bubbles are captured so that size distributions are accurately quantified (F. Koksel et al., *unpublished results*).

Examining the frequency dependence of the ultrasonic properties of fermenting dough in the 2–10 MHz range is even more challenging because the bubbles are expanding. Lee et al. (2004) tackled this task by using a wavelet transformation technique. In concordance with expectation based on the frequency spectrum of Figure 4

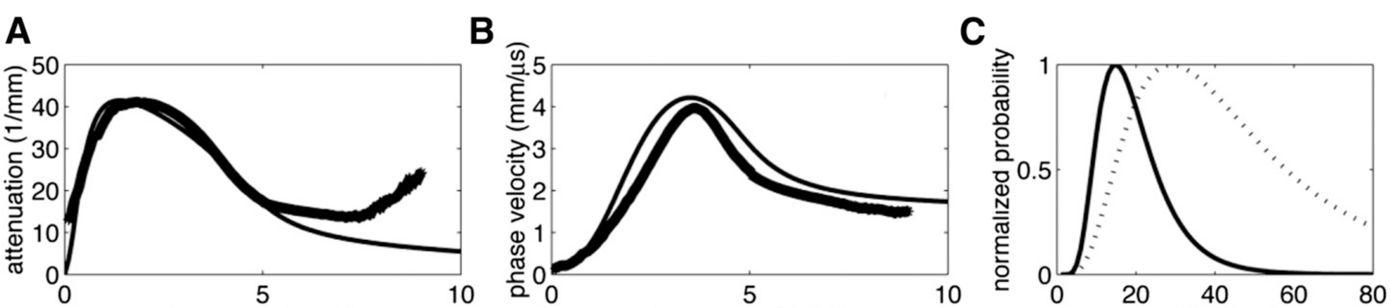

Fig. 8. Comparison of experimental results (broad line) and ultrasonic resonance model predictions (thin solid line) for attenuation coefficient (**A**) and phase velocity (**B**) as a function of frequency for doughs made without yeast analyzed 96 min after mixing. Model predictions (**C**) of the bubble size distribution (thin solid line) compared with the bubble size distribution in dough acquired 90 min after mixing ascertained by X-ray microtomography measurements (dashed line) (data from Bellido et al. 2006) (reproduced from Leroy et al. [2008a]).

and the results of Létang et al. (2001), Lee et al. (2004) found that changes in ultrasonic velocity with fermentation time were pronounced at 2 MHz, whereas at higher frequencies, ultrasonic velocity was essentially insensitive to bubble growth. Fermentation was monitored for 30 min, at which point the gas volume fraction was approximately 0.3 (our calculation from the density results of Lee et al. [2004]). The inability to follow events at longer fermentation times is not unexpected given the increase in attenuation at the higher frequency (Fig. 4) and the high attenuation coefficient values (Lee et al. 2004).

One test of a technique's ability to investigate bubbles in dough is its ability to follow bubble disproportionation, a phenomenon evident in doughs made without yeast (van Vliet 1999). In such a situation, the bubble surface area to volume ratio decreases and mean bubble size increases with time. To examine how ultrasonic measurements were affected by changes in the bubble distribution, Fan and coworkers (Fan 2007; Scanlon et al. 2011a; Fan et al. 2013) measured the attenuation coefficient in the vicinity of the attenuation peak at 2 min intervals in dough subsamples excised from the dough piece at various times after mixing (Fig. 9). The peak in attenuation decreased with time and shifted to lower frequencies (longer wavelengths), events consistent with the growth of larger bubbles at the expense of smaller ones, as the gas diffused from small to large bubbles within the dough (van Vliet 1999). Therefore, from the work of Lee et al. (2004) and Fan and coworkers (Fan 2007; Scanlon et al. 2011a; Fan et al. 2013), it is apparent that low MHz ultrasonic measurements are valuable probes of bubble dynamics in dough, regardless of the mechanism by which the bubble distribution evolves. Recent work with a reflectance technique endorses this conclusion (Strybulevych et al. 2012).

From their velocities and attenuation coefficients, Lee et al. (2004) calculated the storage and loss parts of the longitudinal modulus as a function of fermentation time, using the $\beta^*(\omega)$ equivalents of $G^*(\omega)$ introduced in equations 4 and 5. They reported decreases in both parts of the longitudinal modulus as fermentation proceeded, with the changes attributed to "the dough [becoming] less elastic during fermentation" (Lee et al. 2004). Most of this change in the elastic modulus was not because of changes in the dough's elasticity at these frequencies but was undoubtedly attributable to how bubble size changes affect the measured ultrasonic velocity and attenuation coefficient (Fig. 9). Nevertheless, dough matrix elasticity might be a factor in the modulus change with increasing fermentation time, because Lee et al. (2004) observed substantial changes in the viscoelastic modulus at 10 MHz as a function of fermentation time. Changes in mechanical properties at this frequency should not be influenced by bubble resonance effects (Fan et al. 2013).

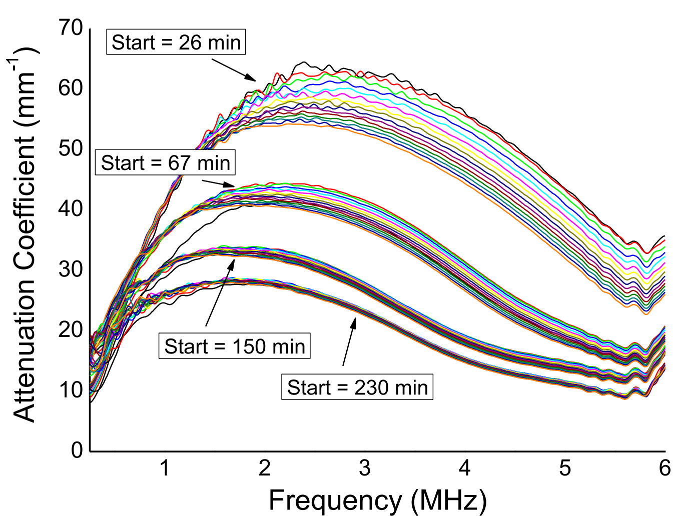

Fig. 9. Time-dependent changes in the attenuation coefficient of dough subsamples excised from a dough piece at various postmixing times with signals recorded at 2 min intervals thereafter (reproduced from Scanlon et al. [2011a], with permission from AGROBIOS International).

High-Frequency Region. At frequencies higher than those of the broad resonance peak of the bubbles in the dough, ultrasonic attenuation is lower than in the resonance region, but it is still considerably higher than in the long wavelength region. In the high-frequency region, the short wavelengths of the ultrasonic pulses are sensitive to events occurring in the dough matrix. The only measurements that appear to have been conducted at these high frequencies are those of Fan et al. (2013). They used a classical ultrasonic relaxation model (Litovitz and Davis 1965) to understand how the frequency dependence of velocity and attenuation is influenced by molecular relaxations of the various polymers present in the dough. A comparison of doughs mixed under vacuum (thus, without bubbles) versus those mixed in air revealed that the volumetric structural relaxation occurring at a time of 7 ns was shifted to less than 2 ns when dough was mixed under vacuum. Fan et al. (2013) advanced the idea that the gluten proteins were able to store the strain energy input of the ultrasonic pulses. The difference in relaxation times indicated that the protein molecules responded faster to ultrasonic compressions and rarefactions in a dough devoid of bubbles, consistent with a picture of surface-active molecules whose relaxation behavior is slowed by them being constrained by their location at bubble interfaces.

CONCLUSIONS

This overview of ultrasound as a complementary rheological tool has shown that it is essential that frequency is reported when defining rheological parameters such as the complex longitudinal modulus, primarily because of the profound effect of frequency on ultrasonic velocity and attenuation of the bubbles within the dough. Bubbles in the dough resonate at specific frequencies that depend on the bubble sizes. Relaxation phenomena within the dough matrix also influence the frequency dependence of the phase velocity and attenuation coefficient. Because of the relative ease with which experimental results can be obtained, most ultrasonic analyses on dough have been conducted in the low-frequency region, in which dough behaves as an aerated "composite" material. The potential for using ultrasound as a high-frequency extension for conventional rheological assessments means that ultrasonic techniques will definitely see greater use in future cereal science studies to better understand dough rheology and structure.

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