Chapter 2
An Overview of Ultrasound

2.1 Wave Propagation

2.1.1 General Aspects

Sound is a waveform that propagates away from a source in an elastic media generating density variations. The generation and perception of sound is a consequence of the transmission of mechanical energy through the media. That is, a device that generates sound must perform some kind of mechanical work to a medium. In the case of human voice, sound is generated by the mechanical work produced by the vocal cords in the air (medium of propagation). Similarly, to detect sound, mechanical work must be applied to the detector. In the human hearing system mechanical work is achieved through vibrations in the eardrum. Since mechanical work or energy is associated with the transmission of sound, the elastic and inertial properties of the material in which sound propagation occurs will affect the efficiency of wave propagation. For example, sound propagation in air is slower than in water with values of 343 and 1,497 m s\(^{-1}\), respectively (Leighton 1994).

Acoustic waves are characterized by their frequency (cycles per second), wavelength (distance between cycles), and amplitude (height of the wave). Depending on the frequency of the waveform, sound waves can be classified as infrasonic, sonic, and ultrasonic. Sonic waves have frequencies between 20 and 20,000 Hz, which correspond to the frequency range of the human hearing. Waves with frequencies below 20 Hz are classified as infrasonic, while waves with frequencies above 20,000 Hz are classified as ultrasonic. The detection of sound in nature occurs over the entire spectrum of frequencies where certain animals can detect acoustic waves in the infrasonic range; while others detect sounds in the ultrasonic range. The frequency range of sound detection of different species, including humans, is detailed in Fig. 2.1a. The maximum and minimum frequency values of the detection range are reported in this figure. For example, elephants can detect sounds in the range of 5–12,000 Hz, while moths can detect sounds in a significantly smaller range that include frequencies between 20,000 and 50,000 Hz. Bats and porpoises can detect sounds with frequencies as high as...
200,000 and 150,000 Hz, respectively, while salamanders can detect sounds at a maximum frequency of 220 Hz (Leighton 1994). Animals not only detect sound, they also emit sound over a wide range of frequencies (Fig. 2.1b). Bats emit sounds of frequencies in the range of 30–80,000 Hz to locate and identify objects. On the other extreme of the frequency scale, acoustic waves, with frequencies between 1 and 10 MHz are commonly used in diagnostic ultrasound techniques (Leighton 1994).

2.1.2 Wave Propagation

When acoustic waves travel through a material they do so at a specific velocity. This velocity is determined by the frequency and wavelength of the wave. Equation (2.1) describes the relationship between acoustic velocity, frequency, and wavelength.

\[ c = \nu \lambda \]  \hspace{1cm} (2.1)

where \( c \) is the acoustic velocity [m s\(^{-1}\)], \( \nu \) is the acoustic frequency [s\(^{-1}\)], and \( \lambda \) is the wavelength [m] of the acoustic wave. As previously mentioned, the speed of sound is affected by the characteristics of the material through which the sound is being propagated. If the sound propagates in a liquid or a gas, the speed of sound is a function of the bulk modulus of the material (Eq. 2.2):
\[ c = \sqrt{\frac{K}{\rho}} \]  

(2.2)

where \( K \) is the bulk modulus and \( \rho \) is the density. When sound waves propagate in the solid, the Young (or elastic) modulus is used instead. The relationship between the Young (\( E \)) and bulk modulus (\( K \)) is shown in Eq. (2.3) (McClements 1991).

\[ E = K + \frac{4}{3}G \]  

(2.3)

where \( G \) is the shear modulus. The change in acoustic velocity as a function of the material properties has been used to evaluate the chemical compositions of vegetable oils (McClements and Povey 1988a, b, 1992), to quantify the structural and mechanical properties of fats (Maleky et al. 2007), to evaluate the rheological behavior of xanthan/sucrose mixtures (Saggin and Coupland 2004a, b), and to evaluate ice formation in frozen food systems (Gülseren and Coupland 2007b).

Table 2.1 shows the speed of sound values in different materials. In general, the speed of sound is the lowest in gases with values in the range of 200–500 m s\(^{-1}\), followed by the speed of sound in liquids, with values in the range of 1,200–2,000 m s\(^{-1}\). The highest values of speed of sound are found in solids, with values in the range of 3,200–6,500 m s\(^{-1}\).

Acoustic waves propagate in the media through longitudinal or transversal waves that generate localized displacement of particles or molecules present in the material. These two types of waves differ in the direction of particle displacement that occurs during wave propagation. In longitudinal waves particles are displaced parallel to the direction of the wave, while in transversal waves particles are displaced perpendicular to the direction of the wave. Acoustic waves are usually longitudinal but they can be transversal when they propagate through solids. It is important to note here that when acoustic waves travel through a material they generate only local displacement of particles; there is no movement of particles from one point to the other. Instead, particles oscillate around their equilibrium position as a consequence of wave propagation from the source to the detector. To better understand this concept, Fig. 2.2 shows a typical acoustic wave and the relationship between acoustic pressure and particle displacement (Leighton 1994).

<table>
<thead>
<tr>
<th>Solids</th>
<th>Liquids</th>
<th>Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>( c ) (m s(^{-1}))</td>
<td>Material</td>
</tr>
<tr>
<td>Aluminum(^a)</td>
<td>6,400</td>
<td>Ethyl alcohol</td>
</tr>
<tr>
<td>Cork</td>
<td>500</td>
<td>Distilled water</td>
</tr>
<tr>
<td>Pyrex glass</td>
<td>5,640</td>
<td>Sea water</td>
</tr>
<tr>
<td>Gold</td>
<td>3,240</td>
<td>Mercury</td>
</tr>
<tr>
<td>Maple wood</td>
<td>4,110</td>
<td>Glycerol</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>5,790</td>
<td>Castor oil(^a)</td>
</tr>
</tbody>
</table>

\(^a\) Leighton (1994)
The first line of Fig. 2.2 shows particles in equilibrium position. When an acoustic wave travels from left to right in the direction shown by the arrow, particles move around their equilibrium position generating zones of compression and rarefaction. As already mentioned, no net displacement of particles is observed. The oscillation of particles results in gradients in the media where zones of high and low concentration of particles are observed. Highly concentrated zones of particles are observed when the media is compressed, while a low concentration of particles is observed in the rarefaction zones. The compression and rarefaction zones correspond to maximum and minimum amplitudes in the acoustic wave, respectively, as shown in the third line of Fig. 2.2 (Leighton 1994).

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2.1.3 Introduction to Ultrasonic Techniques

Within the ultrasound range, acoustic techniques can be categorized into different groups according to the frequency and power of operation. High frequency and low power techniques are classified into diagnostic and high frequency ultrasound, while low frequency and high power techniques are classified into power
ultrasound. Note that the category of diagnostic ultrasound includes techniques that use higher frequencies than those used by techniques included in the category of high frequency ultrasound. These techniques will be described in the following sections.

2.2 Diagnostic Ultrasound

Diagnostic ultrasound includes a series of pulse-echo techniques commonly used by the medical industry to evaluate the state of internal tissue structures (medical imaging). These are non-invasive, low power (<100 mW cm\(^{-2}\)), high frequency (1–10 MHz) techniques. Acoustic waves used for diagnostic applications are so low in intensity or power that they do not impart change to the physicochemical properties of the tissue.

Ultrasound is also used in the medical industry as a therapeutic tool. Low intensity (∼1 W cm\(^{-2}\)) ultrasound is used as a deep-heating agent and ultrasound with higher intensities (∼10 W cm\(^{-2}\)) can be used to treat oncological diseases. Finally, significantly higher power intensities (10\(^3\) W cm\(^{-2}\)) are used in short duration pulses to modify body tissues (Frizzell 1988).

2.3 High Frequency Ultrasound

High frequency ultrasound techniques use frequencies between 100 kHz and 1 MHz, which are lower than those used in diagnostic ultrasound. High frequency ultrasound also use low power levels and therefore they do not induce changes in the material. High frequency ultrasound has been used extensively in several food science applications including monitoring of crystallization of lipids (McClements and Povey 1987, 1988a; Singh et al. 2004; Saggin and Coupland 2002; Santacatalina et al. 2011; Martini et al. 2005a, b, c), characterizing edible oils and fats (McClements and Povey 1988b, 1992), predicting viscoelastic properties of the material (Saggin and Coupland 2001; 2004a, b; Maleky et al. 2007; Mert and Campanella 2007), characterizing emulsions and suspensions (McClements 1991; McClements et al. 1990; McClements and Povey 1989; Coupland and McClements 2001), monitoring crystallization of lipids in emulsions (Hodate et al. 1997; Kashchiev et al. 1998; Kaneko et al. 1999; Vanapalli and Coupland 2001; Gülseren and Coupland 2007a, b; McClements et al. 1993), monitoring dissolution and crystallization of carbohydrates (Gülseren and Coupland 2008; Yucel and Coupland 2010, 2011a, b), and monitoring gel formation (Benguigui et al. 1994; Audebrand et al. 1995; Corredig et al. 2004; Dwyer et al. 2005; Wan et al. 2007) to name a few. A significant advantage of this technique over other tools used to characterize materials is that it is non-invasive, non-destructive, and can be used in concentrated and opaque materials.
2.4 Power Ultrasound

Power ultrasound or high intensity ultrasound uses significantly lower frequencies than those used in diagnostic and high frequency ultrasound. Frequencies used in power ultrasound range between 20 and 100 kHz. When low frequencies and high power (10–10,000 W cm\(^{-2}\)) acoustic waves such as those used in these techniques travel through a medium they induce formation of cavities (Rastogi 2011; Bermudez-Aguirre and Barbosa Canovas 2011). Acoustic cavitation and the events associated with this phenomenon are responsible for inducing several physico-chemical changes in the material. These events will be discussed in detail in Chap. 5.

Power ultrasound is a highly invasive technique that uses high intensity acoustic waves to purposely change the properties of materials. Some examples of the use of power ultrasound include therapeutic medicine such as physiotherapy, chemotherapy, ultrasonic thrombolysis, and drug delivery (Mason 2011). Other common uses of power ultrasound include inducing crystallization of materials (sonocrystallization) and inducing or causing chemical reactions (sonochemistry) that would not occur in the absence of ultrasound (Petrit et al. 1994; Suslick et al. 1997; Gedanken 2004; Mason 1999; Kasai et al. 2008; Wu et al. 2008).

Sonocrystallization has been used extensively by industries including pharmaceutical (Luque de Castro and Priego-Capote 2007; Krishna et al. 2007; Miyasaka et al. 2006; Louhi-Kultanen et al. 2006; Manish et al. 2005; McCausland 2007), chemical (Mansour and Takrouni 2007; Bucar and MacGillivray 2007; Paradkar et al. 2006; Li et al. 2003, 2006; Ruecroft et al. 2005; Oldenburg et al. 2005; Kaerger and Price 2004; Cains et al. 1998) and food (Bund and Pandit 2007a, b).

In addition to the use of power ultrasound in sonochemistry and sonocrystallization, this technique has recently been used to change the physicochemical properties of proteins (Villamiel and de Jong 2000; Kresic et al. 2008; Jambrak et al. 2008, 2009; Ashokkumar et al. 2009; Martini et al. 2010; Zisu et al. 2010, 2011; Arzeni et al. 2012; Martini and Walsh 2012; Hu et al. 2013). Power ultrasound has been used in food protein suspensions to increase the clarity of whey suspensions, to increase protein solubility, to change suspension viscosity, to decrease particle size, and to narrow particle size distributions. The source and concentration of sonicated protein determine the nature of change induced by sonication.

The use of ultrasonic techniques has caught the attention of the industry given the many advantages offered. Some benefits include: (a) improvements in product quality, (b) reduction in food processing costs, (c) decreased processing times, (d) reduced chemical and physical hazards, (e) environmentally friendly and sustainable, and (f) scalable throughput (Patist and Bates 2008; Chemat et al. 2011).
References

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