1 Basic Principles of Ultrasound

Juan A. Gallego-Juárez[1,2]

[1] *Instituto de Tecnologías Físicas y de la Información (ITEFI), Consejo Superior de Investigaciones Científicas (CSIC), Madrid, Spain*

[2] *PUSONICS S. L, Arganda del Rey (Madrid), Spain*

Ultrasound in Food Processing: Recent Advances, First Edition. Edited by Mar Villamiel, José V. García-Pérez, Antonia Montilla, Juan A. Cárcel, and Jose Benedito.

1.1 Introduction

As is well known, *acoustics* is the science of elastic waves, a broad interdisciplinary field which comprises such diverse areas as life and earth sciences, engineering, and arts. It may be divided into three main branches according to the frequency spectrum and the hearing characteristics to which the human auditory system responds: *infrasound*, *sound*, and *ultrasound*.

Infrasound is the branch dealing with frequencies below the human hearing range (0–20 Hz), *sound* refers to the human audible range (20Hz–20kHz), and *ultrasound* covers the very wide range of elastic waves from 20 kHz up to the frequencies associated to wavelengths comparable to intermolecular distances (about 10^{12} Hz). The basic principles and equations of acoustics are used to explain the general behavior of waves in the three branches. Nevertheless, the special characteristic of the ultrasound and infrasound waves of being inaudible establishes a fundamental difference in their applications with respect to the audio frequency field. The applications and uses of ultrasound are totally different from those of infrasound due to the very large differences in their wavelength ranges, as wavelength is inversely proportional to frequency. Infrasound waves are very long waves (wavelengths in the range of meters) generated by some natural phenomena, such as earthquakes or volcanic eruptions, or by human processes, such as sonic booms or explosions. Ultrasound waves are very short waves (wavelengths in the range of centimeters to nanometers) generally generated by specifically designed technological sources and are applied in many industrial, medical, and environmental processes. However, the human use of ultrasound was long preceded by use by animals, for example bats and dolphins, who use ultrasound for navigation and communication.

Beside the range of frequency, the range of wave intensity broadly influences the phenomena related to the production, propagation, and application of acoustic waves. As a consequence, a sub-classification within each of the three branches of acoustics should be adopted related to the use of low- or high-intensity waves. In this way ultrasound may be divided into two areas, dealing respectively with *low-* and *high-intensity waves*. The boundary between low- and high-intensity waves is very difficult to pinpoint, but it can be approximately established for intensity values which, depending on the medium, vary between 0.1 W/cm^2 and 1 W/cm^2.

As mentioned earlier, the general feature of ultrasound is its short wavelength, which determines its applications. In fact the short wavelength implies a high degree of discrimination and a high concentration of energy, therefore ultrasonic waves can be used as a means of exploration, detection, and information, and as a means of action. They can also be used as a means of communication, particularly for propagation in water, where electromagnetic waves have many limitations. In exploration, detection, and information, ultrasonic signals are able to determine the characteristics and internal structure of the propagation media without modifying them. For action applications, ultrasonic waves of high intensity are able to produce permanent changes in the medium on which they act. As a means of communication an ultrasonic signal can be modulated and transmit information.

The applications in which ultrasound waves are used as a means of exploration, detection, and information constitute the area of *low-intensity ultrasound* or *signal ultrasound*. The applications in which the ultrasonic energy is used to produce permanent changes in the propagation medium constitute the area of *high-intensity ultrasound* or *power ultrasound*. One specific use of ultrasound for communication is *underwater acoustics*, where sonic as well as ultrasonic waves are used to detect submerged objects, and for echo ranging, depth sounding, etc.

Typical applications of low-intensity ultrasound include non-destructive testing (NDT), process control, and medical diagnosis. High-intensity applications include a great variety of effects such as cleaning, drying, mixing, homogenization, emulsification, degassing, defoaming, atomization, particle agglomeration, sonochemical reactions, welding, drilling etc. High-intensity ultrasound also plays an important role in medical therapy.

The history of ultrasound is a modern part of the history of acoustics. In fact, although some studies on high acoustic frequencies were carried out in the 19th century, the real history of ultrasound began in 1915 with Paul Langevin, a prominent French physicist at the School of Physics and Chemistry in Paris. During the First World War, France and Britain launched programs for submarine detection and for this purpose Langevin designed and constructed underwater ultrasonic transducers consisting of a quartz plate sandwiched between two metal pieces (Langevin, 1920a,b, 1924). Following Langevin's work, in the 1920s Wood and Loomis conducted interesting experiments with high-intensity ultrasonic waves (200–500 kHz), for example the formation of emulsions, flocculation of particles, etc. (Wood and Loomis, 1927). During the 1930s new effects related to the application of ultrasonic energy were discovered and more than 150 studies were published. In the period 1940–1970 the development of new transducer materials as well as rapid advances in electronics made the production of commercial ultrasonic systems possible. Since 1970, the field of ultrasonics has grown rapidly and presently ultrasound is considered an emerging and expanding field covering a wide range of applications in the industrial, medical, and environmental sectors. Behind any application of ultrasound there is a fundamental scientific basis and the corresponding technology for generation, propagation, and detection of the ultrasonic waves, therefore the development of each specific application requires knowledge of the related basic principles and technologies.

1.2 Generation and Detection of Ultrasonic Waves: Basic Transducer Types

Any device capable of generating and/or detecting ultrasonic waves is called an ultrasonic transducer. As is well known, a transducer converts energy from one form to another. The most common conversion is electrical to ultrasonic energy in the case of transmitters, and ultrasonic to electrical energy in the case of receivers. The main types of electrical transducers are piezoelectric, magnetostrictive, capacitive or electrostatic, and electromagnetic. There are other kinds of transducers that are actuated mechanically, such as whistles and sirens, but in practice they have only historical value.

Piezoelectric transducers are based on the piezoelectric effect and are by far the most commonly used transducers in ultrasonics, therefore we will cover them in more detail later.

Magnetostrictive transducers utilize the magnetostriction effect that is produced in ferromagnetic materials that change dimensions under the application of a magnetic field. Conversely, if the material is deformed as a result of an external perturbation a variation in its magnetic properties is observed. The classical materials that have this effect are iron, nickel, cobalt and their different alloys, and also ceramic materials consisting of cubic ferrites (Mattiat, 1971). Since the 1970s new magnetostrictive materials based on rare earth compounds have been developed with large magnetostrain and high energy density (Clark, 1988).

Capacitive or electrostatic transducers are flat condensers in which one electrode is a very thin membrane very close to the other rigid electrode. The application of an alternate voltage superimposed on a bias voltage means that the membrane moves at the same frequency as the alternate voltage. The use of these transducers dates back to the 1950s (Khul, 1954), but recently the application of micromachining techniques for manufacturing transducers has strongly promoted their development for high-frequency imaging applications (Oralkan *et al.*, 2002).

Electromagnetic transducers make use of the well-known interaction of the magnetic field of a permanent magnet and the alternate electric current in a moving coil to convert the electric oscillations in ultrasonic vibrations. The electromagnetic mechanism is now frequently used in electromagnetic acoustic transducers (EMAT) for non-contact ultrasonic NDT of metallic or ferromagnetic materials (Nakamura, 2012).

Mechanical transducers are only used as transmitters and generally produce high-amplitude vibrations. They don't require electrical activation but employ air or liquid jets to make the cavity vibrate at its natural frequency (whistles) or be interrupted by the rotation of the holes in a rotor, producing puffs of fluid at a certain frequency, thus generating sound waves (sirens). The use of such transducers is very limited and currently they have practically disappeared (Rozenberg, 1969; Allen and Rudnick, 1947).

The wide use of the piezoelectric transducers in ultrasonics requires a more detailed description of them. As is well known, piezoelectricity is the phenomenon produced in certain solid materials of the generation of an electric charge when a mechanical stress is applied, where the charge is proportional to the applied stress. This is the direct piezoelectric effect. There is a converse effect. An applied electric field produces a proportional strain, expansion or contraction depending on polarity. The piezoelectric effect was discovered in 1880 by Pierre and Jacques Curie by using quartz, tourmaline, and other crystals, and it was not used in practical transducers until the First World War, when Paul Langevin used crystal quartz to develop ultrasonic transducers for locating submarines. For more than two decades quartz and other natural and synthetic piezoelectric crystals (Rochelle salt, ammonium dihydrogen phosphate ADP, lithium sulphate, and ethylene diamine tartrate) were the only source of ultrasonic waves. Between 1941 and 1947, a series of studies on barium oxide–titanium oxide compositions conducted independently in the USA, the USSR, and Japan concluded with the discovery of the piezoelectric properties of poled ferroelectric barium titanate ceramics. This was the beginning of a remarkable development in polycrystalline ceramic materials which has continued to the present day. After barium titanate, lead niobate appeared in 1952 and a few years later (1954) lead zirconate titanate (PZT) was discovered by Jaffe (Jaffe *et al.*, 1971). This latter material marked a milestone in the development of piezoelectric ceramics because its strong and stable piezoelectric characteristics for ultrasonic transducers and its wide range of operating parameters. During the last 30 years PZT and related materials (PZT with various additives) have been the dominant piezoceramics in ultrasonic applications (industrial processing, NDT, medical diagnosis, underwater signaling, etc.) (Uchino, 2010). Recently, the requirement of using lead-free materials for environmental protection reasons has promoted the development of lead-free piezo-ceramics (Takenata, 2010; Pardo, 2015).

Figure 1.1 Piezoelectric ceramics.

The basic characteristic of ceramic materials is the ferroelectricity of the single crystals, that is, the presence of spontaneous electric moments in the crystals that are randomly distributed and can be oriented in a preferred direction by applying an external electric field. The application of an electric field produces a mechanical strain, the magnitude of which is proportional to the square of the applied field strength in such a way that the change in dimensions of the material is always in one direction regardless of the polarity of the electric field. However, by applying a permanent strong polarization field above the Curie temperature the ferroelectric ceramics become piezoelectric.

The choice of a piezoelectric material depends on the specific application of the transducer. Efficiency for emitters and sensitivity for receivers are fundamental characteristics that need to be maximized in ultrasonic transducers.

The electrical properties and dimensions of piezoelectric ceramics are dependent on the dielectric, piezoelectric, and elastic constants of the material. Several types (Figure 1.1) with different compositions and shapes of piezoelectric ceramics are commercially available. Each type is tailored towards the requirements of particular applications.

Composites of ceramics and polymers have also attracted much interest because of the potential that a multiphase material offers. Composites of piezoelectric ceramics and polymers are two-phase materials in which the ceramic produces the piezoelectric effect while the polymer phase reduces the density and permittivity of the material and increases elastic compliance. However, difficulties in their commercial production have limited their market.

Finally, piezoelectric polymers such as polyvinylidene fluoride (PVDF) are suitable for use as receivers in hydrophones.

In general, the piezoceramic element is the heart of a composite device and constitutes the actual transducer. Ultrasonic transducers can be classified into two main groups: *narrow-band* and *broad-band*. The bandwidth of a transducer is a measure of its sharpness of resonance and is the relation between the difference of the frequencies on each side of the center frequency, where the amplitude is 0.707 times the amplitude of the center frequency, and the center frequency. The bandwidth is the inverse of the quality factor (Q).

Narrow-band transducers (a few per cent bandwidth) are generally used for the generation of high-intensity ultrasound in the low frequency range (20–100 kHz). Broad-band transducers (30–70% bandwidth) are generally used in exploration, detection, and information applications ranging from NDT and medical imaging, using very short ultrasonic pulses (typically three or four cycles) and frequencies in the range 0.5–50 MHz, to measuring the propagation characteristics of a medium over a wide range of frequencies.

The basic narrow-band piezoelectric transducer for high-power applications is the well-known sandwich transducer, which is reminiscent of the Langevin transducer.

The sandwich transducer (Figure 1.2) is a half-wave resonant length-expander structure which, in a simple form, consists of a disc, or paired discs, of piezoelectric ceramics sandwiched between two identical metal blocks. The resonant frequency is determined by the dimensions and acoustic characteristics of the metal blocks and the ceramics. This basic construction is generally the driving engine of more complex power ultrasonic systems and in these cases is often known as the converter.

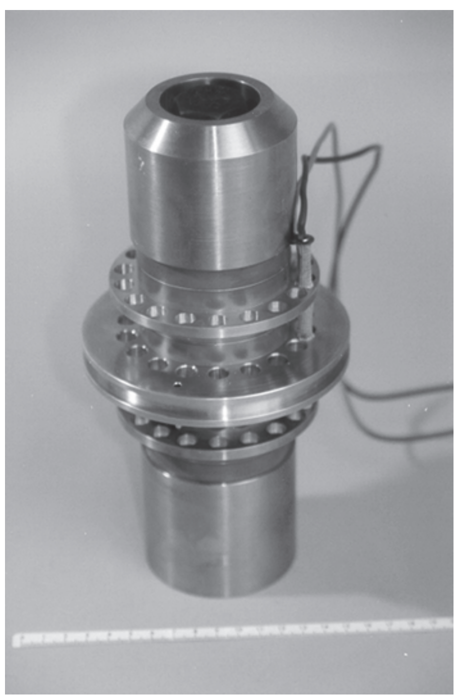

Figure 1.2 The piezoelectric sandwich transducer.

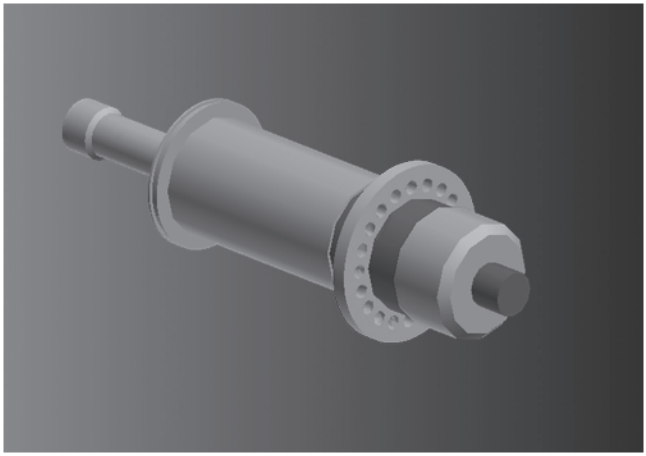

Figure 1.3 Basic structure of a power ultrasonic transducer with stepped horn for applications in solids.

High-intensity applications of ultrasonic energy in solids such as machining, soldering, welding, cutting, metal forming, etc., are based on mechanical effects as a result of particle motion. In these processing applications, the sandwich transducer is also used but is followed by a metallic transmission line of special shape which act as mechanical amplifier and ensures a high displacement at the working end (Figure 1.3). Such mechanical amplifiers or horns are resonant vibrating solid bars of different shapes, generally stepped, conical or exponential, that because of the conservation of momentum show different displacements at their two ends inversely proportional to their areas (Graff, 2015). Recently, micromachined silicon horns have been introduced in power transducers for biomedical applications (Ramkumar and Lal, 2012).

For high-intensity applications in liquids vessels of different geometries with a large number of sandwich transducers attached to the bottom and/or the walls are generally used. Such ultrasonic reactors can also be used as a flow system (Gogate and Pandit, 2015).

The generation of ultrasonic energy in gases has many problems due to the difficulties related to the low density, the low specific acoustic impedance, and the high absorption of these media. To obtain an efficient ultrasonic transmission and to produce high-pressure levels, it is necessary to achieve good impedance matching between the transducer and the gas, large amplitudes of vibration, and highly directional beams. There are very few airborne transducers based on piezoelectric ceramics and almost none of them seem to cover all the requirements mentioned above. In recent years, a new type of stepped-plate transducer (Figure 1.4a) has been developed in which these prerequisites have been attained. It essentially consists of an extensive circular plate of stepped shape driven at its centre by a piezoelectrically activated vibrator. The vibrator itself consists of a piezoelectric element of transduction in a sandwich configuration and a solid horn, which acts as a vibration amplifier. The extensive surface of the plate increases the radiation resistance and offers the vibrating system good impedance-matching with the medium. The elements of the transducer are calculated to be resonant at the working frequency. The special shape of the radiating plate allows the acoustic field to be tailored to obtain

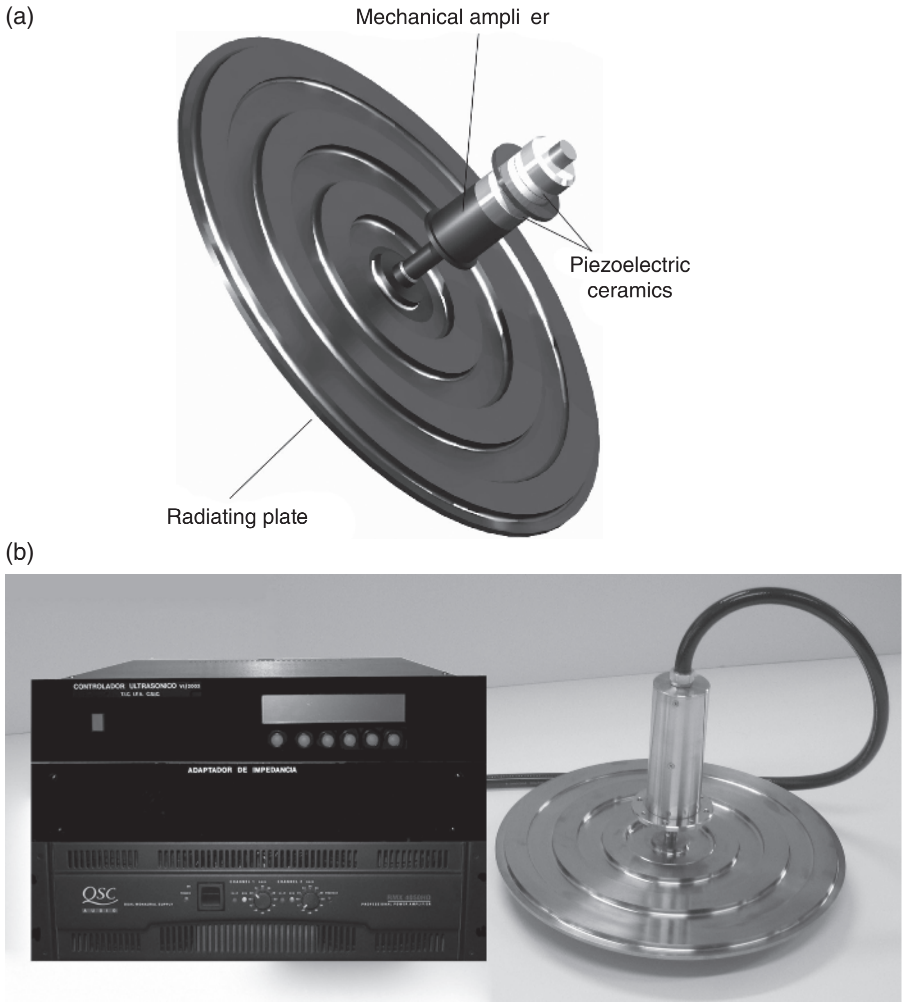

Figure 1.4 The stepped plate airborne transducer: (a) scheme of the basic structure and (b) picture of a real transducer with driving electronics.

high-directional, focusing or any other radiation pattern (Gallego-Juárez *et al.*, 2015a). Stepped-plate transducers, driven by an innovative electronic frequency control device (Figure 1.4b), are presently commercialized by the Spanish company Pusonics SL (www.Pusonics.es) and are used in several industrial and environmental processes (defoaming, drying, aerosol agglomeration and precipitation, etc.).

Broad-band transducers are required for applications involving short pulses where high resolution is desirable. Such transducers are used for producing and/or receiving an ultrasonic signal which, in turn, is used for detecting an obstacle, measuring a physical quantity or sensing the condition of some system. Medical diagnosis and NDT are the major application areas. Another group of applications is related to the measurement of diverse quantities such as temperature, velocity of a fluid, density,

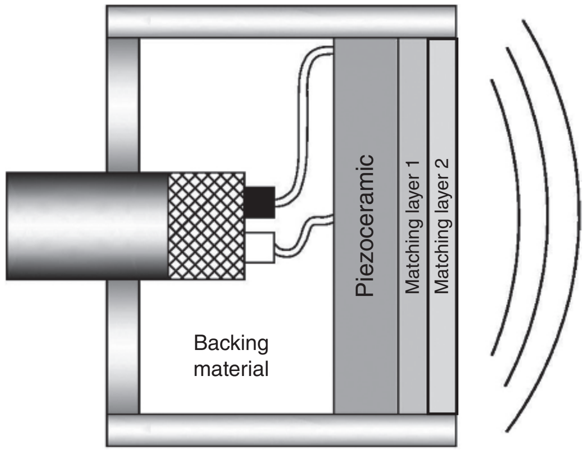

Figure 1.5 Basic structure of a broad-band ultrasonic transducer.

viscosity, thickness, position, etc. In general, the frequencies employed are in the range of some hundred kilohertz to several megahertz.

Unlike the need for high efficiency in narrow-band transducers, for broad-band applications it is often acceptable to use only a part of the total available acoustic energy, provided that the transducer is able to transform the electrical input waveform accurately into the corresponding ultrasonic wave and this, after being used, can be retransduced without distortion.

The basic structure of broad-band transducers consists essentially of a piezoelectric ceramic plate, vibrating in its thickness mode, bonded to a backing block on one of its faces and to one or several matching layers on the other (Figure 1.5). The backing block is made of a high-loss material exhibiting an acoustic impedance similar to that of the piezoceramic element. The effect of the backing is to dampen the vibration of the piezoceramic, reducing the mechanical Q and thus increasing the bandwidth. The matching layers are designed to act as transformers for matching the acoustic impedance of the piezoceramic to the medium. As is well known, the transmission of an acoustic wave from one medium to another through an intermediate medium depends on the acoustic impedance of each medium involved, as well as on the thickness of the intermediate medium. Materials for the transducer backing and the matching layers are usually mixtures of epoxy and powders of heavy metals, which are selected on the basis of their acoustic impedance and attenuation coefficient.

The basic transducer previously described is adequate for transmitting a short pulse into an object and recording the echoes from different scattering centers as a function of time. The image of internal stationary objects can therefore be obtained.

To achieve real-time images of moving objects, an array of multi-element transducers is used. Linear and annular configurations are generally employed for multi-element transducers. Linear array transducers consist of a large number of transducer elements of rectangular cross-section in a linear arrangement. Linear phased arrays which allow the ultrasonic beam to be electronically steered and focused are now widely available. In annular array transducers the transducer elements are arranged in concentric rings.

1.3 Basic Principles of Ultrasonic Wave Propagation

The propagation of ultrasound involves the generation of vibrations of the source that provides the elastic energy and the motion of the particles in the medium through which the waves are passing. Ultrasound as a wave motion obeys the well-known acoustical wave equations derived from the equation of motion, equations of conservation (mass and energy), and the equation of state or constitutive equations. A detailed discussion about the application of the wave equation to the different types of perturbations can be found in many general acoustic texts. Here the attention will be focused on the main basic specific characteristics of the ultrasound propagation in different media. The propagation of ultrasound waves in a medium may take different forms according to the nature of the medium and the characteristics of vibration generation. The most general types of propagation waves are longitudinal (compressional) and transverse (shear) waves. In longitudinal or compressional waves, particles oscillate in the direction of propagation while in transverse waves particles oscillate in the normal direction to the propagation. Longitudinal waves can propagate in any medium possessing bulk elasticity (solids and fluids) while transverse waves only propagate in media possessing elasticity of form (solids and some viscoelastic liquids). In addition to purely longitudinal and transverse waves there are waves that involve a combination of both longitudinal and transverse motion, such as flexural waves, surface waves, and torsional waves. Figure 1.6 illustrates the particle displacement of (a) purely longitudinal, (b) purely transverse, (c) flexural, and (d) extensional motions.

In gases and liquids the velocity of propagation of purely longitudinal or compressional waves is (Hueter and Bolt, 1955):

$$c = \sqrt{\frac{K}{\rho}} \tag{1.1}$$

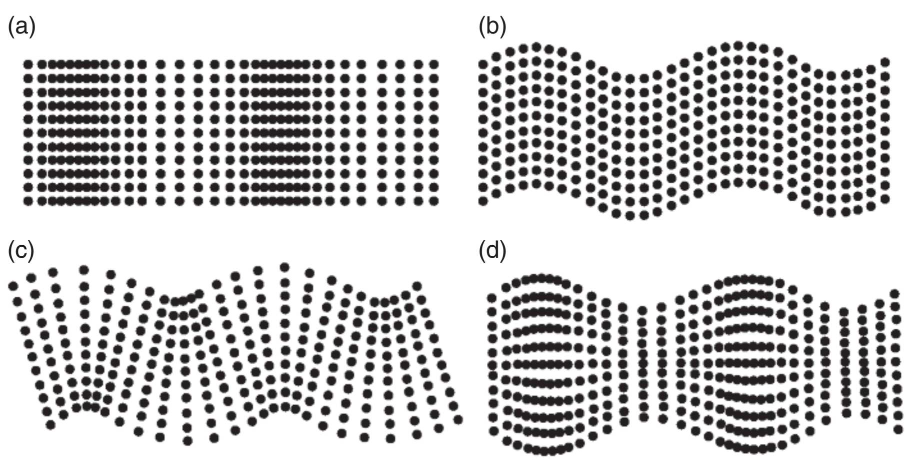

Figure 1.6 Particle displacement of different waves: (a) longitudinal, (b) transverse, (c) flexural, and (d) extensional.

where K is the modulus of bulk elasticity and ρ is the density. In infinite isotropic solids the velocity of purely longitudinal or compressional waves is:

$$c = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1.2}$$

where G is the shear modulus, E is Young's modulus, and ν is Poisson's ratio. The propagation velocity of purely transverse or shear waves is:

$$c = \sqrt{\frac{G}{\rho}} \tag{1.3}$$

From a point source in an infinite isotropic solid, two spherical wavefronts are propagated corresponding to the longitudinal and transverse motions, respectively. The greater velocity is associated to the longitudinal motion. In an anisotropic solid a point source generates three wavefronts, one longitudinal and two transverse, usually with different velocities.

Flexural waves may propagate in a solid medium having the shape of an infinitely long rod of small radius in comparison with the wavelength. Flexural waves may also propagate in plates of small thickness with respect to the wavelength. Extensional waves are longitudinal waves and may propagate in solid rods with diameters that are small relative to the wavelength. Torsional waves may propagate in solid rods or tubes. Surface waves (also known as Rayleigh waves) may propagate along a thin layer of the surface of an unbounded solid medium.

For the generation of any different type of wave the corresponding oscillation has to be transferred to the medium in the correct way.

An important concept to be considered in the generation and propagation of ultrasonic waves is the impedance of the acoustic system. This is a similar concept to the impedance in electrical systems but in acoustics is specified in different ways. In fact it is usual to talk of different types of impedance, such as acoustic impedance, specific acoustic impedance, and characteristic impedance. Acoustic impedance on a surface lying in a wave front is the complex ratio of the sound pressure to volume velocity (particle velocity multiplied by the surface area). The specific acoustic impedance is the complex ratio of the sound pressure to the particle velocity at a given point. The characteristic impedance of a medium is the specific acoustic impedance for a progressive plane wave propagating in a free field. In this case the specific acoustic impedance is given by the very simple relation $Z = \rho c$ that is generally used to characterize a medium acoustically.

The main quantities used to specify the acoustic field are the sound pressure p and the particle velocity u. However, in practical applications it is generally important to know the power that the wave is transferring. In order to illustrate the basic relations among the quantities that specify the wave and the power transported we can consider as example the simple case of the plane wave propagation. The sound power is the force exerted by the wave over an area (pS) multiplied by the particle velocity (u), therefore $W = pSu$. It should be noted that in a plane wave u and p are in phase therefore they can represent the root mean square values and from the definition of the specific acoustic impedance $Z = p/u$ the following relations are obtained:

$$W = upS = u^2 ZS = p^2 \frac{S}{Z} \tag{1.4}$$

The sound intensity, that is, the power transmitted through the unit area, will then be:

$$I = up = u^2 Z = \frac{p^2}{Z} \tag{1.5}$$

and as for plane waves, $Z = \rho c$:

$$I = \rho c u^2 = \frac{p^2}{\rho c} \tag{1.6}$$

The basic studies of the propagation of ultrasonic waves are generally referred to as the free-field propagation of plane or spherical waves in infinite homogeneous media. However, the real cases are frequently far removed from this situation because the ultrasonic field is generated in inhomogeneous media with boundary and interfaces. The original incident wave is therefore reflected and/or refracted by the inhomogeneities and boundaries, and consequently interferences are produced inside the limited medium. As a result the waves are no longer progressive but stationary or standing waves. The treatment of such waves is far more complex because it depends very much on the specific characteristics and configuration of each limited medium. The simplest case is the combination of two waves into a standing wave with pressure maxima spaced at half-wavelength intervals and pressure minima midway between. At the maxima the two component waves combine in phase and their pressures added, and at the minima the components are in counterphase and their pressures are subtracted. The relation between the pressure maxima and minima is known as the standing wave ratio (SWR). In a standing wave the intensity I is zero because there is no net flow of energy, but there is energy stored along the wave. In this case we can talk about the *energy density*. The kinetic energy has a maximum value at the instant of maximum velocity while the potential energy is zero, and inversely at the instant of zero velocity all the energy is potential. The total energy per unit volume remains constant during the cycle.

In ultrasonics, and in general in acoustics, decibels (dB) are commonly used to measure the levels of intensity and sound pressure. The decibel, one-tenth of a bel, expresses the ratio between two values of a physical quantity. For intensity a decibel is defined as 10 times the logarithm to the base 10 of the ratio of two intensities:

$$IL = 10\log\left(\frac{I}{I_{\text{ref}}}\right) \tag{1.7}$$

As the ratio of sound pressures is the square root of the corresponding intensity ratio, the number of decibels for this variable is expressed by 20 times the logarithm to the base 10 of the ratio of the two pressures:

$$PL = 20\log\left(\frac{p}{p_{\text{ref}}}\right) \tag{1.8}$$

One of these quantities is a reference value that for common usage has been standardized. In acoustics the reference value used for the sound pressure level (PL) in air and other gases is 2×10^{-5} Pa. For sound intensity in air the corresponding reference value is 10^{-12} W/m^2, which provides an identical numerical result for plane progressive waves.

In water an effective reference generally used for pressure levels is 0.1 Pa but this is not the only one. In other cases, as the measurement of the ship noise, it is used as a reference pressure 2×10^{-5} Pa, therefore in water it is always necessary to specify the reference of the corresponding pressure level. In addition, due to the difference in impedance between air and water (about 3560 times greater in water), a much higher power level is required in air to produce an identical pressure level in water. The levels of ultrasound in liquids are therefore not comparable with those in gases (Kinsler and Frey, 1962).

1.4 Basic Principles of Ultrasound Applications

1.4.1 Low-intensity Applications

Low-intensity applications mainly include the exploitation of the sensing capability of ultrasonic signals. In fact ultrasound can be propagated in any material medium and due to its short wavelengths has the ability to discriminate between very small differences in the mechano-elastic constitutive characteristics of the medium. The propagation of ultrasonic waves consists of a very high number of pressure cycles per second, which travel forward. Any change in the structure of the medium results in a change in the characteristics of the wave propagation, that is, velocity, attenuation, refraction, and reflection. The accurate measurement of these characteristics and their variations is therefore the basic principle of low-intensity applications.

Among the numerous applications of low-intensity ultrasound we will highlight the *non-destructive testing and evaluation of materials, imaging*, and *process control*.

1.4.1.1 Non-destructive Testing of Materials This is one of the most widespread applications of ultrasound. This application, which began in the 1930s using continuous waves, experienced rapid development with the utilization of the pulse technique. Essentially the application procedure involves passing a beam of ultrasound through the material under test and receiving the transmitted beam on the opposite side of the sample and/or the reflected beam by the face and/or by the imperfections or discontinuities of the material. Consequently, the basic pulse methods employed for testing are of two types: *through-transmission* and *pulse-echo*.

Through-transmission methods (Figure 1.7) involve the use of two transducers located at each side of the sample in such a way that one transducer receives the beam transmitted from the other. Discontinuities within the material medium, such as flaws, cracks, inclusions or changes of density, cause energy losses that characterize the detection. When longitudinal waves are used, the transmitter and receiver are located on opposite sides of the sample, one in front of the other. Trough-transmission is the oldest method and is still employed for testing but it has the disadvantage, in the case of longitudinal waves, of the need for access to both sides of the sample. When shear waves are applied (Figure 1.8) transmitter and receiver may be placed on the same side of the sample or on opposite sides but not in front. Trough-transmission methods are not suitable for determining the location of targets in the material.

In the pulse-echo technique (Figure 1.9) a short pulse of ultrasound waves is sent to the object and echoes come back from discontinuities, inclusions, defects or boundaries. One single transducer is used as emitter and receiver. The pulse-echo method allows the sample to be tested from one side only in all cases (longitudinal

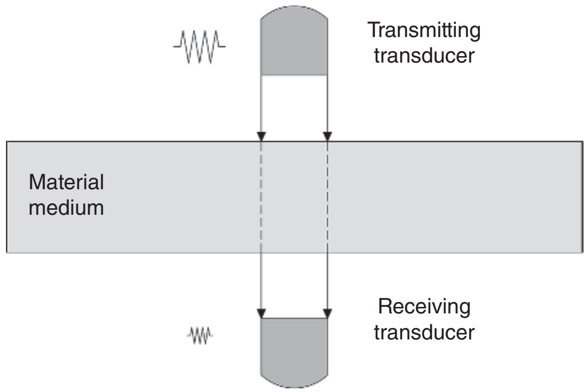

Figure 1.7 Through-transmission method with longitudinal waves for material exploration and evaluation.

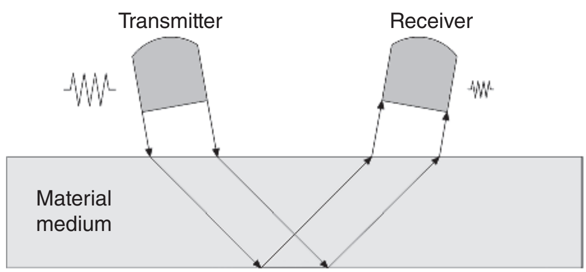

Figure 1.8 Through-transmission method with shear waves for material exploration and evaluation.

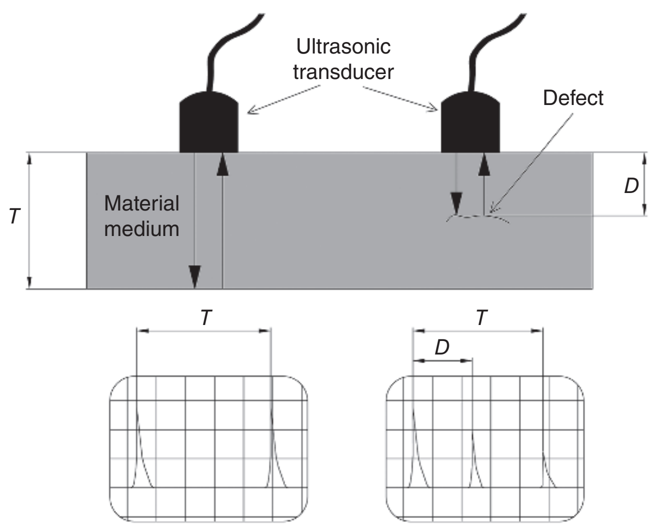

Figure 1.9 Pulse-echo technique for material exploration and evaluation.

or shear waves) and it is possible to determine the position of discontinuities and/or defects.

There are three typical arrangements for the inspection of materials to get a proper matching between the acoustic impedances of the transducer and the medium: *direct coupling*, *coupling by immersion* and *water jet coupling*. In direct coupling the transducer is applied to the surface of the sample using a fat or oil as adapter to match the impedances, avoiding the presence of air in the interlayer. In coupling by immersion both the sample and the transducers are immersed in water or another liquid that acts as adapter to the material medium to be explored. An intermediate technique uses an ultrasonic beam transmitted through a water jet. It should be noted that the smaller the difference between the specific acoustic impedances of two materials or two media, the greater the transmission through them, therefore ultrasound transmission to a solid through the air has traditionally been avoided. However, new techniques for making this type of transmission more efficient are presently being investigated in order to examine materials without contact with the transducer or any intermediate solid or liquid transmission medium (*air-coupled ultrasonic testing*).

The detection and characterization of inhomogeneities or inclusions in a material medium is done by the analysis of the echo signals they produce. Methods of signal analysis can be divided into two groups: *time amplitude* and *frequency analysis*. In time-amplitude analysis it is difficult to directly determine the size of an inhomogeneity based on signal amplitude. Frequency analysis (ultrasonic spectroscopy) allows more advanced signal processing and provides much more information on the tested medium.

Besides the application for detection of imperfections, propagation of ultrasonic waves is one of the most useful methods for non-destructive evaluation of materials through the correlations between ultrasonic velocities and attenuation, and the properties of materials. The velocity of sound is related to the elastic constants of a material while attenuation is linked to the internal structures and mechanisms producing losses of elasctic energy. In general, a variation in the velocity and attenuation of ultrasound in a material reveals a change in its properties. There are many different methods for measuring the velocity and attenuation of ultrasound in a material. The most common method for velocity measurement is measurement of the pulse transit time for a known propagation distance. Such measurement can be done by through-transmission or pulse-echo methods. Pulse methods are also useful for determining ultrasonic attenuation by measuring the relative amplitude of the pulse propagated through a known length of the specimen or the rate of decay of echo amplitude with distance (Breazeale *et al.*, 1981).

1.4.1.2 Ultrasonic Imaging The present remarkable role of ultrasound in medicine is mainly due to visualization techniques. The now familiar echography is a technique for seeing by sound that started to be explored in the early 1930s but was actually introduced in the 1970s. The capability of ultrasonic waves to propagate in opaque bodies and to detect different media as well as small inclusions by echos without producing negative effects in the body (ultrasound is a non-ionizing radiation) has given ultrasound a predominant role in many fields of medicine. This technique is also a means of visualizing objects in other opaque media. Echographic procedures are based on the pulse-echo technique already described for NDT. The main difference is that while in NDT you are looking for the detection of a small imperfection, in echography the objective is to obtain a full image of the interior of the opaque media, therefore to obtain high-quality imaging many echo signals are needed. As a consequence the transducers used are array transducers with a large number of elements that are electronically switched either as single elements or in groups. In this way it is possible to introduce different delays in the electrical signals driving the transducer elements to obtain different acoustic fields that are scanned on the part of the opaque medium to be visualized (Greguss, 1980).

Ultrasound is also used for measuring biological parameters. Techniques based on the Doppler effect are used to measure the speed of moving structures such as cardiac valves or blood flow. The speed is calculated by the frequency shift produced on the incident wave by the moving reflector (Goldstein and Pows, 1999).

Finally, in NDT and medical imaging the normal frequencies applied are in the range 1–10 MHz, although there is a tendency to increase the frequency in order to improve resolution.

1.4.1.3 Process Control Ultrasonic sensors are frequently employed in many industrial processes to obtain information about different variables. In general they work in a similar way to the NDT systems that transmit and receive ultrasonic waves, and extract information from the received signals that are processed and evaluated. There is a great variety of ultrasonic sensors for measuring distances, levels, flows, temperatures, pressures, concentration of components in gas and/or liquid mixtures, etc. Because of the wide range of processes and variables treated, the ultrasonic frequencies used vary from 20 kHz to gigahertz (Lynnworth and Mágori, 1999).

1.4.2 High-intensity Effects and Applications: Power Ultrasound

Power ultrasound is the part of ultrasound devoted to the study of high-intensity applications wherein the ultrasonic energy is used to produce permanent effects in the medium in which is applied.

The applications of high-intensity ultrasonic waves are generally based on the effective exploitation of the nonlinear phenomena associated with high amplitudes. The most relevant nonlinear phenomena related to high-intensity acoustic waves, which are briefly described below, are *wave distortion*, *acoustic saturation*, *radiation pressure*, *acoustic streaming*, *cavitation in liquids* and the *formation and motion of dislocations in solids*.

Wave distortion. For a high-amplitude wave the propagation velocity is a function of the local particle velocity, therefore it varies from point to point on the waveform. As a consequence, the profile of the wave gradually changes up to a certain distance where it becomes multi-valued, which implies that a discontinuity or shock is formed. The propagation path of an original sinusoidal wave of finite amplitude in a fluid may be divided into three regions (Figure 1.10): the first extends up to the *shock formation*, the second region corresponds to the *formation and propagation of a relatively stable sawtooth* wave, and the third is known as *old age region*, where nonlinear effects are balanced by ordinary absorption and the wave becomes again sinusoidal.

Acoustic saturation. A direct consequence of wave distortion is acoustic saturation, a phenomenon which limits the real acoustic energy that it is possible to transport at a certain distance from the source. In fact, as the wave distortion increases when

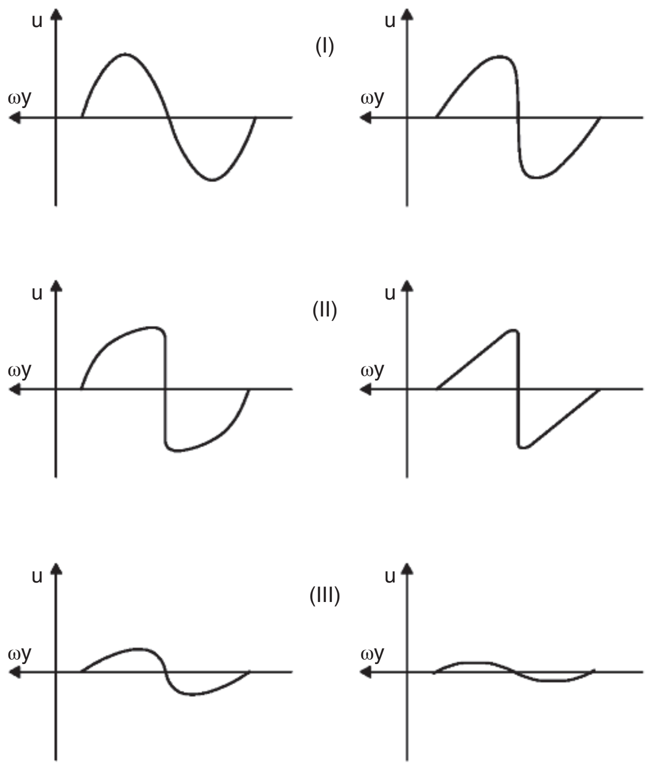

Figure 1.10 Evolution stages of the waveform in the propagation of a high-intensity wave at different distances of the source. I, Shock wave formation; II, sawtooth wave formation; III, old age region (returns to sinusoidal wave).

the source amplitude increases, the wave energy is transferred to higher-order harmonics, which are absorbed more intensely, causing an excess of attenuation of the wave, which compensate any increase in the wave amplitude at the source (Figure 1.11). There thus exists a limiting value of the sound pressure level that can be reached at a fixed distance from the source in a given medium (Gallego-Juárez and Gaete-Garretón, 1983).

Radiation pressure. Steady forces on obstacles and interphases are produced related to the change in the momentum of a wave at a target (Beyer, 1978). The action of these forces represents one important mechanism in many effects of ultrasonic waves in multiphase media. Figure 1.12 shows a radiation pressure effect at an air/water interface.

Acoustic streaming. Acoustic streaming is a phenomenon in which steady fluid flows are induced by high-amplitude ultrasonic waves in the free acoustic beam and near obstacles (Figure 1.13). Acoustic streaming seems to be mainly induced by radiation forces set up by absorption. Streaming can have a considerable influence on a variety of ultrasonic effects involving mass and heat transfer (Beyer, 1997).

Cavitation in liquids. Cavitation is the main phenomenon produced by high-intensity ultrasonic waves in a liquid. Cavitation may be defined as the formation, pulsation, and/or collapse of vapor or gas cavities in a liquid under acoustic stresses. There are two types of cavitation: *stable* and *transient*.

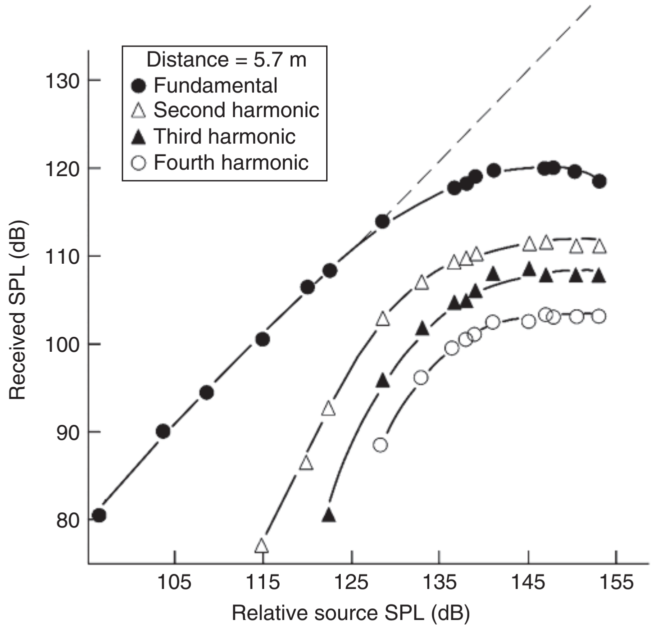

Figure 1.11 Acoustic saturation in the propagation of a high-intensity wave.

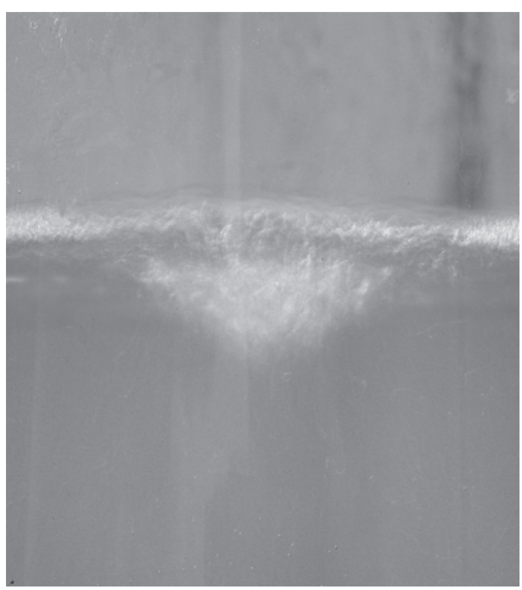

Figure 1.12 Radiation pressure effect at an air–water interface.

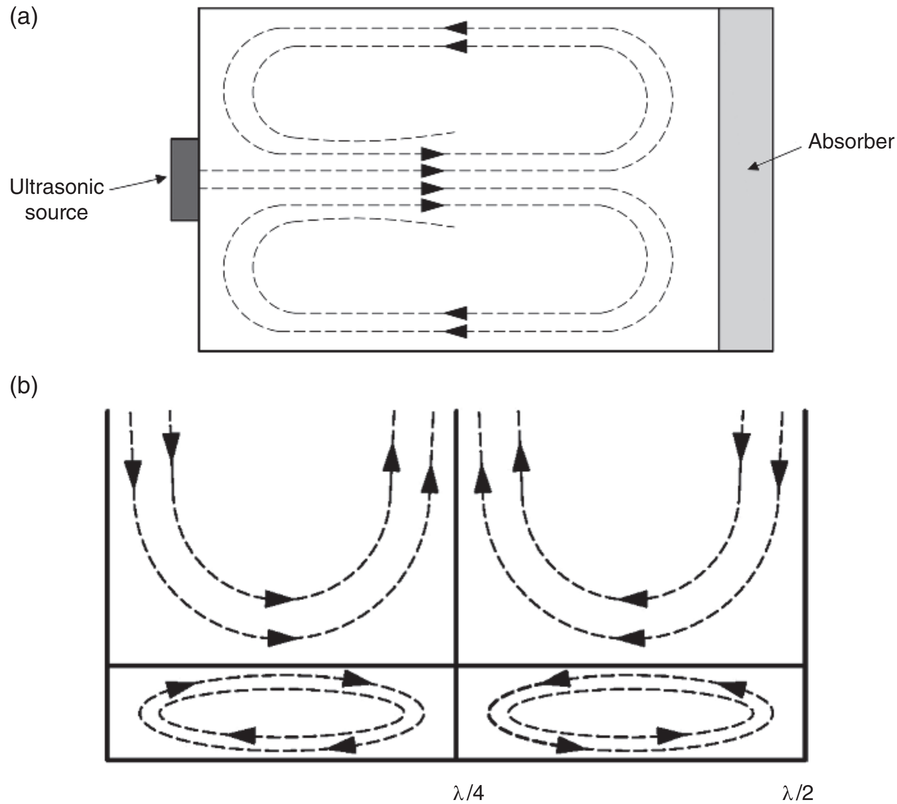

Figure 1.13 Acoustic streaming: (a) traveling wave over a cylindrical container and (b) standing wave and microstreaming near a wall.

Stable cavitation is usually produced at moderate acoustic intensities and the bubbles inside the liquid oscillate, generally in a nonlinear way, around their equilibrium size and may grow, trapping the dissolved gas. The second type of cavitation, known as transient or inertial cavitation, is generated under high-intensity acoustic fields. During the negative pressure half-cycle, the bubble expands to several times its original size. Then, during the compression half-cycle the bubble collapses violently, forming jets and shock waves. Pictures of the collapsing bubble have been obtained by Lauterborn and collaborators under different conditions (Lauterborn and Mettin, 2015). The collapsing bubbles produce very high temperatures (thousands of degrees) and pressures (thousands of atmospheres), which are important in many ultrasonic effects. The high pressures produce erosion, dispersion, and mechanical rupture while the high temperatures are responsible for sono-luminiscence and sonochemical effects.

Formation and motion of dislocations in solids. Finally, it should be mentioned that high-intensity ultrasonic waves may affect the structure of solids by setting the dislocations to vibrate. As a consequence, fatigue and rupture of the material may occur. Such effects may be useful in different processes where structural changes in solids have to be induced (Campos-Pozuelo *et al.*, 2007).

As a consequence of these nonlinear phenomena a series of mechanisms may be activated by ultrasonic energy, such as heat, agitation, diffusion, interface instabilities, friction, mechanical rupture, chemical effects, etc. These mechanisms can be used to produce or enhance a wide range of physical and chemical processes. Physical processes are mainly ascribed to the mechanical effects of the high-intensity waves in any medium, while chemical processes refer to the chemical effects induced by ultrasonic cavitation in liquids. The latter processes are included in the term *sonochemistry*. The general term for the whole area is *sonoprocessing* or *ultrasonic processing*.

The best-known ultrasonic processes are plastic and metal welding, machining, metal forming, etc., in solids and cleaning, atomization, mixing, homogenization and emulsification, defoaming, drying and dewatering, extraction, degassing, bioremediation, particle agglomeration, and sonochemical reactions in fluids.

Those applications that may have more impact in the food sector will be described here. The application of power ultrasound to food processing technology is one of the most promising fields for the future of ultrasound. The clean action of ultrasonic energy as a mechanical, non-contaminant, non-ionizing radiation plays a defining role in the continuous search for finding safer and higher-quality production methods.

1.4.2.1 Cleaning Cleaning of materials is one of the oldest and best known applications of high-intensity ultrasound. The cleaning action of ultrasonic energy is mainly due to cavitation and streaming. The collapsing cavities develop shock waves and very high temperatures, which favor the separation of the soiled material from the dirty solid. Such action may occur even in the small pores of the solid material, producing very effective cleaning. In addition, the ultrasonic energy produces liquid agitation, which helps the dispersion of contaminants (Fuchs, 2015).

1.4.2.2 Atomization Ultrasonic energy may produce liquid atomization. The production of fine droplets by ultrasound may be attributed to radiation pressure and the formation of capillary waves on the surface of the liquid. The droplet size is related to the frequency. Ultrasound is used in the formation of fogs or mists with a fine and uniform distribution of droplet size (Gogate, 2015).

1.4.2.3 Mixing, Homogenization, and Emulsification Power ultrasound is effective in obtaining uniform solid/liquid and liquid/liquid dispersions. The basic mechanisms that enhance this process are cavitation and streaming. The high stresses produced by bubble collapse impinge on the particles, making them smaller and compelling them to mix. Stable emulsions of immiscible liquids and dispersions of particles in liquids have been obtained by ultrasound without the use of additives (Delmas and Barthe, 2015).

1.4.2.4 Defoaming Foams are produced in many processes and generally are an unwanted by-product that causes difficulties in process control and product manufacture. A typical case is in the fermentation industry, where foam is one of the main problems. Classical methods for controlling foams, frequently produced in the manufacture of food and beverages, employ chemical anti-foaming agents, which may be responsible for product contamination. High-intensity ultrasonic waves are a novel, clean, and effective way of breaking down foam bubbles. Although the mechanisms for acoustic foam destruction are still not clear, experimental work shows that radiation pressure and resonance frequency are determinant parameters. Ultrasonic defoaming systems operating at frequencies of 21 and 26 kHz are currently available (Gallego-Juárez *et al.*, 2015b).

1.4.2.5 Drying and Dewatering Dehydration is a method of preserving food that conventionally is performed either through hot-air, which can produce deteriorative changes in products, or via freeze-drying, which maintains food quality, but is expensive. Ultrasonic dehydration via airborne radiation or in direct contact with food products has been proven to be an attractive alternative for separating moisture from food. The food material is subjected to high ultrasonic stresses, which produce a kind of 'sponge' effect and quick migration of moisture through natural channels. In addition, the production of ultrasonic cavitation inside the liquid may help the separation of the strongly attached moisture. Moreover, ultrasound has great potential for intensifying low-temperature drying. Ultrasonic drying maintains the quality of food products (García-Pérez *et al.*, 2015).

1.4.2.6 Supercritical Fluid Extraction Assisted by Ultrasound Supercritical fluid extraction (SFE) is a separation process based on the contact of a product containing the extractable compound with a solvent under supercritical conditions. Such a process is considered very useful but has slow dynamics. The beneficial effect of ultrasound in SFE is the enhancement of the penetration of the solvent into the product by the action of the radiation pressure, microstreaming and agitation. The application of ultrasound in SFE has been successfully tested on the extraction of several products (Riera *et al.*, 2010).

1.4.2.7 Bioremediation Ultrasonic energy irradiated into a biological material at high intensity may produce cellular destruction. The mechanisms for this are mainly cavitation and streaming, giving rise to mechanical and thermal effects. The application of ultrasound can therefore accelerate and improve bioprocesses such as sterilization of food for thermal treatment (thermosonication) and altering enzyme characteristics (Virkutyte, 2015).

1.4.2.8 Particle Agglomeration Suspended airborne particles, especially very fine particles, may be collected by agglomerating them. High-intensity ultrasonic fields applied to an aerosol may induce interaction effects among suspended particles, giving rise to collisions and agglomerations resulting in larger particles that can be more easily collected or precipitated (Riera *et al.*, 2015).

1.4.2.9 Sonochemical Processes Sonochemical reactions are mainly based on the very high temperatures and pressures produced by cavitation and agitation due to streaming. The treatment of the nature and applications of sonochemical reactions is a very wide field known as sonochemistry and covers applications in chemical synthesis, electrochemistry, water treatments, and fabrication of nanomaterials (Tagliapietra *et al.*, 2015).

1.5 Conclusions

The use of ultrasound in food technology is a very promising area that has not been sufficiently explored. This is particularly shocking bearing in mind that ultrasound is a non-ionizing, non-contaminating, green mechanical energy that is sustainable. The slow introduction of ultrasonic technology in food processing is probably due both to technical problems related to scaling up the ultrasonic systems and lack of knowledge of the power of ultrasound in the food area. However, this situation started to change in the early 1990s (Povey and Mason, 1998). Ultrasound technologies are now emerging in the food sector, therefore the objective of this introductory chapter is give an overview of the basic principles of ultrasound to help food sector specialists understand the mechanisms that can be exploited in ultrasonic energy applications. In addition, the references give the reader the opportunity to deepen their knowledge of each specific topic.

Acknowledgments

This chapter has been written in the framework of the Project DPI 2012-37466-C03-01 of the Spanish Ministerio de Economía y Competitividad. The author is grateful to Florence Buisson and Alberto Pinto for their help in the preparation of the manuscript and drawings.

References

Allen, C.H. and Rudnick, I. (1947) A powerful high frequency siren. *Journal of the Acoustical Society of America* **19**, 857–865.

Beyer, R.T. (1978) Radiation pressure – the history of a mislabeled tensor. *Journal of the Acoustic Society of America* **63**, 1025–1030.

Beyer, R.T. (1997) Nonlinear acoustics. In *Acoustical Society of America*, pp. 239–268, Woodbury.

Breazeale, M.A., Cantrell, J.H. Jr., and Heyman, J.S. (1981) Ultrasonic wave velocity and attenuation measurements. In *Methods of Experimental Physics,* Volume 19, *Ultrasonics* (ed. P.D. Edmonds), pp 67–135, Academic Press, London.

Campos-Pozuelo, C., Vanhille, C., and Gallego-Juárez, J.A. (2007) Nonlinear elastic behavior and ultrasonic fatigue of metals. In *Universality of Nonclassical Nonlinearity* (ed. P.P. Delsanto), pp. 443–464, Springer, New York.

Clark, A.E. (1988) Highly magnetostrictive rare earth compounds for high power acoustic projectors. In *Power Sonic and Ultrasonic Transducers Design*, (eds B. Hamonic and J.N. Decarpigny), pp 43–99, Springer-Verlag, Berlin.

Delmas, H. and Barthe, L. (2015) Ultrasonic mixing, homogenization, and emulsification in food processing and other applications. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 757–792, Woodhead Publishing, Cambridge.

Fuchs, F.J. (2015) ltrasonic cleaning and washing of surfaces. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 577–609, Woodhead Publishing, Cambridge.

Gallego-Juárez, J.A. and Gaete-Garretón, L. (1983) Propagation of finite-amplitude ultrasonic waves in air. Spherically diverging waves in the free field. *Journal of the Acoustic Society of America* **73**(3), 761–767.

Gallego-Juárez, J.A., Rodriguez, G., Acosta-Aparicio, V.M., Riera, E. and Cardoni, A. (2015a) Power ultrasonic transducers with vibrating plate radiators. In *Power Ultrasonics: Applications of High-intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 159–193, Woodhead Publishing; Cambridge.

Gallego-Juárez, J.A., Rodriguez, G., Riera, E., and Cardoni, A. (2015b) Ultrasonic defoaming and debubbling in food processing and other applications. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 793–814, Woodhead Publishing, Cambridge.

García-Pérez, J.V., Carcel, J.A., Mulet, A., Riera, E., and Gallego-Juárez, J.A. (2015) Ultrasonic drying for food preservation. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 875–910, Woodhead Publishing, Cambridge.

Gogate, P.R. (2015) The use of ultrasonic atomization for encapsulation and other processes in food and pharmaceutical manufacturing. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 911–936. Woodhead Publishing, Cambridge.

Gogate, P.E. and Pandit, A.B. (2015) Design and scale-up of sonochemical reactors for food processing and other applications. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 725–755. Woodhead Publishing, Cambridge.

Goldstein, A. and Pows, R.L. (1999) Medical ultrasonic diagnostics. In *Ultrasonic Instruments and Devices* (ed. E.P. Papadakis), pp 46–191, Academic Press, San Diego.

Graff, K.F. (2015) Power ultrasonic transducers: principles and design. In *Power Ultrasonics: Applications of High-Intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 127–158, Woodhead Publishing, Cambridge.

Greguss, P. (1980) *Ultrasonic Imaging*, Focal Press, London.

Hueter, T.F. and Bolt, R.H. (1955) *Sonics*, John Wiley & Sons, New York.

Jaffe, B., Cook, W.R. Jr., and Jaffe, H. (1971) *Piezoelectric Ceramics*, Academic Press, London.

Khul, W., Schodder, G.R., and Schröderl, F.K. (1954) Condenser transmitters and microphones with solid dielectric for airborne ultrasonics. *Acustica* **4**, 520–532.

Kinsler, L.E. and Frey, A.R. (1962) *Fundamentals of Acoustics*, John Wiley and Sons, New York.

Langevin, P. (1920a) French Patent Nr 502913.

Langevin, P. (1920b) French Patent Nr 505703.

Langevin, P. (1924) French Patent Nr 575435.

Lauterborn, W. and Mettin, R. (2015) Acoustic cavitation: bubble dynamics in high-power ultrasonic fields. In *Power Ultrasonics: Applications of High-intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 37–78, Woodhead Publishing, Cambridge.

Lynnworth, C.L. and Mágori, V. (1999) Industrial process control sensors and systems. In *Ultrasonic Instruments and Devices* (ed. P. Papadakis), pp. 275–470, Academic Press, San Diego.

Mattiat, O.E. (ed.) (1971) *Ultrasonic Transducer Materials*, Plenum Press, New York.

Nakamura, K. (ed.) (2012) *Ultrasonic Transducers*. Woodhead Publishing, Cambridge.

Oralkan, O., Ergun, S.A., Jojnson, J.A., Karaman, M., Demirci, U., Kaviani, K., Lee, T.H. and Khuri-Yakub, B.T. (2002) Capacitive micromachined ultrasonic transducers: next-generation arrays for acoustic imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **49**(11), 1596–1610.

Pardo, L. (2015) Piezoelectric ceramic materials for power ultrasonic transducers. In *Power Ultrasonics: Applications of High-intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp 101–125, Woodhead Publishing, Cambridge.

Povey, M.J.W. and Mason, T.J. (eds) (1998) *Ultrasonics in Food Processing*, Blackie Academic and Professional, London.

Ramkumar, A. and Lal, A. (2012) Microscale ultrasonic sensors and actuators. In *Ultrasonic Transducers* (ed. K. Nakamura), pp. 572–618, Woodhead Publishing, Cambridge.

Riera, E., Blanco, A., García, J., Benedito, J., Mulet, A., Gallego-Juárez, J.A., and Blasco, M. (2010) High-power ultrasonic system for the enhancement of mass transfer in supercritical CO_2 extraction processes. *Ultrasonics* **50**, 306–309.

Riera, E., González-Gómez, I., Rodriguez, G., and Gallego-Juárez, J.A. (2015) Ultrasonic agglomeration and preconditioning of aerosol particles for environmental and other applications. In *Power Ultrasonics: Applications of High-intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp. 1023–1058, Woodhead Publishing, Cambridge.

Rozenberg, L.D. (ed.) (1969) *Sources of High-intensity Ultrasound*, Plenum Press, New York.

Tagliapietra, S., Calcio Gaudino, E., and Cravotto, G. (2015). The use of power ultrasound for organic synthesis in green chemistry. In *Power Ultrasonics: Applications of High-intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp 997–1022, Woodhead Publishing, Cambridge.

Takenata, T. (2010) Lead-free piezo-ceramics. In *Advanced Piezoelectric Materials: Science and Technology* (ed. K. Uchino), pp. 130–170, Woodhead Publishing, Cambridge.

Uchino, K. (ed.) (2010) *Advanced Piezoelectric Materials: Science and Technology*, Woodhead Publishing, Cambridge.

Virkutyte, J. (2015) The use of power ultrasound in biofuel production, bioremediation, and other applications. In *Power Ultrasonics: Applications of High-intensity Ultrasound* (eds J.A. Gallego-Juárez and K.F. Graff), pp.1095–1122, Woodhead Publishing, Cambridge.

Wood, R.M. and Loomis, A.I. (1927) The physical and biological effects of high-frequency sound waves of great intensity. *Philosophical Magazine* **4**(22), 416–436.