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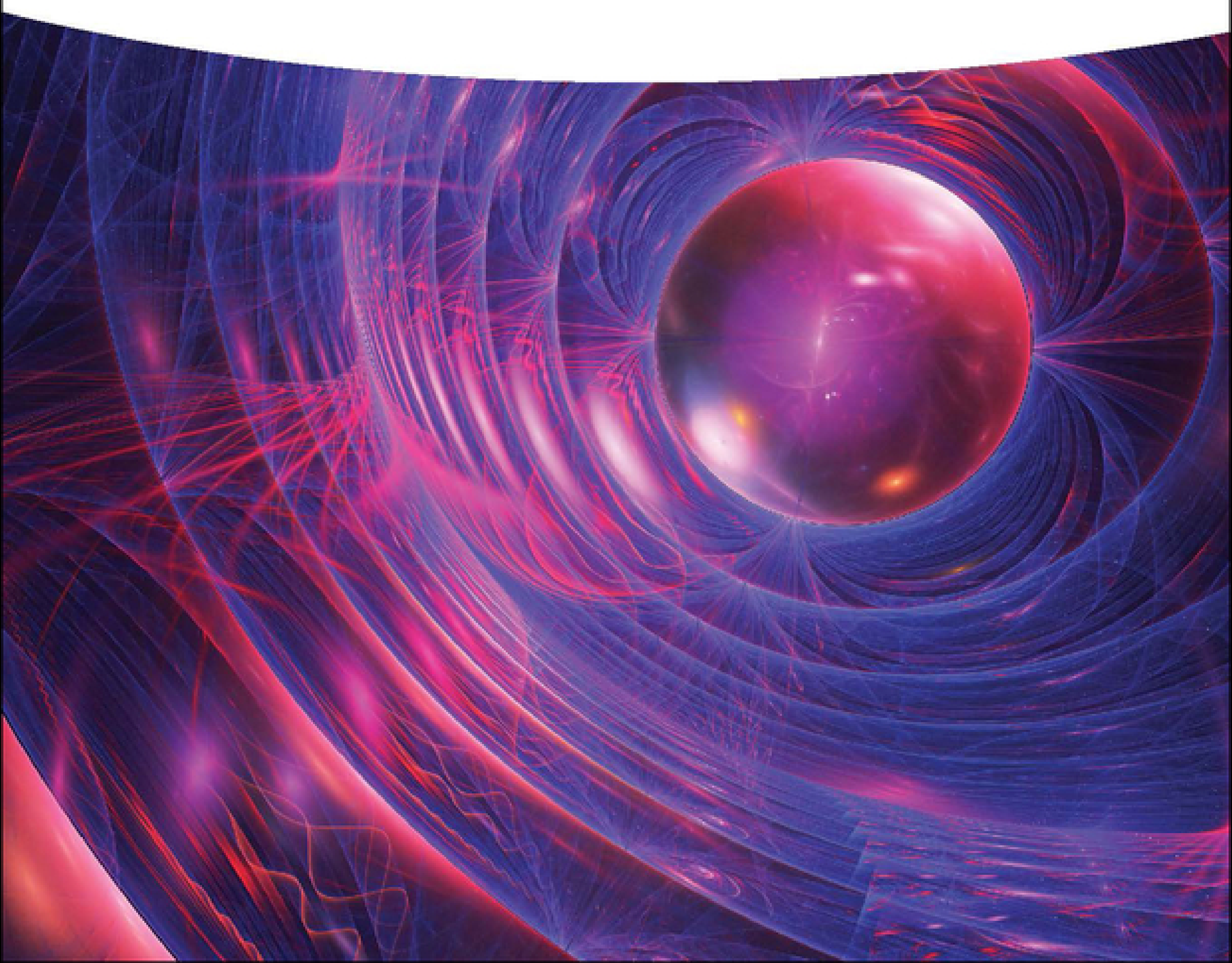
Edited by Adem Ozcelik, Ryan Becker,
and Tony Jun Huang

# Acoustic Technologies in Biology and Medicine



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# Preface

Acoustic technologies have played an increasingly significant role in both biology and medicine, empowering scientists and clinicians to explore and understand the intricate workings of living organisms and develop innovative diagnostic and therapeutic approaches. From ultrasound imaging to acoustic tweezers, from acoustic biosensors to acoustic stimulation, acoustic technologies have become indispensable tools in the arsenal of researchers and practitioners in these fields.

*Acoustic Technologies in Biology and Medicine* is designed to be a cornerstone reference bridging the rapidly advancing acoustic technologies with state-of-the-art applications in biology and medicine. The research in acoustics for biology and medicine requires a multidisciplinary approach involving fluid mechanics, physics, chemistry, electronics, and the life sciences. The burgeoning success and eminence of this field is fueled by the realization of groundbreaking technological innovations and impactful solutions addressing significant biological problems. Thus, it is imperative to present this field to a diverse audience spanning multiple engineering disciplines and the life sciences, targeting their involvement and education on the basic principles, breadth of technologies, and interdisciplinary applications of the acoustics. In this respect, *Acoustic Technologies in Biology and Medicine* adopts a unique role and context to introduce the graduate students and professionals from a broad range of backgrounds to this active research field, aiming to increase the synergy and interaction between the engineers and life scientists.

The book takes an interdisciplinary approach by covering the mechanistic and physical basics, as well as the applications. First, the book covers the underlying physical and theoretical principles of acoustic technologies. This aims to help the reader grasp the fundamental principles of acoustics. Second, different technologies of acoustic systems, including bulk and surface acoustic wave-based platforms, acoustic imaging, acoustic sensors, and acoustic levitators, are discussed. A clear understanding of the principles, advantages, and disadvantages of different acoustic technologies is crucial for evaluating and determining which acoustic methods are most suitable for particular biological applications. Third, state-of-the-art applications of acoustics in biology and medicine are presented. These applications include single cell and organism manipulation, acoustic biosensing, cancer cell isolation (liquid biopsy), cell/tissue stimulation and ablation, micro-robot actuation, acoustic imaging, and drug delivery.

The book is intended for a broad audience, including researchers and students in physics, biology, and engineering, as well as clinicians and practitioners in medicine. It is our hope that this book will provide a useful reference and inspire further research and innovation in the exciting and rapidly evolving field of acoustic technologies in biology and medicine.

February 28, 2023
Durham, NC, USA

*Dr. Adem Ozcelik*
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# 1

# Fundamentals of Acoustic Wave Generation and Propagation

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## 1.1 Introduction

### 1.1.1 Acoustic or Sound Waves

The use of acoustic technologies is widespread, from radio frequency (RF) surface acoustic wave (SAW) filters in most telecommunication devices and nondestructive testing (NDT) of solid parts in expensive machineries to ultrasonic imaging of fetuses during pregnancy and of joints and bones in case of injuries. At the heart of any acoustic technology are sound waves at work – a combination of pressure and velocity fluctuations propagating through a medium. The terms "acoustic" or "sound" waves are interchangeably used. Since "sound" is commonly associated with hearing audible acoustic waves as perceived by the human auditory organs, it would be restrictive to limit the term sound to human perception only, the audible frequency range of 20 Hz to 20 kHz (Figure 1.1). Dogs and cats can even hear much higher-frequency ultrasound waves, whereas elephants via their feet can sense very low-frequency seismic vibrations propagating long distances across the land, i.e. infrasound. The ability of whales and bats to echolocate their targets at much higher frequencies of up to 200 kHz is also well known. Moreover, the use of MHz frequency waves in NDT and GHz frequency waves in SAW filters further broadens the scope of sound/acoustic waves. Therefore, any periodic pressure/velocity fluctuation in a solid, liquid, or gaseous media over a wide range of frequencies ($10^0$–$10^9$ Hz) can be safely called a sound/acoustic wave [1].

### 1.1.2 Dominos Effect

In an acoustic wave, the localized pressure at any given point within the medium oscillates between the maximum and minimum pressure values, linked to regions

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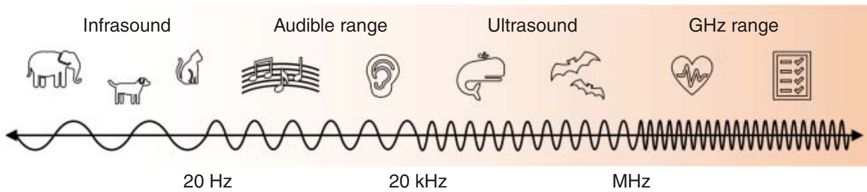


**Figure 1.1** Categorization of acoustic waves based on frequency range.

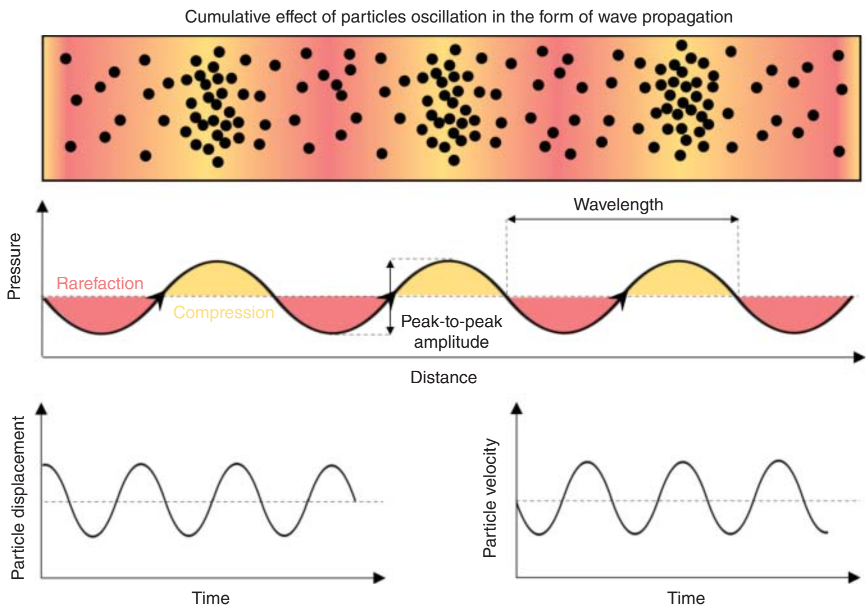


**Figure 1.2** Particle oscillation in a medium because of an acoustic wave propagation.

of compression and rarefaction, respectively (Figure 1.2). Any particle of the discretized medium, without moving along the propagating wave, will vibrate about a mean position with an oscillating velocity field. Propagation of an acoustic wave with these oscillating pressure and velocity fields through a medium can be understood by a simple analogy of a stack of falling dominoes, where the disturbance originating from one end of the dominoes' stack reaches the opposite end in no time, even without a single domino piece significantly moving away from its original position. Here, the average velocity of an individual domino is related to the particle velocity of the medium, whereas the disturbance moving across the stack is analogous to wave propagation. It is important to distinguish the oscillating particle velocity from the velocity of wave propagation [2].

### 1.1.3 Elastic vs Inelastic Waves

Acoustic waves under discussion are broadly categorized as elastic waves since they need an elastic medium to propagate. For an acoustic wave propagation, as the particles of the elastic medium move about an equilibrium position, the velocity of

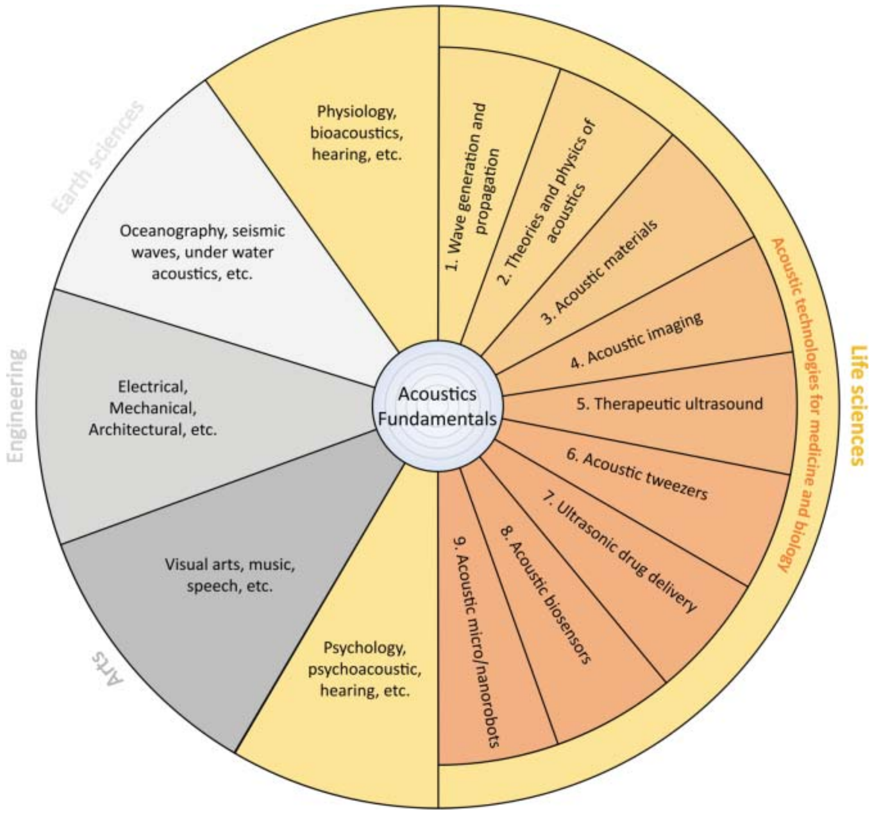


**Figure 1.3** Position of "acoustic technologies for medicine and biology" within the scope of acoustics plotted in a circular chart analogous to Lindsay's wheel. Source: Adapted from Lindsay [5].

these particles determines the kinetic energy, whereas the displacement away from the equilibrium position (i.e. wave amplitude) determines the potential energy associated with the acoustic wave. Similarly, mechanical waves, e.g. a transverse wave visualized on a vibrating string, require a medium to propagate that can store kinetic and potential energies. Elastic waves also share a lot in terms of wave propagation and energy with electromagnetic waves that can even travel through vacuum and have an enormous frequency range: 10–$10^6$ Hz radio waves, $10^{14}$ Hz visible light, $10^{20}$ Hz gamma rays, etc. Since vacuum can store electric and magnetic energies, analogous to potential and kinetic energies in elastic waves, it can sustain electromagnetic waves propagation. Electromagnetic waves (e.g. visible light) can also propagate through medium other than vacuum; however, the waves will be subjected to phenomena like reflection and refraction at interfaces where electromagnetic properties of media (e.g. refractive index) change. Similarly, acoustic waves can be reflected and refracted at an interface where the wave propagation velocity or acoustic impedance is not continuous. Building upon the fundamental assumptions of geometrical optics, where a wave can be represented by a ray directed normal to the wavefront, the paths taken by an acoustic wave in a complex medium can be described by Snell's law [3, 4].

### 1.1.4 Scope of Acoustics

The scope and ramifications of acoustics span across disciplines, i.e. from arts and engineering to earth and life sciences, where the boundaries separating them are not strictly defined (Figure 1.3). For example, acoustics of large spaces are closely linked to architectural engineering and have deep connections with how visual art is perceived in a theater. Details on the underlying acoustic connection between different disciplines can be found elsewhere [2]. Here, we will focus mainly on the role of acoustics and its applications within life sciences. Inspired by Lindsay's wheel [5], Figure 1.3 briefly indicates how acoustics, with its fundamental concepts at the center, is associated with various disciplines, including the topic of "acoustic technologies for medicine and biology" with additional subtopics (1–9) under the umbrella of life sciences. The subtopics are analogous to the chapters of this book, starting with the first chapter "Fundamentals of Acoustic Wave Generation and Propagation" followed by the rest as indicated in Figure 1.3.

## 1.2 Brief History of Acoustic Waves

### 1.2.1 Early History

In the sixth century BCE, Pythagoras discovered the relationship between the length of the vibrating strings and the variable-pitch musical sounds they produced. More than two millennia later, in 1643, Torricelli demonstrated that sound does not propagate in vacuum, thus establishing the need for media for sound propagation. Half a century later, in 1701, Sauveur introduced the term "acoustics" to describe the science of "sound," thereby pitching the two terms as synonyms to each other. A century later, in 1802, Chladni brought acoustics to the spotlight by introducing it as a separate branch of physics. With the development of acoustic resonators in 1859, also known as Helmholtz resonators, which are based on resonance of sound waves within a cavity, acoustics principles later found their applications in sound amplification or silencing in loudspeakers or mufflers, respectively. In 1866, Kundt measured the speed of sound propagating through a tube filled with fine powder to trace the acoustic pressure nodes of standing waves. As the classical acoustics matured by the end of the nineteenth century, Rayleigh culminated the state of the art of that time in his book *The Theory of Sound* (1896), which is still relevant today [2, 6, 7].

### 1.2.2 History of Acoustic Streaming

A historical advancement of acoustics can be further traced at multiple fronts; however, for the sake of brevity, we will only focus on the development of the following two topics: acoustic streaming flow and acoustic radiation force (ARF). Lord Rayleigh (1884), while explaining observations done by Faraday (patterns on vibrating Chladni plates) [8] and Dvorak (circulation of air in Kundt's tubes experiment), [9] described a "boundary layer driven" flow within the context of standing wave resonators with mean fluid motion outside of the boundary layer, also known as "outer streaming" or "Rayleigh streaming" [10]. A mean flow within the boundary layer is called "Schlichting streaming" after Schlichting provided detailed analysis of this secondary flow within an incompressible boundary layer [11]. Contrary to a standing wave, a progressive or traveling wave dissipating acoustic energy within a viscous media along its path results in a time-averaged flow field in the form of "quartz wind" or "Eckart streaming," first described by Eckart [12]. With the advent of SAW technology (1965), it became possible to produce high-frequency (>10 MHz) acoustic waves in an efficient manner [13]. Shiokawa et al. later (in 1990s) coupled the SAW with small droplet volumes to study phenomena like acoustic streaming flow, jetting, and atomization [14, 15]. Acoustic manipulation of small droplets (2003) and mixing using SAW-induced streaming flow (2006) were further elaborated with potential applications in biomedicine by Wixforth et al. using frequencies as high as 146 MHz [16, 17]. Friend and coworkers demonstrated ultrasonic atomization using a bulk acoustic waves (BAWs) device operated at 1.6 MHz, which highlights the contrast between the BAW- and SAW-based techniques [18]. These earlier works have led to discovery of interesting phenomena and exciting applications in recent years, e.g. unique finger instabilities (2012) and micro-centrifugation (2021) [19, 20].

### 1.2.3 History of Acoustic Radiation Force

On the other front, with King's [21] theoretical model of the "ARF" on a rigid spherical particle, a foundation was laid to calculate the force on a compressible droplet or bubble [22] or an elastic particle [23] exposed to a traveling or a standing acoustic wave. Gorkov's [24] simplified expression of the ARF model of Yosioka and Kawasima [22] is still a common reference for modern-day theoretical as well as experimental works on the subject. While the aforementioned theoretical models were being validated with corresponding experimental demonstrations of acoustic waves pushing on suspended particles in a fluidic media, it was not until 1993 that Mandralis and Feke [25] used the ARF to fractionate particles in a *continuous flow*. With the work of Coakley and coworkers [26] and Laurell and coworkers [27], a continuous acoustic manipulation of suspended particles was brought to the realm of microfluidics with the use of silicon-based microfabricated channels attached to a BAW transducer. Following suit, Huang et al. demonstrated standing SAW-based focusing (2008) [28] and separation (2009) [29] of microparticles in a continuous flow within a polydimethylsiloxane (PDMS) microchannel. Continuous separation of particles by a traveling SAW was demonstrated only in 2013 by Sung and coworkers [30] and Franke and coworkers [31] Over the past decades, the objects manipulated by the acoustic waves are getting smaller and smaller from cm-scale (1969) [23] elastic spheres to μm-scale (2004) [27] microparticles, droplets, and cells to nm-scale (2022) [32] nanoparticles, extracellular vesicles, etc. For further reading on the historical development of the field, readers may also refer to the following references: [2, 33].

## 1.3 What Is an Acoustic Wave?

### 1.3.1 Acoustic Parameters

An acoustic wave is an elastic wave where a medium is needed to carry disturbances within the displacement, velocity, and pressure fields to transfer energy from one point in space to another, where the medium properties play a critical role in regulating energy transport. Ripples on the surface of water, vibrations in a guitar string, and seismic activities resulting in earthquakes are examples of such waves. In contrast, inelastic electromagnetic waves do not depend upon any medium to carry the oscillating electric and magnetic fields to transport energy, and can propagate even in vacuum. For visualization of elastic waves, one can imagine a transverse wave on a vibrating rope in a sinusoidal shape, where one end of the rope is moving up and down while the other is tied to an anchor. The highest and lowest points on the rope are called the wave *crest* and *trough*, respectively. The peak-to-peak wave amplitude is measured vertically from crest to trough, whereas the wavelength is measured horizontally between adjacent crests or troughs (Figure 1.2). The number of crests (or troughs) passing by a specific point per second defines the wave frequency, which is directly related to the wavelength of a given waveform and the speed of that waveform propagating in the media. More specifically, the wave frequency equals the ratio of wave speed to wavelength. Some examples of waves propagating at very different frequencies and wavelengths within very different media include seismic waves (0.01–10 Hz) traveling through the earth, audible sound waves (20–20 000 Hz) traveling through the atmospheric air, and ultrasound (2–20 MHz) traveling through the body for biomedical imaging. In addition to the wave frequency, wave speed, and wavelength, other key parameters that are important to fully characterize an acoustic wave include particle displacement, particle velocity, absolute acoustic pressure, oscillating acoustic pressure, density fluctuations (as a result of oscillating pressure), acoustic attenuation, acoustic intensity and acoustic impedance. Since most of these parameters are interdependent, it is hard to manipulate one without affecting the others. For example, displacement, velocity, and pressure fields have the same waveforms with certain phase differences, where a variation in one field would directly alter the rest. Acoustic intensity, a measure of acoustic energy carried by a wave per unit area per unit time, is defined as the product of acoustic pressure and particle velocity. Similarly, acoustic impedance, a measure of the opposition a material offers to an acoustic wave propagation, is a product of the speed of sound and density of the medium.

### 1.3.2 Displacement, Velocity, and Pressure Fields

At the heart of acoustic wave propagation through a medium is the particle–particle interaction, where any particle of the medium transfers energy by simply interacting with its adjacent neighbor, triggering a displacement of the neighboring particle from its rest position. Although the acoustic wave causes local oscillations in the medium it travels through, the particles of the medium do not translocate with the wave (Figure 1.2). The particles' to-and-fro displacement over time is represented by a time-dependent particle velocity field depicting the acoustic wave. Oscillation of these particles with a certain velocity field leads to periodic regions of compression (high pressure) and rarefaction (low pressure) within a medium, which constitute a periodic pressure field that is 90° out-of-phase with the displacement field [34]. The phase difference between the pressure field and velocity field is 0° or 180° depending upon the reference coordinates and direction of wave propagation. That means, in a traveling wave, the particles having the highest or the lowest displacement at any given point correspond to the pressure value of zero, and vice versa. A period of displacement, velocity, or pressure field containing exactly one compression and one rarefaction region forms one complete wavelength of the acoustic wave. It is worth noting that an increase in the acoustic pressure or the particle velocity would result in an increased intensity of the acoustic wave, as both of these parameters work in perfect synchrony.

### 1.3.3 Wave Propagation

Just like an optical beam of light, acoustic waves can also exhibit phenomenon like reflection, refraction, and transmission, where the mechanical properties of the media, e.g. density, compressibility, and speed of sound, play a pivotal role in acoustic wave propagation, in contrast to the important optical properties of media, e.g. refractive indices, for light wave propagation. At an interface between two media of different mechanical properties, i.e. acoustic impedances, a part of the incident acoustic wave is reflected back, and a part is transmitted across the interface (Figure 1.4). The angles, proportions, wavelengths (or frequencies), and velocities of the reflected and transmitted waves depend upon the relative acoustic properties of the two media. The angles and proportions will be decided by Snell's law and acoustic impedances of media, respectively. The acoustic wavelength across an interface would vary based on the relative acoustic wave velocity within the respective medium.

### 1.3.4 Wave Dissipation

Imagine an acoustic wave at 2 kHz frequency traveling from air (sound velocity of ~330 m/s) to water (~1500 m/s) (Figure 1.4). The acoustic wavelength would change

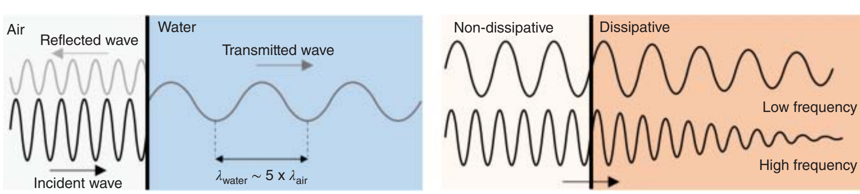


**Figure 1.4** (left) Acoustic wave reflection and transmission at an air–water interface. (right) Transmission of an acoustic wave from a non-dissipative medium to a dissipative medium where the wave amplitude attenuates faster for high-frequency waves compared to low-frequency waves.

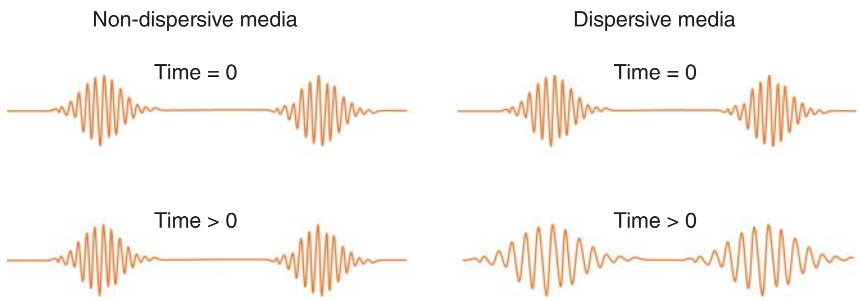


**Figure 1.5** Nondispersive vs dispersive media.

from 165 to 750 mm across the air–water interface. A large portion of the wave amplitude will be reflected back into the air, and only a small portion will be transmitted into the water, which, in addition to ~5× longer wavelength, would make it extremely difficult to hear any sound underwater. Acoustic waves traveling through a viscoelastic dissipative medium such as water would also lose their energy due to viscous damping as the wave amplitude gradually attenuates over a length scale that is dependent on the acoustic wave frequency and medium viscosity (Figure 1.4). High-frequency waves attenuate faster in high-viscosity media, leading to shorter attenuation lengths, and vice versa. Since air viscosity is two orders of magnitude lower than that of water, it can sustain acoustic waves for longer distances for similar attenuation and frequency. Therefore, it is possible to hear low-frequency sounds through air over long distances compared to high-frequency sounds that dampen faster over short length scales.

### 1.3.5 Wave Dispersion

Acoustic wave velocity, or the speed of sound, stays constant for any range of frequencies in a nondispersive medium, but in a dispersive medium, it is frequency dependent (Figure 1.5). For instance, a sound waves packet composed of different frequencies can travel through the nondispersive media while maintaining a constant wave velocity for any given frequency and a consistent pulse shape over time. However, in a dispersive medium, high-frequency waves would travel faster than low-frequency waves; therefore, the acoustic pulse spreads out with time as it travels forward. The change in acoustic wave velocity is generally insignificant for most materials but not totally absent. For example, the speed of sound in air would increase by meager 0.1 m/s as the frequency is increased by an order of magnitude, i.e. <0.05% increment in the average speed of sound ~330 m/s.

## 1.4 Modes of Acoustic Waves

Acoustic waves can exist in several different modes, each with their own unique characteristics. They can be categorized based on the frequency range, wave propagation mode, or wave configuration.

### 1.4.1 Categorization Based on Frequency Range

Acoustic waves with frequencies in the audible range of 20 Hz to 20 kHz are known to human ears, which provides a good reference point to categorize the rest based on this frequency range (Figure 1.1). Low-frequency acoustic waves with frequencies below the audible range, i.e. <20 Hz, fall into the infrasound category. Avalanches, volcanoes, meteorites, and earthquakes are a few examples of infrasound-producing natural phenomena. Acoustic waves with frequency above the audible frequency range, i.e. >20 kHz, are usually referred to as ultrasound or ultrasonic. Ultrasonic waves are widely used in industrial settings, e.g. for cleaning parts located in difficult-to-reach regions where high-frequency acoustic waves remove the dirt, grease, and dust particles off the targeted surfaces. Moreover, ultrasonic waves have found a plethora of applications in biomedical sciences, including therapeutics, drug delivery and diagnostics (Figure 1.6). With their characteristic short wavelengths, ultrasonic waves imply a high degree of discrimination and a high concentration of energy; therefore, they can be used as a means of exploration, detection, actuation, etc. Starting beyond the audible frequency limit of 20 kHz, ultrasonic waves cover another three orders of magnitude higher frequencies beyond 10 MHz. These waves, with their broad range of frequencies, have been used for the improved delivery of drugs and genes to organs that are difficult to access, such as brain, for sono-dynamic and gene therapies, for thrombolysis and hemostasis, for healing bone fractures and treating osteoporosis, to mention a few. Acoustic waves having frequencies in GHz can be employed effectively in a variety of applications, including RF filters for 5G communication technologies, ultrawide band filters, and also in the components (such as actuators) of microelectromechanical systems. Bulk and SAW devices have been utilized at the RF front-end for a long time for filtering purposes where their operating frequencies are below 2.6 GHz range [36, 37]. Ultrasonic imaging, also known as ultrasound imaging or sonography, uses high-frequency sound waves to create images of the inside of the body. Also, ultrasonic sensors use sound waves at similar frequencies to measure distance, detect objects, and monitor fluid levels.

### 1.4.2 Categorization Based on Propagation Mode

Mechanical waves traveling at distances of 100s of kilometers during earthquakes to 10s of micrometers within microfluidic channels and miniaturized substrates demonstrate similar characteristics, which help in their categorization (Figure 1.7). Acoustic waves are categorized into following different types of waves based on particle movement in the medium and direction of wave propagation.

#### 1.4.2.1 Longitudinal Waves

Longitudinal waves are the waves in which the particles of a medium vibrate in the same direction as the wave propagation. Material experiences periodic regions of compression and expansion as the waves travel forward (Figure 1.7). Longitudinal waves are also known as primary (P) compressional waves since they travel faster

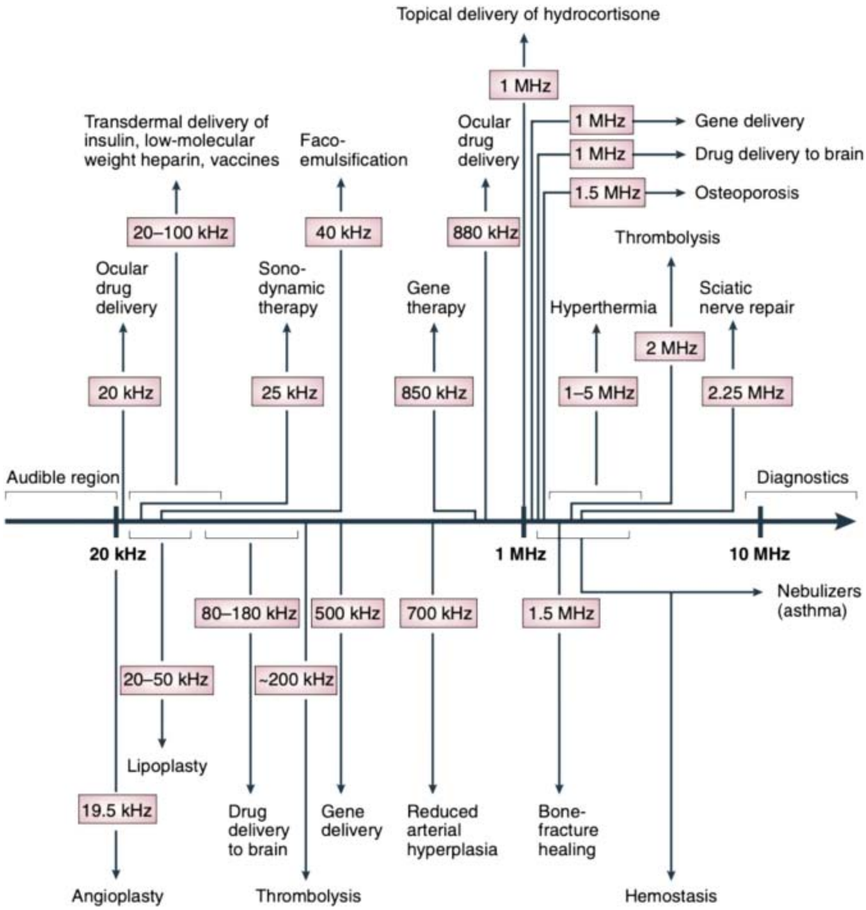


**Figure 1.6** Summary of ultrasonic frequencies and their applications. Source: Reproduced from Mitragotri [35].

through the earth's crest than shear waves, which are also known as secondary (S) transverse waves (Figure 1.7a). A piezoelectric substrate sandwiched by a pair of electrodes can produce, on a much smaller scale, similar longitudinal or shear waves depending upon the orientation of piezo crystals, frequency of input current, thickness of the substrate, etc. (Figure 1.7b).

#### 1.4.2.2 Shear Waves

Transverse or shear waves are waves in which the particles of a medium vibrate perpendicular to the direction of the wave propagation. This type of wave can propagate only in solids and not in liquids or gases since fluids cannot sustain a shear stress and only allow longitudinal waves to pass through. During an earthquake, the transverse S waves propagate with a velocity slower than the longitudinal P waves, arriving several seconds later than the longitudinal waves at

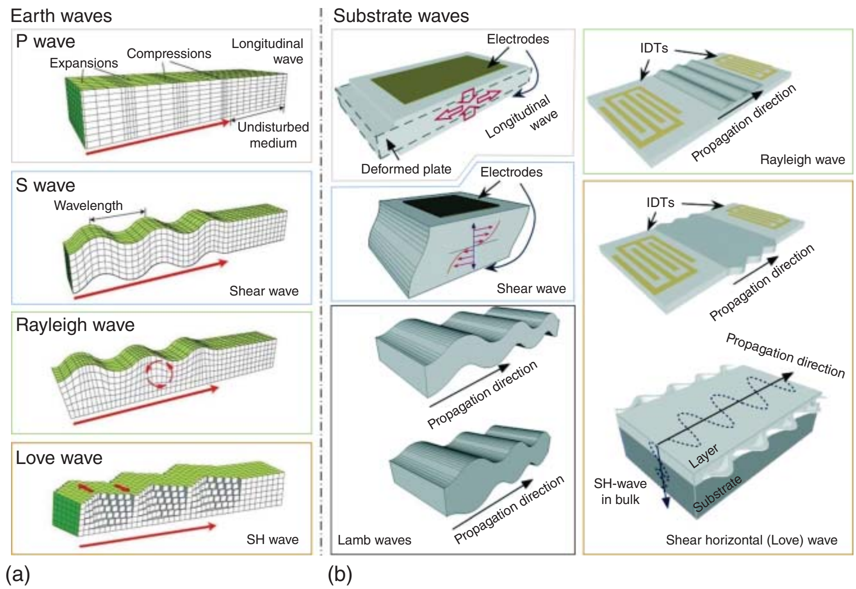


**Figure 1.7** Categorization of waves based on propagation. (a) Propagation modes of earth waves. Source: Images courtesy: Copyright, Science Learning Hub - Pokapü Akoranga Pütaiao, University of Waikato [38]. (b) Wave propagation modes at a much smaller scale, i.e. within a substrate. Source: Fu et al. [39]/Reproduced with permission from Royal Society of Chemistry.

any given point. The same is true for a piezoelectric substrate, where longitudinal wave velocity is always greater than shear wave velocity.

#### 1.4.2.3 Rayleigh Waves

Rayleigh waves, also known as surface waves, propagate across the surface of a medium where the particle displacements are both in the longitudinal and transverse directions. This renders a Rayleigh wave as a modal superposition of the longitudinal and shear waves. Due to these characteristics, the medium particles move in an elliptical orbit with velocity components parallel and normal to the wave propagation direction simultaneously. The amplitude of the particle displacement diminishes exponentially from the surface into the medium; therefore, the Rayleigh wave energy is mainly concentrated within a few wavelengths from the surface of the medium. These waves are mostly found in solids with wave velocity solely dependent on the material and the orientation of the crystals in the solid substrate. In liquids, a similar surface wave type is observed, i.e. water waves. However, the medium particles move in circular clockwise orbits in a rightward propagating water wave instead of elliptical orbits in Rayleigh wave, which switch from counterclockwise rotation to clockwise moving from the surface of a substrate to inwards of a substrate [34]. Rayleigh-type SAWs can be produced on specially oriented bulk piezoelectric substrates such as ST-cut and Y-cut quartz, 128° Y-X-cut lithium niobate ($LiNbO_3$), and X-112° Y-cut lithium tantalite ($LiTaO_3$) substrates.

Additionally, films made of zinc oxide, aluminum nitride, lead zirconate titanate, or $LiNbO_3$ that are vertically oriented (commonly referred to as *c*-plane or *z*-plane oriented) are also utilized to generate Rayleigh-type SAWs [39].

#### 1.4.2.4 Love Waves

Love waves are horizontally polarized surface waves, which are named after Augustus Edward Hough Love, who first predicted them mathematically in 1911. These waves are responsible for horizontal shifting of the earth's crust during an earthquake and are only observed when the wave velocity in the upper layer is lower than the underlying sublayer. On a substrate, these shear-horizontal (SH) Love waves propagate through an isotropic thin layer sitting on a relatively thicker substrate and have a lower shear wave velocity compared to that of the substrate [40]. The isotropic layer on the substrate is usually much thinner than the wavelength of the SH Love waves, which are characterized by a unique horizontal shearing motion of the particles perpendicular to the direction of wave propagation and parallel to the device surface [39]. The SH Love waves can be produced on specially oriented bulk piezoelectric substrates, such as ST-cut quartz, 64° Y-X-cut $LiNbO_3$, and 36° Y-X-cut $LiTaO_3$.

#### 1.4.2.5 Lamb Waves

Lamb waves are produced in a wave guide sandwiched between two parallel surfaces, such as the top and bottom surfaces of a plate or a substrate; therefore, they are also known as guided waves or plate waves [41]. The Lamb waves can propagate in a symmetric or an antisymmetric mode, where motion on the top surface is a mirror image of the bottom surface about the midplane of the plate or both surfaces are moving exactly in sync, respectively. Contrary to the Rayleigh waves, Lamb waves produce stresses throughout the plate thickness. The motion of any given particle within the plate vibrating in Lamb wave mode is always in the plane defined both by the surface normal and the wave propagation direction. The number of modes that each form of Lamb wave can achieve is unlimited. Frequency of the wave, angle of incidence, and material are some of the variables that affect the modes. The relation of frequency to wafer thickness determines the Lamb wave velocity. Because Lamb waves are extremely dispersive, their velocities change with frequency. Lamb waves can be used to solve a wide range of problems involving the identification of subsurface discontinuities for NDT since they can flow within thin plates.

### 1.4.3 Categorization Based on Wave Configuration

#### 1.4.3.1 Traveling Waves

One can observe the crest of the wave moving along with the particles as it travels. After this crest, there is a trough, which is then followed by the next crest. In fact, one would identify a clear wave pattern moving through the medium in the shape of a sine wave. This sine wave pattern moves continuously until it encounters another wave in the same direction or until it changes the medium that have different property. This type of wave form that is observed traveling through a medium is described as a traveling wave (Figure 1.8).