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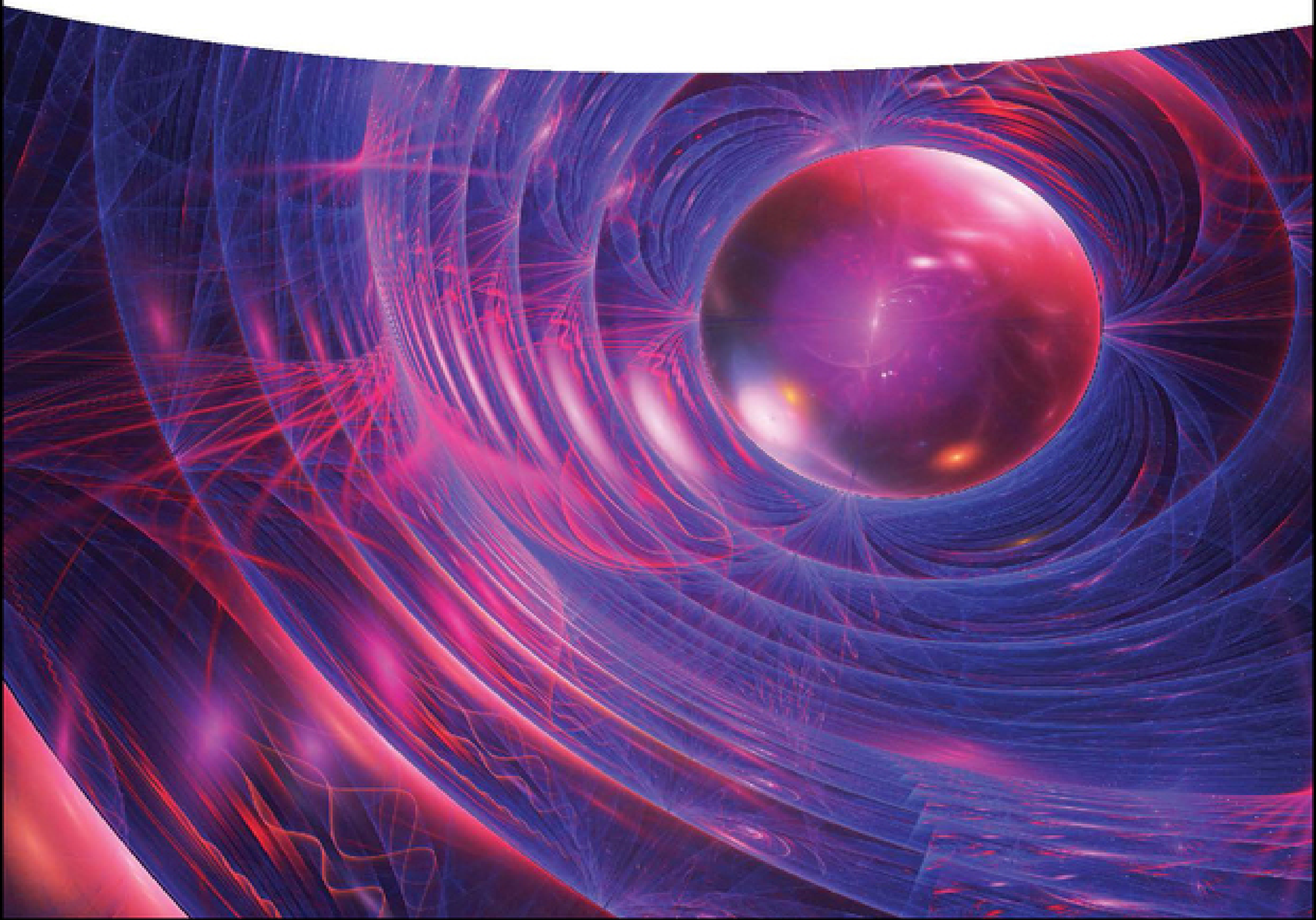
Edited by Adem Ozcelik, Ryan Becker, and Tony Jun Huang

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

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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 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].

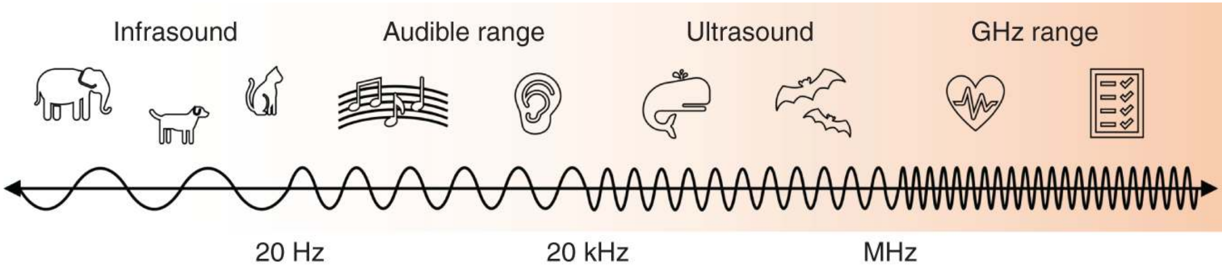

Figure 1.1 Categorization of acoustic waves based on frequency range.

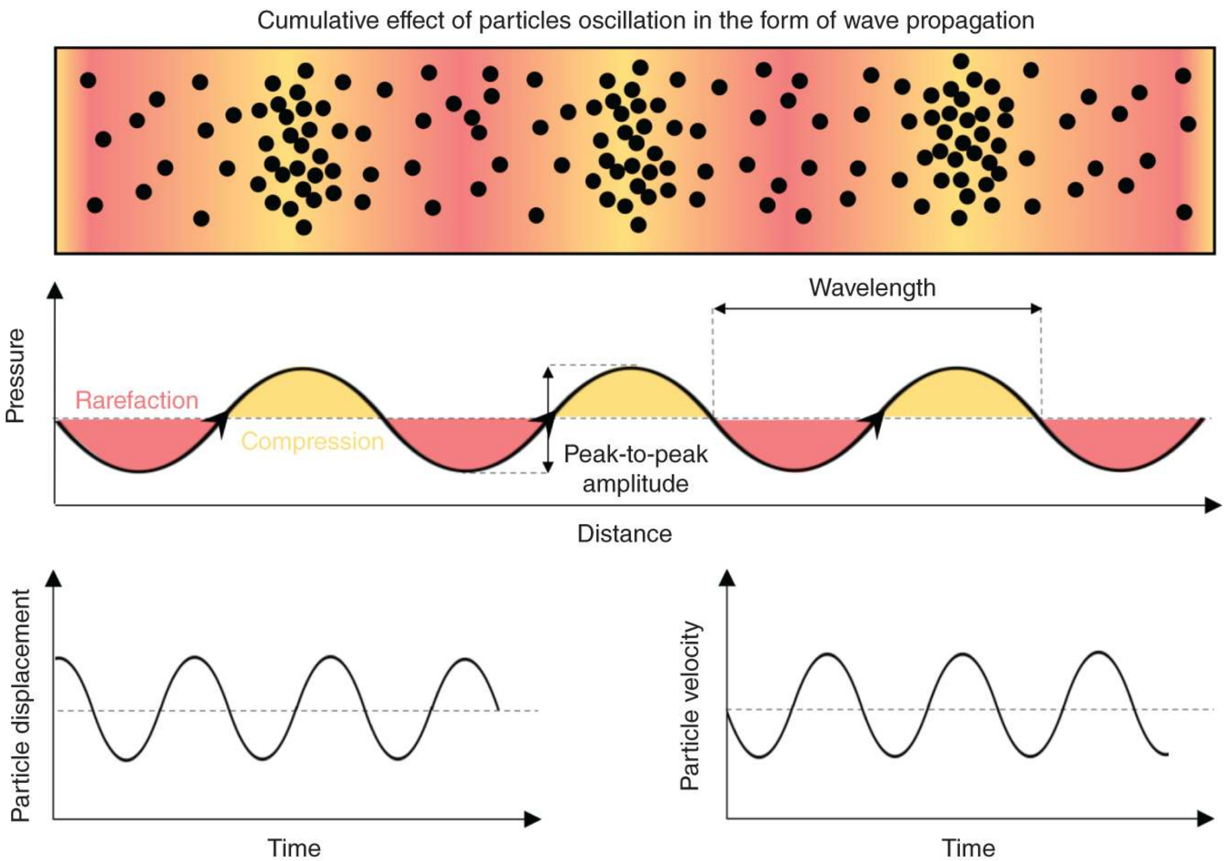

Figure 1.2 Particle oscillation in a medium because of an acoustic wave propagation.

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 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].

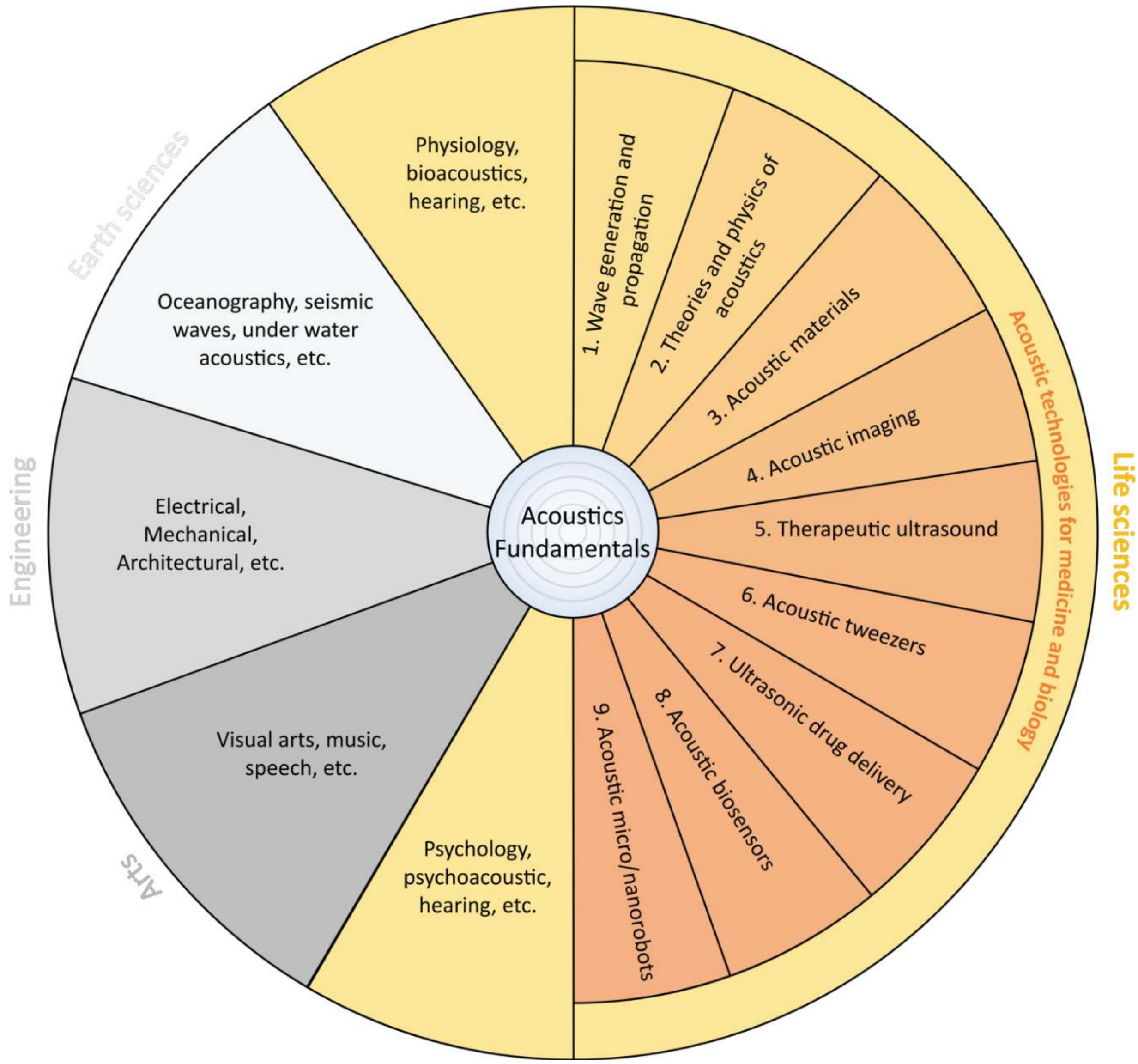

Figure 1.3 Position of “acoustic technologies for medicine and biology” within the scope of acoustics plotted in a circular chart analogous to Lindsay's wheel.

Source: Adapted from Lindsay [5].

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

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