EFSUMB Course Book, 2nd Edition

Editor: Christoph F. Dietrich

Physical principles of medical ultrasound

Michiel Postema[1,2,3], Spiros Kotopoulis[4], Klaus-Vitold Jenderka[5]

[1]School of Electrical and Information Engineering, University of the Witwatersrand, South Africa;

[2]Inserm Research Unit U930: Imaging and Brain, Université François-Rabelais de Tours, France;

[3]LE STUDIUM Loire Valley Institute for Advanced Studies, Orléans, France;

[4]National Centre for Ultrasound in Gastroenterology, Haukeland University Hospital, Bergen, Norway;

[5]Department of Engineering and Natural Sciences, Merseburg University of Applied Sciences, Merseburg, Germany.

Corresponding author: Michiel Postema

Content

Inhalt

Sound and ultrasound

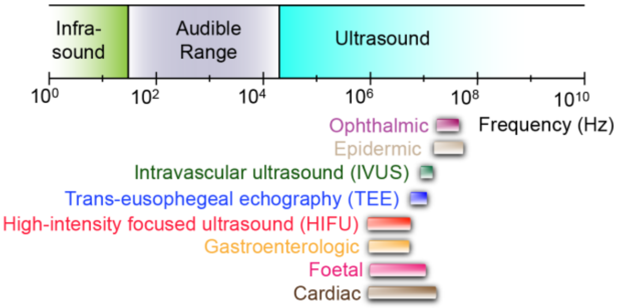
Acoustics is the scientific field that studies sound. Sound is a form of mechanical periodic molecular displacement (vibration) of matter. The time it takes for a vibration cycle to complete is called a period. The number of vibration cycles that occur during a set time is referred to as the frequency. The frequency f of a vibration is the inverse of its period T:

$$f = \frac{1}{T}.$$

Sound with frequencies below 20 cycles per second, *i.e.*, below 20 Hz, is called infrasound. Although infrasound is too low to be heard by human beings, it can be perceived (felt).

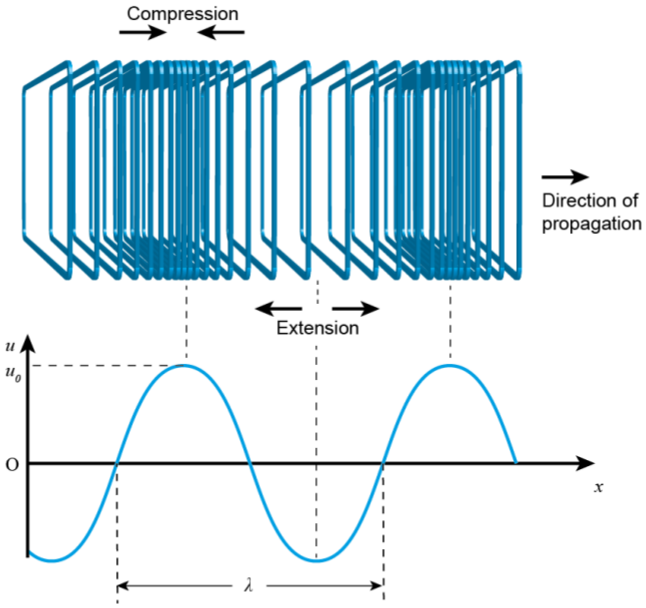
The audible range is defined by frequencies between 20 Hz and 20,000 Hz (20 kHz). This range has been defined by the average hearing of healthy 18-years-old men. Frequencies higher than 20 kHz are referred to as ultrasound. **Error! Reference source not found.** shows some clinical application of ultrasonics and their respective frequency bands.

Figure 1 **Clinical applications of ultrasound and their corresponding frequency bands.**



Sound propagates from a source through matter. Although many different elastic wave types exist in solid materials, fluids only support longitudinal waves. Longitudinal waves, also known as acoustic waves, displace matter only in the direction on propagation [Figure 2]. As human tissue consists mostly of fluid materials, primarily longitudinal waves are generated and observed in the field of medical ultrasonics.

Figure 2 **Schematic representation of the axial displacement of matter by a longitudinal sound wave.**



The highest displacement in a sound wave is called the displacement amplitude. Generally, the matter displacement in space and time by a low-amplitude sound wave has the form

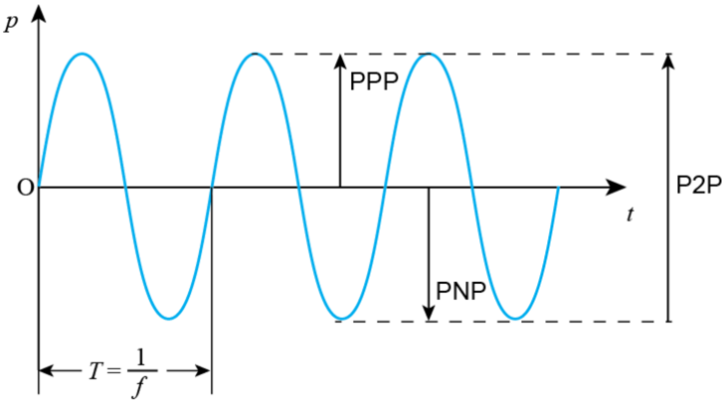
Equation 1

$$u(x,t) = u_0 \sin 2\pi \left(\frac{t}{T} - \frac{x}{\lambda} \right),$$

where u_0 is the displacement amplitude and λ is the wavelength of the sound (*cf*. **Error! Reference source not found.**). Notice the minus between $\frac{t}{T}$ and $\frac{x}{\lambda}$ in (2): obviously, the wave at given time farther from the source is equal to the wave at earlier time closer to the source. Taking only one dimension into account, the compressive and extensive displacements are related to local pressure changes by the equation of motion from which the wave equation is derived (*cf*. Appendix, Eq. A 1 – A 3).

Figure 3 shows some often-used parameters to express the pressure amplitudes of medical ultrasound, which are handy especially if the sound waves are asymmetric.

Figure 3 Common parameters used to express pressure amplitudes: peak-positive or peak-compression pressure (PPP), peak-negative or peak-rarefaction pressure (PNP), peak-to-peak pressure (P2P).



Let us define an imaginary sound source with <u>power</u> W, *i.e.*, every second, a certain amount of energy is radiated from the source. The power is an intrinsic property. At equal distances from the source, we can define a surface S, through which this energy must pass. The power per unit surface area is called the <u>instantaneous intensity</u>:

Equation 2

$$I = \frac{W}{S}.$$

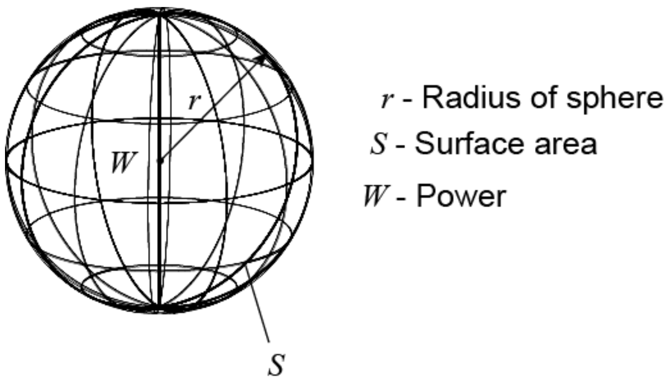
The averaged derived intensity of a harmonic sound wave at a point in a sound field is:

Equation 3

$$< I >= \frac{{p_\mathrm{A}}^2}{2\rho c},$$

where p_A is the pressure amplitude, c is the speed of sound in the medium, and ρ is the density of the medium. Thus, for a point source, the surface through which the energy must pass is a sphere of radius r (*cf*. **Error! Reference source not found.**) and a surface area $S = 4\pi r^2$. Consequently, for a point source, the intensity is inversely proportional to the distance to the source squared, and the acoustic pressure is inversely proportional to the distance itself. This acoustic pressure decay with distance is called geometric damping.

Figure 4 Radiated field through a spherical surface S at a distance r from a point source with power W.



Thermal and viscous material properties are other causes of damping of the acoustic wave (*cf*. **Error! Reference source not found.**). Damping coefficients are frequency-dependent. In human tissue, the damping coefficient is proportional to the frequency to a power between 1.0 and 1.4. Thus, the higher the frequency, the lower the penetration depth of the sound.

Figure 5 Damped wave with wavelength λ and damping coefficient α.