Water Encyclopedia: Physics and Chemistry, pp. 569-571

SOUND IN WATER

D.L. MARRIN
Hanalei, Hawaii

As a sound travels through an elastic medium such as water, a wave is created that imparts energy to the individual molecules—causing them to compress and then to relax along the path of the wave. Because the medium is elastic, the distance separating individual water molecules is permitted to vary just slightly, such that the propagation of sound may be defined as a periodic variation in pressure that is transmitted via adjacent molecules. Sound emanating from a point source in water usually (but not always) results in a three-dimensional waveform that spreads spherically through the medium.[1] Similarly, a planar source of sound in water can be considered as multiple point sources that create a wave consisting of all the individual waves.

Sound waves are *longitudinal*, meaning that molecules (e.g., water or air) comprising the elastic medium move in direction that is parallel to the propagating wave. Because water has a significantly higher density than air, water transmits sound more rapidly and efficiently than does air. The water molecules essentially oscillate, or move back and forth over a very short longitudinal distance; hence, sound waves are classified as *mechanical*. By contrast, light waves and microwaves are classified as *electromagnetic* and do not involve the movement of water molecules for propagation. The speed of sound in water is about 1500 meters per second or 3300 miles per hour (i.e., approximately five times greater than that in air), which varies slightly with temperature, pressure, and salinity.

FREQUENCY AND AMPLITUDE

The frequency of a sound wave is defined as the number of waves that pass by a given point during a specified period of time. A single wave consists of a cycle that includes both compression (squeezing together) and rarefaction (rebounding apart); the distance over which a cycle is continually repeated is known as the wavelength. The period of time over which waves are normally counted is one second; therefore, sound frequencies are expressed as cycles per second or *hertz*. Whereas high frequency sounds possess short wavelengths, low frequency sounds possess long wavelengths. Frequency ranges and estimated intensity levels for common underwater sounds are listed on Table 1. Frequency-dependent differences in underwater sound attenuation result in low-pitched sounds traveling farther than high-pitched ones generated at similar intensities.

The amplitude of a sound wave is defined by the maximum longitudinal displacement (i.e., during one cycle of compression and rarefaction) of water molecules relative to their resting, or equilibrium, position. The intensity of a sound wave is proportional to its amplitude and is often quantified in the units of *decibels*. The decibel scale is based on a ratio between the intensities (expressed as a power) of a measured sound and a reference sound corresponding to a standard pressure. Many of the man-made sounds listed on Table 1 are actually more intense than the naturally-produced sounds, contributing—at least in part—to the controversy regarding the possible effects of anthropogenic noise on marine organisms. Sound intensities are commonly presented for a distance of only one meter from the source and, as such, are rarely indicative of ambient underwater noise (e.g., the cumulative intensity of sounds measured at greater distances from the respective sources).

FATE OF OCEANIC SOUND

The propagation of sounds in the ocean is a rather complex matter owing to differences in water density as a function of depth, latitude, seafloor topography, and many other factors. Changes in seawater temperature, salinity, and pressure all contribute to changes in density that, in turn, affect sound waves traveling through the media. Generally, sound is attenuated via the processes of *spreading* (proportional to distance), *reflection* (due to solid structures or boundaries between water of different densities), *scattering* (due to rough surfaces), *absorption* (conversion of acoustic to thermal energy), and *refraction* (deflection of sound waves from a straight path).[5] While ambient noise in a shipping channel can exceed that outside a channel by as much as 45 decibels (re 1 μPa), noise in a channel is attenuated about 100 decibels from that measured directly beneath ships.[2]

Due to the vertical stratification of oceans, sound behaves differently in turbulent shallow waters than it does in either more isothermal mid-depth waters or the waters immediately overlying the bottom (see Table 2). Sound transmission at the surface is highly dependent on local conditions (e.g., wind, precipitation, swells, bubbles) and is usually restricted to low frequency sounds. However, most of the ocean lies between shallow and bottom waters, creating a relatively thick layer that transmits a spectrum of sound waves with far less attenuation than that encountered in either shallower or deeper waters. Both humans and whales have taken advantage of this *sofar channel* to broadcast signals and songs, respectively, over vast oceanic distances.[6] Sounds generated within the sofar channel itself or at shallower depths alongside seamounts are entrained and transmitted within this deep isothermal layer as a result of many contributing physical processes.

UNDERWATER DETECTION

Detecting and identifying an underwater sound from a particular source is often difficult due to the aforementioned effects of the environment and to the myriad of background noises from which any single sound must be distinguished. Sea sounds are detected by hydrophones (i.e., the underwater equivalent of a microphone) that are often positioned in specific arrays, thus permitting the relative position of a sound source to be determined. This type of *passive* detection may be used to locate oceanic precipitation, breaking surface waves, underwater explosions, undersea volcanoes, shipping traffic, and marine organisms that emit audible sounds (e.g., crustaceans, fishes, mammals).[7]

Active detection techniques, such as sonar, are routinely used to locate underwater objects because the objects themselves need not emit sound and because the results are generally more interpretable. The most basic type of sonar is echolocation, whereby a sound pulse (acoustic energy) is introduced into the water. Depending on the sonic wavelength and the size of the objects, a portion of that acoustic energy is reflected back to the source (e.g., a ship) where it is detected, transduced, and analyzed. The distance, movement, size, and even shape of some objects may be determined using sophisticated sonars (e.g., Doppler, multibeam) and data analysis techniques.[8] Several marine organisms (most notably cetaceans) are believed to use echolocation as a means of finding or assessing prey, predators, conspecifics, seabed features, and environmental conditions.[2]

ULTRASOUND AND INFRASOUND

While most of the underwater sounds discussed thus far lie within the *sonic* range of humans (i.e., frequencies of 20 to 20,000 hertz), water also transmits mechanical waves of *ultrasonic* (>20,000 hertz) and *infrasonic* (<20 hertz) frequencies. Dolphins emit whistles at fre-quencies as high as 30,000 hertz and complex echolocation clicks at frequencies exceeding 300,000 hertz.[8] Obviously, the upper limit of hearing for dolphins far exceeds that for humans. In addition to marine organisms, ambient oceanic noise associated with bubbles (i.e., trapped gases), surface winds, waves, and sea spray can reach ultrasonic frequencies. Man-made ultrasounds include everything from complex signals for communication to guided waves for inspecting underwater pipelines.[9]

The moans of baleen whales are the most common source of biologically-produced infrasound, which has been documented down to about 10 hertz.[8] By contrast, a number of geological and meteorological events (e.g., volcanoes, earthquakes, sea ice cracking, hurricanes) produce infrasonic waves that propagate through the ocean at frequencies of approximately 0.1 to 10 hertz. Even the breaking of large surf, either onto the shore or on the water itself, creates infrasound at frequencies of 1 to 5 hertz.[10] Anthropogenic infrasound in the ocean is created primarily via shipping traffic, low frequency active sonar (LFAS), and acoustic thermography. A thermography technique known as ATOC generates tones down to about 1 hertz, whereas LFAS sweeps multiple tones of 100 to 500 hertz across each other and produces resulting tones as low as 0.1 hertz.[2] Both ATOC and LFAS generate peak intensity sounds that are greater than those of ships.

REFERENCES

1. Leighton, T.G. *The Acoustic Bubble*, Academic Press, San Diego, Chapter 1 (1994).

2. Stocker, M., "Ocean bio-acoustics and noise pollution," *The Journal of Acoustic Ecology* **4**, 16-29 (2003).

3. *Science of Sound in the Sea*. Office of Marine Programs, University of Rhode Island, HTML format (2004).

4. Greene, C.R., S.E. Moore, "Man-made noise," In: *Marine Mammals and Noise* (W.J. Richardson et al., Eds.), Academic Press, San Diego, Chapter 6 (1995).

5. Haines, G. *Sound Underwater*, Crane Russak, New York, pp. 22-25 (1974).

6. Payne, R. *Among Whales*, Scribner, New York, Appendix (1995).

7. Medwin, H., C.S. Clay. *Fundamentals of Acoustical Oceanography*, Academic Press, San Diego, Chapters 1 and 10 (1998).

8. Thompson, D.H., W.J. Richardson, "Marine mammal sounds," In: *Marine Mammals and Noise* (W.J. Richardson et al., Eds.), Academic Press, San Diego, Chapter 7 (1995).

9. Na, W.B., T. Kundu, "Underwater pipeline inspection using guided waves," *Journal of Pressure Vessel Technology* **124**, 196-200 (2002).

10. Garcés, M., C. Hetzer, M. Marrifield, M. Willis, J. Aucan, "Observations of surf infrasound in Hawai'i," *Geophysical Research Letters* **30**, 2264-2266 (2003).

TABLE 1. Approximate ranges for the frequencies and intensity levels of common underwater sounds. Reported ranges were complied from data presented in various sources.[2,3,4] Intensity levels are presented in the units of decibels relative to a reference pressure of one micropascal at a distance of one meter from the sound source. Sound level decreases are a function of distance from the source, frequency range, and various environmental factors.

Sound Source	Frequency (hertz)	Intensity Level (decibels)
Ship Engines and Propellers	10-5000	160-190
Navigation and Profiling Sonars	100-3000	180-230
Explosive Devices/Air Guns	1000-17,000	190-260
Military Surveillance Sonars	1000-10,000	190-235
Icebreaking/Drilling Operations	20-1000	100-150
Whale Songs and Moans	10-8000	120-190
Dolphin Clicks and Whistles	500-25,000	100-180
Cetacean Echolocation	10,000-150,000	130-230
Snapping Shrimp Colony	2000-15,000	180-190
Lightning Strikes/Volcanoes/Earthquakes	0.1-20,000	up to 260

TABLE 2. Approximate depths and representative sound speeds for various water layers in the ocean. Reported ranges were complied from data presented in various sources.[2,6,7]

Vertical Zone	Depth (meters)	Speed (m/sec)	Comments
Overlying Air	NA*	330	Significantly lower acoustic impedance than water; minimal transfer of sound energy.
Surface Water Layer	0 to 50	1515	Influenced by weather (e.g., wind, rain, temp.) and turbulence that affect sound waves.
Seasonal Thermal Layer	50 to 800	1485-1505	Sound channel (mostly for low frequencies); limited vertical thickness; refracts sound waves originating shallower and deeper.
Deep Isothermal Layer	800 to 4,000+	1485-1525	Optimal sound channel (all frequencies); extensive vertical thickness and horizontal extent; minimal sound attenuation.
Bottom Water Layer	4,000+ to seafloor	1525	Influenced by seafloor topographic features that reflect and scatter sound waves.
Underlying Rock	NA	2000-6000	Higher acoustic impedance than water; moderate transfer of sound energy.

* *Not applicable.* + *Indicates that the transition between deep isothermal layers and bottom water layers may exceed 4,000 meters, depending on the exact location within an ocean basin.*