APPENDIX C

UNDERWATER SOUND CONCEPTS

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C UNDERWATER SOUND CONCEPTS

C.1 What is Sound?

Subjectively, the term *sound* refers to what is heard with the ears. Objectively, sound is a time-varying mechanical disturbance in an elastic medium. In modern usage, sound refers not only to the phenomenon in air that one hears, but also to whatever else is governed by the same physical principles (Pierce, 1989).

Sound is produced when an elastic medium is set into motion, often by a vibrating object within the medium. As the object vibrates, its motion is transmitted to adjacent "particles" of the medium. The motion of these particles is transmitted to adjacent particles, and so on. The result is a mechanical disturbance (the "sound wave") that moves away from the source and propagates at a medium-dependent speed (the "sound speed"). As the sound wave travels through the medium, the individual particles of the medium oscillate about their static positions but do not propagate with the sound wave. As the particles of the medium move back and forth they create small changes, or perturbations, about the static values of the medium density, pressure, and temperature.

C.2 Physical and Subjective Attributes of Sound

Sounds may be described in terms of physical and subjective attributes. Physical attributes may be directly measured. Subjective (or psychophysical) attributes may not be directly measured and require a listener to make a judgment about the sound. Physical attributes of a sound at a particular point in space are normally quantified by measuring perturbations in the pressure of the medium that accompany the passage of a sound wave. Two of the most important physical attributes are frequency and amplitude.

Frequency is the physical attribute most closely associated with the subjective attribute ***pitch***; the higher the frequency, the higher the pitch. Frequency is related to the speed at which the medium particles oscillate about their static positions. Frequency is the number of times that the medium pressure varies from its static pressure through a complete cycle in unit time (Galloway, 1988). The unit of frequency is hertz (Hz); 1 Hz is equal to 1 cycle per second. Pure tones have a constant, single frequency. Complex tones contain sound energy at multiple, discrete frequencies, rather than a single frequency (ANSI, 1994).

Amplitude is the physical attribute most closely associated with the subjective attribute ***loudness***. Amplitude is related to the amount that the medium particles vary about their static positions. As the amplitude increases, the loudness also increases.

C.3 Impulsive and Continuous-Type Sounds

Although no standard definitions exist, sounds may be broadly categorized as ***impulsive*** or ***continuous-type***. All non-impulsive sounds (e.g., continuous, varying, intermittent) are collectively referred to as "continuous-type" (NIOSH, 1998). Impulsive sounds feature steep rises and high peaks in the medium pressure, followed by rapid return to the static pressure. Impulsive sounds have short durations and broad frequency content. Impulsive sounds are often produced by processes involving a rapid release of energy (e.g., chemical explosions) or mechanical impact (e.g., mechanical punch press or pile driving) (Hamernik and Hsueh, 1991).

Although they may have brief durations, most sonar "pings" may be considered to be continuous-type sounds because their durations are relatively long compared to their harmonic period — the time for the medium pressure to move through one complete cycle.

C.4 Sound Metrics

C.4.1 Sound Pressure

Sound pressure is the incremental variation in a medium's static pressure as a sound wave travels through it. The unit of sound pressure is the pascal (Pa) (1 Pa = 10 μbar = 1.45×10^{-4} psi).

Instantaneous sound pressure $p(t)$ is the total instantaneous pressure at a point minus the static pressure at that point (ANSI, 1994). Figure C-1 shows instantaneous sound pressures for a hypothetical (a) pure tone and (b) impulsive sound. Instantaneous sound pressure is a time-varying quantity. Standard descriptors used for time-varying quantities, such as the peak value or root-mean-squared value, are also used to describe the instantaneous sound pressure.

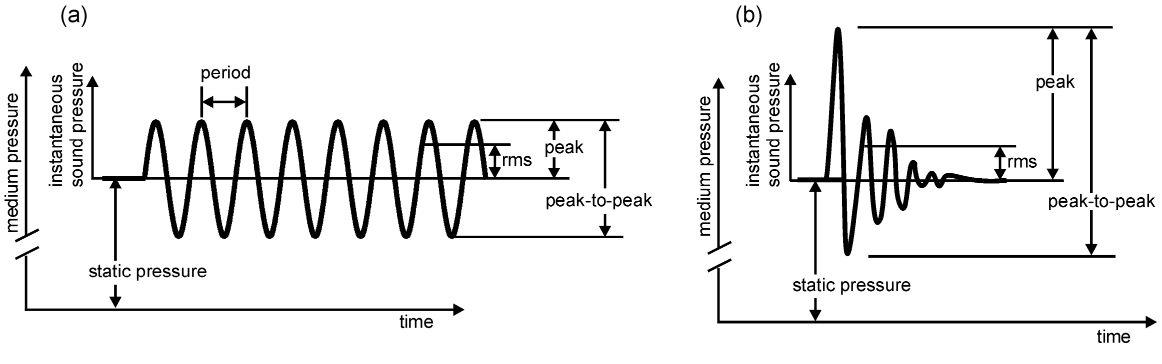

Figure C-1

Peak sound pressure is the maximum absolute value of the instantaneous sound pressure during a specified time interval (ANSI, 1994). The ***peak-to-peak (p-p) sound pressure*** is the difference between the maximum and minimum values of the instantaneous sound pressure.

The ***mean-squared sound pressure*** $\overline{P^2}$ is

$$\overline{P^2} = \frac{1}{T}\int_0^T p^2(t)\,dt\,, \tag{C-1}$$

where T is the time over which $p^2(t)$ is integrated. For impulsive sounds the "effective duration" may be defined using different criteria (see Hamernik and Hsueh, 1991). For periodic sounds it is common to integrate over an integral number of periods. For other continuous-type sounds it is common to integrate over long time periods. The unit of $\overline{P^2}$ is pascal-squared (Pa^2).

Since $\overline{P^2}$ does not have the same physical units as $p(t)$, the ***root-mean-squared* (*rms*) *sound pressure*** is often used instead. The rms sound pressure $\overline{P}$ is the square-root of the mean-squared sound pressure:

$$\overline{P} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\,dt}\,. \tag{C-2}$$

For pure tones (with T equal to an integral number of periods), Eq. (C-2) simplifies to $\overline{P} = P_\mathrm{p}/\sqrt{2}$, where P_p is the peak sound pressure. This relation may not hold for more complex sounds. In general, $\overline{P}$ must be calculated from Eq. (C-2) using $p(t)$ for the specific sound of interest.

C.4.1.1 Sound Levels and Decibels

Because mammalian ears possess a large dynamic range and humans judge the relative loudness of sounds by the ratio of the sound pressures (a logarithmic behavior), it is common to describe physical attributes of sounds with logarithmic units called ***sound levels*** (Kinsler *et al*., 1982). The term "level" indicates the logarithm of the ratio of a given quantity divided by some reference quantity with the same units (ANSI, 1994; Young, 1988). The use of a logarithmic scale compresses the range of numerical values that must be used.

When using logarithmic units, the base of the logarithm and the reference value must be specified. Typically, the logarithm is taken to the base 10, so the logarithm is written as $\log_{10}$. The logarithm of a number y to a base b is the exponent x required so that b raised to the $x = y$: if $x = \log_b y$, then $y = b^x$. As an example, $\log_{10}(100) = 2$, since $10^2 = 100$. Some important mathematical relations involving logarithms are:

- $\log_b(xy) = \log_b x + \log_b y$
- $\log_b(x/y) = \log_b x - \log_b y$
- $\log_b x^a = a \log_b x$

Sound levels are normally expressed in ***decibels***. A decibel is 1/10 of a bel, a unit of level when the logarithm is to the base ten and the quantities concerned are proportional to power (ANSI, 1994).

To express a quantity *X* in decibels using a reference X_{ref}, the equation is

$$10\log_{10}\left(\frac{X}{X_{ref}}\right), \qquad \text{(C-3)}$$

if *X* and X_{ref} have units of power or energy, or

$$20\log_{10}\left(\frac{X}{X_{ref}}\right) = 10\log_{10}\left(\frac{X^2}{X_{ref}^2}\right), \qquad \text{(C-4)}$$

if *X* and X_{ref} have units of pressure, force, velocity, voltage, or a similar quantity. The use of X^2 and X_{ref}^2 arises because power is related to the product of pressure and velocity, force and velocity, voltage and current, etc.

When a numeric value is presented in decibels, it is important to also specify the numeric value and units of the reference quantity. Normally the numeric value is given, followed by the text "re", meaning "with reference to", and the numeric value and unit of the reference quantity (Harris, 1998). For example, a pressure of 1 Pa, expressed in decibels with a reference of 1 μPa, is written 120 dB re 1 μPa.

C.4.1.2 Sound Pressure Level

The most common sound level is ***sound pressure level*** (SPL). SPL is defined as

$$SPL = 10\log_{10}\left(\frac{\overline{P^2}}{P_{ref}^2}\right) = 20\log_{10}\left(\frac{\overline{P}}{P_{ref}}\right). \qquad \text{(C-5)}$$

The standard reference pressure P_{ref} is 1 μPa for water (and media other than gases) and 20 μPa for air (and other gases) (ANSI, 1994). The different reference pressures for air and water means that the same sound pressure will result in different numeric values of SPL in-air and underwater.

C.4.2 Impulse

Impulse is the time integral of a force over the time that the force is applied (ANSI, 1994). ***Acoustic impulse*** I_a, or "impulse per unit area of $p(t)$" (Hamernik and Hsueh, 1991), is defined as

$$I_a = \int_0^T p(t)\,dt\,, \tag{C-6}$$

where T is the effective duration of the waveform. Often the "A-duration", defined as the time required for the instantaneous sound pressure in the initial wave to reach the peak pressure and then return to zero, is used (Hamernik and Hsueh, 1991). Impulse is often used in structural mechanics where the effects of impulsive loads must be taken into account (Hamernik and Hsueh, 1991), in certain source modeling situations (Marshall, 1996), and characterizing some effects of impulsive sounds on marine animals (Marshall, 1996; Yelverton *et al*., 1975). The unit of impulse is the pascal-second (Pa-s).

C.4.3 Sound Intensity

Sound energy transfer and power flow are often described in terms of the sound intensity. ***Sound intensity*** is the average rate of sound energy transported in a specified direction through a unit area perpendicular to the propagation direction. Power is energy per time, so sound intensity is equivalent to ***sound power flux density*** — a measure of the sound power transported through a unit area perpendicular to the propagation direction (Fahy, 1995). The units of sound intensity are watts per square-meter (W/m^2).

Instantaneous sound intensity is the product of the instantaneous sound pressure and instantaneous particle velocity. The instantaneous intensity consists of two parts: the *active intensity* associated with the particle velocity component in-phase with the sound pressure and the *reactive intensity*, which is associated with the particle velocity component in-quadrature (90º out-of-phase) with the sound pressure (Fahy, 1995). The term ***sound intensity*** normally refers to the time-averaged (mean) active intensity (Kinsler *et al*., 1982; Fahy, 1995); this quantity corresponds to local net transport of sound energy. In contrast, the reactive intensity represents local oscillatory transport of energy and has a mean of zero.

For a free plane or spherical wave, the sound intensity in the direction of propagation, I, is

$$I = \frac{\overline{P}^{\,2}}{\rho c}\,, \tag{C-7}$$

where ρ is the medium density and c is the sound speed (ANSI, 1994). Equation (C-7) is only valid for plane and spherical waves and does not apply to the general case, for which both sound pressure and particle velocity must be known to calculate sound intensity.

Sound intensity level (IL) is

$$IL = 10\log_{10}\left(\frac{I}{10^{-12}\ \mathrm{W/m^2}}\right), \tag{C-8}$$

where I is the sound intensity in a given direction (ANSI, 1994).

C.4.4 Sound Energy Flux Density

C.4.4.1 Energy Flux Density

Sound energy can also be described by the ***sound energy flux density*** (EFD). In contrast to sound intensity, which is sound *power* flow per unit area, EFD is the sound *energy* flow per unit area. EFD is defined as:

$$E = \int_0^T I(t)\, dt\,, \tag{C-9}$$

where E is the energy flux density, $I(t)$ is the instantaneous acoustic intensity in a given direction and T is the duration of the sound (Urick, 1983). In practice, Eq. (C-9) is rarely used and plane waves are assumed. This makes $I(t) = p^2(t)/\rho c$ and

$$E = \int_0^T \frac{p^2(t)}{\rho c}\, dt\,. \tag{C-10}$$

The units of EFD are joules per square-meter (J/m^2).

Note that Eq. (C-10) is only valid for plane waves. The plane wave assumption may not be valid under some conditions, especially underwater at low frequencies close to a sound source or in an enclosed space. Equation (C-10) is also problematic because sound speed may vary substantially underwater.

C.4.4.2 Energy Flux Density Level

Energy flux density level (EL) is calculated from

$$EL = 10\log_{10}\left(\frac{E}{E_{ref}}\right) = 10\log_{10}\left(\frac{\int_0^T p^2(t)/\rho c\,dt}{P_{ref}^2 T_{ref}/\rho c}\right), \tag{C-11}$$

where E_{ref} is the EFD of a plane wave with rms pressure P_{ref} and duration T_{ref}, in the same environment, so the factor ρc in E and E_{ref} cancel. For underwater applications, the reference quantities P_{ref} and T_{ref} are normally taken to be 1 μPa and 1 s, respectively (Marshall, 1996), so Eq. (C-11) becomes

$$EL = 10\log_{10}\left(\frac{\int_0^T p^2(t)\,dt}{(1\,\mu\text{Pa})^2(1\,\text{s})}\right), \tag{C-12}$$

and EL is in dB re 1 μPa^2-s. For airborne applications, P_{ref} = 20 μPa and EL is expressed in dB re $(20\ \mu\text{Pa})^2$-s.

C.4.4.3 Relationship between EL, SPL, and Exposure Duration

Since $\overline{P^2} = 1/T\int_0^T p^2(t)\,dt$, Eq. (C-12) may be written

$$\begin{aligned} EL &= 10\log_{10}\left(\frac{\overline{P^2}T}{P_{ref}^2 T_{ref}}\right) \\ &= 10\log_{10}\left(\frac{\overline{P^2}}{P_{ref}^2}\right) + 10\log_{10}\left(\frac{T}{T_{ref}}\right) \\ &= SPL + 10\log_{10}\left(T/T_{ref}\right) \end{aligned} \tag{C-13}$$

If T_{ref} = 1 s, and T is the sound duration in seconds,

$$EL = SPL + 10\log_{10}(T). \tag{C-14}$$

Equation (C-14) reveals some important relationships between EL, SPL, and the sound duration:

- $\log_{10}(1) = 0$, so if the sound duration is 1 second, SPL and EL have the same numeric value (but not the same reference quantities). For example, a 1-second sound with an SPL of 100 dB re 1 μPa has an EL of 100 dB re 1 μPa^2-s.

- If the sound duration is constant but the SPL changes, EL will change by the same number of decibels as the SPL.
- If the SPL is held constant and the duration changes, EL will change as a function of $10\log_{10}(T)$:
    - $10\log_{10}(10) = 10$, so **increasing duration by a factor of 10 raises EL by 10 dB**.
    - $10\log_{10}(0.1) = -10$, so **decreasing duration by a factor of 10 lowers EL by 10 dB**.
    - Since $10\log_{10}(2) \approx 3$, **doubling the duration increases EL by 3 dB**.
    - $10\log_{10}(1/2) \approx -3$, so **halving the duration lowers EL by 3 dB**.

C.4.4.4 Total EFD for Multiple Exposures

The ***total energy flux density*** for multiple exposures is found by summing the energy flux densities of the individual exposures:

$$E = \sum_{n=1}^{N} E_n = \sum_{n=1}^{N} \left[\int_0^{T_n} \frac{p_n^2(t)}{\rho c} \, dt \right], \tag{C-15}$$

where N is the number of exposures and E_n, $p_n(t)$, and T_n are the energy flux density, instantaneous sound pressure, and duration of the n^{th} exposure, respectively.

Total energy flux density level is similarly defined:

$$EL = 10\log_{10}\left(\frac{\sum_{n=1}^{N} E_n}{P_{ref}^2 T_{ref}} \right). \tag{C-16}$$

Figure C-2 illustrates the summation of energy for a succession of sonar "pings". In this hypothetical case, each ping has the same duration and SPL. The EL at a particular location from each individual ping is 100 dB re 1 µPa^2-s (red circles). The upper, blue curve shows the running total or cumulative EL.

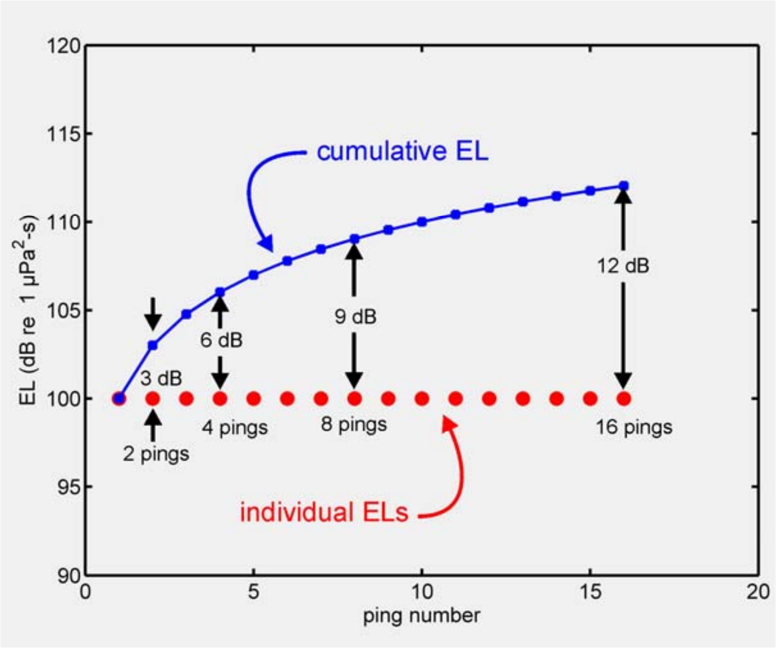

Figure C-2

After the first ping, the cumulative EL is 100 dB re 1 µPa^2-s. Since each ping has the same duration and SPL, receiving two pings is the same as receiving a single ping with twice the duration. The cumulative EL from two pings is therefore 103 dB re 1 µPa^2-s. The cumulative EL from four pings is 3 dB higher than the cumulative EL from two pings, or 106 dB re 1 µPa^2-s. Each doubling of the number of pings increases the cumulative EL by 3 dB.

Figure C-3 shows a more realistic example where the individual pings do not have the same SPL or EL. These data were recorded from a stationary hydrophone as a sound source approached, passed, and moved away from the hydrophone. As the source approached the hydrophone, the received SPL from each ping increased, causing the EL of each ping to increase. After the source passed the hydrophone, the received SPL and EL from each ping decreased as the source moved further away.

Although the cumulative EL increases with each additional ping received, the main contributions are from those pings with the highest individual ELs. Individual pings with ELs 10 dB or more below the ping with the highest level contribute little (less than 0.5 dB) to the total cumulative EL. This is shown in Fig. C-3 where only a small error is introduced by summing the energy from the 8 individual pings with EL > 185 dB re 1 µPa^2-s (black line), as opposed to including all pings (blue line).

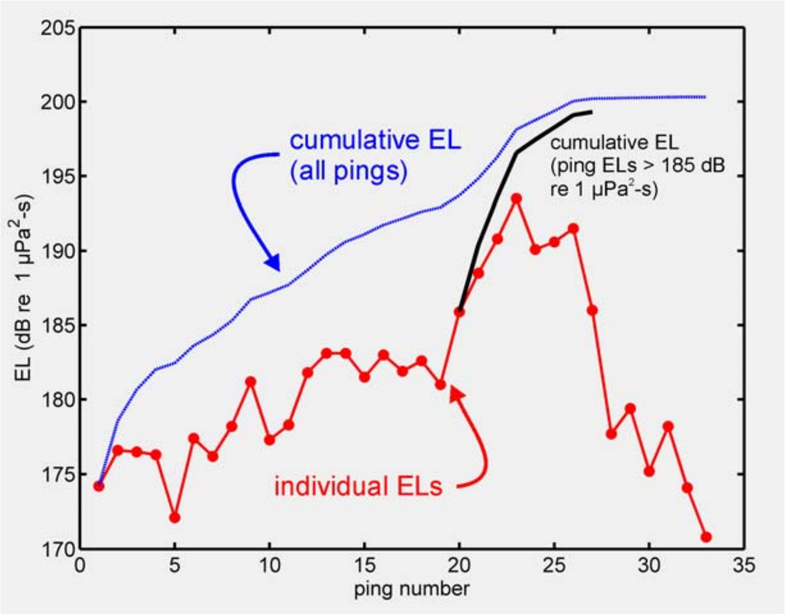

Figure C-3

C.4.5 Sound Exposure

Sound exposure (SE) is defined as

$$SE = \int_0^T p^2(t)\, dt\,, \tag{C-17}$$

and has units of pascal-squared seconds (Pa^2-s). Sound exposure and sound energy flux density are closely related and differ only by the factor of ρc.

The level quantity for sound exposure is called the ***sound exposure level*** (SEL):

$$SEL = 10\log_{10}\left(\frac{\int_0^T p^2(t)\, dt}{P_{ref}^2 T_{ref}} \right). \tag{C-18}$$

If $P_{ref} = 1$ µPa and $T_{ref} = 1$ s, Eq. (C-18) is identical to Eq. C-12).

An expression analogous to Eq. (C-14) may also be developed for SEL, yielding

$$SEL = SPL + 10\log_{10}(T), \tag{C-19}$$

where T is in seconds.

Sound exposure and sound exposure level are often used in airborne applications. In these situations, $p(t)$ is normally replaced with the instantaneous A-weighted sound pressure and the reference pressure $P_{ref} = 20$ μPa (ANSI, 1994).

C.5 Sound Propagation

C.5.1 Reflection and Refraction

When a sound wave propagating in a medium encounters a second medium with a different density or sound speed, part of the incident sound will be ***reflected*** back into the first medium and part will be ***transmitted*** into the second medium. If the second medium has a different sound speed than the first, the propagation direction will change as the sound wave enters the second medium; this phenomenon is called ***refraction***. Refraction may also occur within a single medium if spatial gradients exist in the sound speed.

Refraction of sound resulting from spatial variations in the sound speed is one of the most important phenomena that affects sound propagation in water. The sound speed in the ocean primarily depends on hydrostatic pressure (i.e., depth) and temperature. Sound speed increases with both hydrostatic pressure and temperature. In seawater, temperature has the most important effect on sound speed for depths less than about 300 m. Below 1500 m, the hydrostatic pressure is the dominant factor because the water temperature is relatively constant. The variation of sound speed with depth in the ocean is called a sound speed profile. Although the actual variations in sound speed are small, the existence of sound speed gradients in the ocean has an enormous impact on the propagation of sound in the deep ocean.

C.5.2 Diffraction, Scattering, and Reverberation

Sound waves experience diffraction in much the same manner as light waves. ***Diffraction*** may be thought of as the bending of a sound wave around an obstacle. Common examples include sound heard from a source around the corner of a building and sound propagating through a small gap in an otherwise closed door or window.

An obstacle or inhomogeneity (for example, smoke, suspended particles, or gas bubbles) in the path of a sound wave causes ***scattering*** if secondary sound spreads out from it in a variety of directions (Pierce, 1989). Scattering is similar to diffraction. Normally *diffraction* is used to describe sound bending or scattering from a single object and *scattering* is used when there are multiple objects.

Reverberation refers to the prolongation of a sound that occurs when sound waves in an enclosed space are repeatedly reflected from the boundaries defining the space, even after the source has stopped emitting.

C.5.3 Sound Attenuation and Transmission Loss

As a sound wave passes through a medium, the intensity decreases with distance from the sound source. This phenomenon is known as attenuation or propagation loss. The effects of sound attenuation may be described using the ***transmission loss*** (*TL*), defined as

$$TL = 20\log_{10}\frac{P(1)}{P(r)}, \tag{C-20}$$

where $P(1)$ is the sound pressure at a distance of 1 m from the source and $P(r)$ is the sound pressure at a distance r (Kinsler *et al*., 1982). The units of transmission loss are dB. The transmission loss is used to relate the ***source level*** (*SL*), defined as the *SPL* produced by a sound source at a distance of 1 m, and the ***received level*** (*RL*) at a particular location:

$$RL = SL - TL. \tag{C-21}$$

The main contributors to sound attenuation are

- ***geometrical spreading*** or divergence of the sound wave as it propagates away from the source,
- ***sound absorption*** (conversion of sound energy into heat),
- ***scattering***, ***diffraction***, ***multipath interference***, ***boundary effects***, and other non-geometrical effects (Kinsler *et al*., 1982; Urick, 1983).

C.5.3.1 Spreading Loss

Spreading loss or divergence loss is a geometrical effect representing a regular weakening of a sound wave as it spreads out from a source (Urick, 1983). Spreading describes the reduction in sound pressure caused by the increase in surface area as the distance from a sound source increases. Spherical and cylindrical spreading are common types of spreading loss.

A point sound source in a homogeneous, lossless medium without boundaries will radiate spherical waves — the acoustic energy spreads out from the source in the form of a spherical shell. As the distance from the source increase, the shell surface area increases. If the sound power is fixed, the sound intensity must decrease with distance from the source (intensity is power per unit area). The surface area of a sphere is $4\pi r^2$, where r is the sphere radius, so the change in intensity is proportional to the radius squared. For spherical waves, $I = \overline{P}^2/\rho c$, so the pressure decreases as the inverse of radial distance. This prediction is known as the ***spherical spreading law***. The transmission loss for spherical spreading is

$$TL = 20\log_{10} r, \tag{C-22}$$

where r is the distance from the source. This is equivalent to a 6 dB reduction in *SPL* for each doubling of distance from the sound source.

In ***cylindrical spreading***, spherical waves expanding from the source are constrained by upper and lower boundaries and take on a cylindrical shape. In this case the sound wave expands in the shape of a cylinder rather than a sphere and the transmission loss is

$$TL = 10\log_{10} r. \tag{C-23}$$

Cylindrical spreading is an approximation to wave propagation in a water-filled channel with horizontal dimensions much larger than the depth. Cylindrical spreading predicts a 3 dB reduction in *SPL* for each doubling of distance from the source.

C.5.3.2 Multipath Loss

Multipath refers to sound waves from a single source traveling multiple sound paths before reaching a single receiver. Multipath propagation is common when a source is located relatively close to a boundary and, in underwater applications, when the depth is small relative to the horizontal propagation distance. In multipath propagation, sound may not only travel a direct path from source to receiver, but also be reflected from the surface and/or bottom multiple times before reaching the receiver. The existence of multipaths results in a condition that permits constructive and destructive interference between sound waves propagating in the different paths and the received sound amplitude may be reduced as a result.

C.5.3.3 Surface and Bottom Effects

Because it reflects and scatters sound, the sea surface has a major effect on the propagation of underwater sound in applications where either the source or receiver is at shallow depth. If the sea surface is smooth, the reflected sound pressure is nearly equal to the incident sound pressure; however, if the sea surface is rough, the amplitude of the reflected sound wave will be reduced.

For a particular sound source, the relationship between the "direct" sound wave, which propagates directly from the source to the receiver, and the reflected wave depends on the depth of the source and the distance to the receiver. At some distances the reflected wave will be in-phase with the direct wave (their waveforms add together) and at other distances the two waves will be out-of-phase (their waveforms cancel). This results in constructive and destructive interference between the surface reflected sound wave and produces an interference pattern in the underwater sound field. This phenomenon is called the ***Lloyd mirror effect*** and is an example of multipath propagation loss. In this case the resulting sound field contains an alternating series of sound pressure maxima and minima.

The sea bottom is a reflecting and scattering surface, similar to the sea surface. Sound interaction with the sea bottom is more complex, however, primarily because the acoustic properties of the sea bottom are more variable and the bottom is often layered into regions of differing density and sound speed. The Lloyd mirror effect may also be observed from sound sources located near the sea bottom. For a "hard" bottom such as rock, the reflected wave will be approximately in-phase with the incident wave. Thus, near the ocean bottom, the incident and reflected sound pressures may add together, resulting in an increased sound pressure near the sea bottom.

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