Canary 1.2 User's Manual

Appendix C Sound Amplitude Measurements

About this appendix

This appendix provides a summary of the relationships among sound power, sound intensity, and sound pressure. These quantities are sometimes confused, in part because all three are often expressed as levels using a decibel (dB) scale. First we define each quantity and explain how they are related to each other. We then explain the use of a dB scale to express relative levels of power, intensity, and pressure. An understanding of the basic principles introduced here will be helpful in using Canary.

This appendix is not intended to be a comprehensive review of any aspect of the physics of sound. The goal is to provide a minimal level of understanding needed to use Canary effectively.

The references cited at the end of this appendix provide further background.

Sound power, intensity, and pressure

Sound consists of traveling waves of alternating compression and rarefaction in an elastic medium (such as air or water), generated by some vibrating object (a sound source).

Sound power

A sound source transfers acoustic energy to the surrounding medium at some rate. The average amount of acoustic energy radiated in all directions by a source per unit time is called the *sound power* of the source. Since the usual unit of measurement for energy is the joule, power is usually expressed in joules per second, or watts. One watt equals one joule per second.

Because sound power is a characteristic of a sound source, its value does not depend on where an observer or a measurement instrument is located relative to the source. The power of a sound source may vary over time.

Sound intensity

Consider a sound source radiating sound at a constant power uniformly in all directions. If no sound energy is lost as it radiates away from the source, the total power passing through the surface of any sphere centered on the source is the same, irrespective of the size of the sphere. At greater distances, the same amount of power is distributed over spheres with progressively larger surface areas, resulting in a lower density of power per unit area. This density of power passing through a surface perpendicular to the direction of sound propagation is called *sound intensity*, and is usually expressed in watts per square meter.

The surface area of a sphere of radius r is equal to $4\pi r^2$. Therefore the intensity I (in watts / m^2) of sound at distance r (in m) from a source that is radiating acoustic power equally in all directions is given by

$$I = \frac{W}{4\pi r^2} \tag{C.1}$$

where W is the sound power of the source (in watts).

Sound pressure

Sound pressure is the (usually small) alternating incremental change in pressure from ambient pressure that results from a sound. When no sound is present in a medium (i.e., there is no propagating pressure change), we say that sound pressure is zero, even though the medium does exert some static ambient pressure. The dimensions of pressure are force per unit area. The usual unit of sound pressure is the pascal (abbreviated Pa); one pascal equals one newton per square meter.[1] Since the smallest audible sound pressures in air are on the order of 10^{-6} Pa, sound pressures are usually expressed in µPa.

The RMS magnitude of the pressure change that results from sound of a given intensity depends on a property of the medium known as the *characteristic impedance*.[2] Characteristic impedance is equal to the density of the medium ρ (in kg / m^3) times the speed of sound in the medium c (in m / sec). The units of characteristic impedance are mks rayls, named after the famous acoustician Lord Rayleigh. 1 mks rayl equals 1 kg / (m^2 sec).

Pressure and intensity are related by

$$I = \frac{p^2}{\rho c} \tag{C.2}$$

where p is the RMS or root mean square pressure in Pa, ρc is the characteristic intensity of the medium, and I is intensity in W / m^2. The RMS pressure is equal to the square root of the average of the squared pressure.[3]

Sound pressure is the quantity that is directly measured by most sound measurement or transduction devices, such as sound level meters and microphones.

Sound levels: the decibel scale

Sound power, sound intensity, and sound pressure are all different physical quantities with different dimensions. But all are commonly expressed in decibels, which is sometimes a cause of confusion. Decibels are dimensionless units used to express the logarithm of the ratio between a given value and some specified reference value; some authors require that the values used in the ratio be powers.

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[1] Some older acoustic literature uses pressure units of dynes per square centimeter (dyn / cm^2). One pascal equals 10^{-5} dyn / cm^2.

[2] Characteristic impedance is also sometimes called *specific acoustic resistance* (Urick 1983).

[3] If the sound is a constant-amplitude sinusoidal tone, RMS pressure is equal to the peak pressure divided by √2.

Sound levels: definition of decibel measurements

In general, the term “level” in acoustics refers to the logarithm of the ratio of two quantities.

For a given sound power W, the *sound power level* in dB is given by

$$\text{Sound Power Level} = 10\log_{10}\left(\frac{W}{W_{ref}}\right) \tag{C.3}$$

where W_{ref} is some reference power, which should be clearly stated.

For a given sound intensity I, the *sound intensity level* in dB is given by

$$\text{Sound Intensity Level} = 10\log_{10}\left(\frac{I}{I_{ref}}\right) \tag{C.4}$$

where I_{ref} is some reference intensity. The commonly used reference intensity in air is 10^{-12} W / m^2 (or 1 pW), which is approximately equal to the threshold of audibility of a 1000 Hz tone to a human. For a given sound in air, the intensity level calculated using this reference level is usually within 0.1 dB of the sound pressure level calculated using the standard reference pressure of 20 µPa (see below). The reference intensity for sea water is the intensity that corresponds to the standard reference pressure of 1 µPa (see below), equal to .65 aW / m^2 (=.65 × 10^{-18} W / m^2).

For a given RMS sound pressure p, the *sound pressure level* in dB is given by

$$\text{Sound Pressure Level} = 10\log_{10}\left(\frac{p^2}{p_{ref}^{\;2}}\right)$$

$$= 20\log_{10}\left(\frac{p}{p_{ref}}\right) \tag{C.5}$$

where p_{ref} is some reference pressure. Squaring the pressure values when calculating sound pressure level ensures that the numerical dB values for intensity and pressure will be the same for a given measurement, provided that the reference values for intensity and pressure are chosen appropriately. The standard reference pressure in air is 20 µPa, which is approximately equal to the threshold of audibility of a 1000 Hz tone to a human. Use of 20 µPa and 10^{-12} W / m^2 as the reference values for pressure and intensity in air yields dB pressure and intensity levels that are usually within 0.1 dB of each other. (The exact difference depends on the value of ρc, which depends on temperature and pressure; see below).

Why the decibel scale is useful

There are two reasons why the decibel scale is often a more convenient way of expressing power, intensity, and pressure than using the corresponding physical units. First, the values that commonly occur for the physical units of sound power, intensity, and pressure all span very large numerical ranges. For example, acoustic power outputs of sound sources range from approximately .000000001 watt for a whispering human voice to 40,000,000 watts for a Saturn rocket taking off. The range of sound intensities between a barely audible 1000 Hz tone and the same frequency at the intensity threshold of pain is .000000000001 watt / m^2 to 1 watt / m^2. Sound pressures range from 20 µPa for sounds at the threshold of human audibility to 100,000,000 µPa for a jet engine at a distance of 25 m. It is often inconvenient to work with such large measurement ranges. The dB scale compresses these very large ranges to more manageable ones. For example, if we take 20 µPa as our reference level for sound pressure, the range of sound pressures between a barely audible sound and the jet engine at 25 m is 0 to 134 dB.

The second reason why the decibel scale is useful is that the ability of the human auditory system to discern a difference in intensity between two tones is roughly logarithmically related to the intensity ratio of the tones (Moore, 1989). The "just noticeable difference" or *jnd* in sound intensity of pure tones (typically around 0.2-0.4 dB) is nearly constant across most of the human hearing range when expressed in decibels. The jnd in intensity or pressure would vary hugely over the range of audible intensities if expressed in watts/m^2 or µPa.

Note that positive dB levels indicate the measured value is greater than the reference value; negative dB levels indicate that the measured value is less than the reference.

Some pitfalls to avoid in using dB measurements

Perhaps the most common mistake made in using dB levels is the failure to state the reference value used. The statement that a sound was measured with an intensity or pressure level of 87 dB, without specifying the reference intensity or pressure, is analogous to the statement that the mass of some object is 46%. Even though the values of 20 µPa and 10^{-12} W are common standards for determining pressure and intensity levels in air, the value used should always be explicitly stated. The preferred way of expressing sound pressure levels is to write (for example) that a given sound has a "sound pressure level of 87 dB (re 20 µPa)".

The standard pressure and intensity reference values for dB levels in air and water have been chosen to result in the same (or very similar) dB levels for pressure and intensity *within a given medium*. This is convenient because it allows one to know for example, that a sound with a pressure level of 100 dB in air (re 20 µPa) also has an intensity level of approximately 100 dB in air (re 1 pW/m^2), without having to convert the pressure dB level to absolute units, calculate the intensity, and then calculate the intensity level in dB.

When comparing dB levels of sounds in different media, remember that (1) the "standard" reference values for calculating pressure and intensity dB levels may be different, and (2) differences in characteristic impedance mean that the relationship between pressure and intensity may be very different in different media. Thus a sound pressure of 100 dB in air (re the standard value of 20 µPa) is not the same pressure as 100 dB in sea water (re the standard value of 1 µPa). The former is a pressure of 2 Pa, while the latter is 0.1 Pa. Furthermore, a sound pressure of 2 Pa in air has an intensity of 10 mW/m^2, which is an intensity level of 100 dB (re 1 pW/m^2); but a sound of 2 Pa pressure in water would have an intensity of .0026 mW/m^2, which is an intensity level of 126 dB (re .65 aW/m^2). When comparing pressures or intensities of sounds in different media, it is simplest to use absolute pressure or intensity values, rather than dB levels.

Characteristic impedance

The characteristic impedance of an elastic medium is the product of the medium's density (ρ) and the speed of sound in the medium (c). The density of air (in kg/m^3) is approximately equal to

$$\rho = 1.29\left(\frac{273}{T+273}\right)\left(\frac{P}{0.76}\right) \qquad \text{(C.6)}$$

where T = temperature in °C, and P = barometric pressure in meters of mercury (Beranek, 1986).

The speed of sound in air (in m/sec) is approximately equal to

$$c = 331.4\sqrt{1+\frac{T}{273}} \qquad \text{(C.7)}$$

where T = temperature in °C (Beranek, 1986). Over the range -30° to +30°C this is approximately equal to

$$c = 331.4 + 0.607\ T \qquad (C.8)$$

For water, see Millero, et al. (1980) for formulas for density, and MacKenzie (1981) for formulas for speed of sound.

For further reading

Beranek, L.L. 1986. *Acoustics*, revised edition. Published for the Acoustical Society of America by the American Institute of Physics. xii + 491 p.

Beranek, L.L. 1988. *Acoustical Measurements*, revised edition. Published for the Acoustical Society of America by the American Institute of Physics. xiv + 841 p.

Mackenzie, K.V. 1981. Nine-term equation for sound speed in the oceans. *J. Acoust. Soc. Am.* 70(3): 807-812.

Millero, F. J., C-T. Chen, A. Bradshaw, and K. Schleicher. 1980. A new high pressure equation of state for sea-water. *Deep-Sea Res.* 27A: 255-264.

Moore, B.C.J. 1989. *An Introduction to the Psychology of Hearing*, 3rd ed. Academic Press, New York. 350 + xvi p.

Urick, R. J. 1983. *Principles of Underwater Sound*, 3d edition. McGraw-Hill, New York. 422 + xiii p.