Sound

Contributed by: Alan B. Coppens

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Key Concepts

- Sound is any physical disturbance that causes the mechanical excitation of an elastic medium, creating a propagating wave in the surrounding elements of that medium.
- If a sound wave contains the appropriate range of audible frequencies, and impinges on the ear, it generates nerve impulses that are perceived as hearing.
- A sound wave compresses and dilates the material elements it passes through, generating associated pressure fluctuations.
- A basic kind of sound wave, the plane wave, progresses through a medium in one direction.Harmonic waves, transient waves, continuous waves, and standing waves, are all examples of plane waves.
- The intensity of a sound is conventionally expressed in terms of a logarithmic scale with the dimensionless unit of the decibel (dB). The weakest sounds have an intensity level of 0 dB, whereas hearing can be damaged if exposed to levels above about 120 dB.
- Propagation of a sound wave is affected by physical phenomena such as diffraction, density of the surrounding medium (which affects sound speed), reflection, and absorption. Eventually, the acoustic energy of the sound wave is converted to heat, and the sound wave is weakened.

The mechanical excitation of an elastic medium. A source of sound undergoes changes of shape, size, or position that disturb adjacent elements of the surrounding medium, causing them to move about their equilibrium positions. These disturbances in turn are transmitted elastically to neighboring elements. This chain of events propagates to larger and larger distances, constituting a wave traveling through the medium. If the wave contains the appropriate range of frequencies audible to humans—that is, not infrasonic or ultrasonic— and impinges on the ear, it generates the nerve impulses that are perceived as hearing (Fig. 1). *See also:* HEARING (HUMAN).

Acoustic pressure

A sound wave compresses and dilates the material elements it passes through, generating associated pressure fluctuations. An appropriate sensor (a microphone, for example) placed in the sound field will record a time-varying deviation from the equilibrium pressure found at that point within the fluid. The changing total

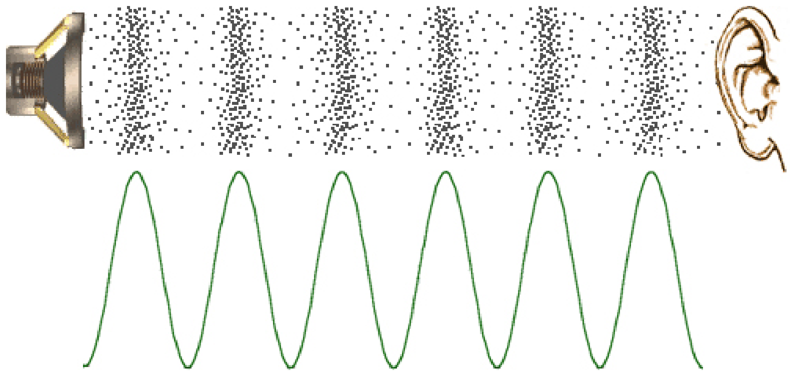

Fig. 1 **Sound from a loudspeaker, depicted as the propagation of waves of air molecules to a human ear (top), and as a two-dimensional sine wave (bottom).**

pressure P measured will vary about the equilibrium pressure P_0 by a small amount called the acoustic pressure, $p = P - P_0$. The SI unit of pressure is the pascal (Pa), equal to 1 newton per square meter (N/m^2). Standard atmospheric pressure is approximately 1 bar = 10^6 dyne/cm^2 = 10^5 Pa. For a typical sound in air, the amplitude of the acoustic pressure may be about 0.1 Pa (one-millionth of an atmosphere); most sounds cause relatively slight perturbations of the total pressure. *See also:* ATMOSPHERE; MICROPHONE; PRESSURE; PRESSURE MEASUREMENT; SOUND PRESSURE.

Plane waves

One of the more basic sound waves is the traveling plane wave. This is a pressure wave progressing through the medium in one direction, say the +x direction, with infinite extent in the y and z directions. A two-dimensional analog is ocean surf advancing toward a very long, straight, and even beach. The surf looks like a long, corrugated surface advancing uniformly toward the shore but extending transversely in a series of parallel peaks and troughs. *See also:* WAVE (PHYSICS); WAVE EQUATION; WAVE MOTION.

Harmonic waves

A most important plane wave, both conceptually and mathematically, is the smoothly oscillating monofrequency plane wave described by Eq. (1).

$$p = P\cos\left[2\pi f\left(t - \frac{x}{c}\right)\right] \tag{1}$$

The amplitude of this wave is P. The phase (argument of the cosine) increases with time, and at a point in space the cosine will pass through one full cycle for each increase in phase of 2π. The period T required for each cycle must therefore be such that $2\pi fT = 2\pi$, or $T = 1/f$, so that $f = 1/T$ can be identified as the frequency of oscillation of the pressure wave. During this period T, each portion of the waveform has advanced through a distance $\lambda = cT$, and this distance λ must be the wavelength. This gives the fundamental relation, Eq. (2),

$$\lambda f = c \tag{2}$$

between the frequency, wavelength, and speed of sound in any medium. For example, in air at room temperature the speed of sound is 343 m/s (1125 ft/s). A sound of frequency 1 kHz (1000 cycles per second) will have a wavelength of $\lambda = c/f = 343/1000$ m = 0.34 m (1.1 ft). Lower frequencies will have longer wavelengths: a sound of 100 Hz in air has a wavelength of 3.4 m (11 ft). For comparison, in freshwater at room temperature the speed of sound is 1480 m/s (4856 ft/s), and the wavelength of 1-kHz sound is nearly 1.5 m (5 ft), almost five times greater than the wavelength for the same frequency in air.

Transient and continuous waves

Monofrequency waves are the building blocks for more complicated waves that are either continuous or transient in time. For example, a sawtooth continuous wave has acoustic pressure which, during each cycle, begins at a positive value $P_{\max}$, decreases uniformly (linearly with time) to a negative value $-P_{\max}$ at the end of the period T, and then jumps instantaneously back to the positive value $P_{\max}$, repeating this cycle indefinitely. It is a direct consequence of the wave equation that this waveform can be described equivalently as a Fourier superposition, or summation, of waves $p_1 + p_2 + p_3 + \cdots$, each of the form of Eq. (3),

$$p_n = \frac{2}{\pi}\frac{P_{\max}}{n}\sin\left[2\pi nf\left(t - \frac{x}{c}\right)\right] \tag{3}$$

where the fundamental frequency $f = 1/T$ gives the repetition rate of the waveform and n has integer values 1, 2, 3, ... The waves p_n constitute the overtones of the waveform. In this case the frequencies nf of the overtones are integer multiples of the fundamental frequency f, and the overtones are termed harmonics. Any signal that is non-repeating or is nonzero only with some limited duration of time can be written as a summation of waves that are not harmonically related or, in the extreme, an integration of waveforms of all frequencies.

These considerations show that a study of monofrequency sound waves is sufficient to deal with all sound waves, and that the fundamental concepts of frequency and wavelength permeate all aspects of sound. *See also:* FOURIER SERIES AND TRANSFORMS; HARMONIC (PERIODIC PHENOMENA); NONSINUSOIDAL WAVEFORM; WAVEFORM.

Standing waves

In many situations, sound is generated in an enclosed space that traps the sound within or between boundaries. This kind of wave would be found within a sounding organ pipe and is analogous to a vibrating guitar string. More complicated standing waves can be formed from waves traveling in a number of directions. For example, vibrating panels or drum heads support standing waves in two dimensions, and steady tones in rooms can excite three-dimensional standing waves. *See also:* VIBRATION.

Particle speed and displacement

As sound passes through a fluid, the small fluid elements are displaced from their equilibrium rest positions by the fluctuating pressure gradients. The motion of a fluid element is described by the particle velocity $\vec{u}$ with which it moves about its equilibrium position. This is related to the pressure by Newton's second law. With the neglect of some small nonlinear and viscous terms, this law can be written as Eq. (4),

$$\rho_o \frac{\partial \vec{u}}{\partial t} = -\nabla p \tag{4}$$

where ρ_0 is the equilibrium density of the fluid and ∇ is the gradient operator. *See also:* CALCULUS OF VECTORS; FLUID-FLOW PRINCIPLES; NEWTON'S LAWS OF MOTION.

For a one-dimensional plane wave moving in the +x direction, the acoustic pressure p and particle speed u are proportional and related by $p/u = \rho_0\ c$. The product $\rho_0\ c$ is a basic measure of the elastic properties of the fluid and is called the characteristic impedance. This is an index of the acoustic "hardness" or "softness" of a fluid or solid. (The term "characteristic impedance" is restricted to the plane-wave value of $\rho_0\ c$; more generally, the term "specific acoustic impedance" is used.) *See also:* ACOUSTIC IMPEDANCE.

Because fluids cannot support shear (except for small effects related to viscosity), the particle velocity of the fluid elements is parallel to the direction of propagation of the sound wave and the motion is longitudinal. In contrast, solids can transmit shearing or bending motion—reeds, strings, drum heads, tuning forks, and chimes can vibrate transversely.

Description of sound

The characterization of a sound is based primarily on human psychological responses to it. Because of the nature of human perceptions, the correlations between basically subjective evaluations such as loudness, pitch, and timbre and more physical qualities such as energy, frequency, and frequency spectrum are subtle and not necessarily universal.

Intensity, loudness, and the decibel

The strength of a sound wave is described by its intensity I. From basic physical principles, the instantaneous rate at which energy is transmitted by a sound wave through unit area is given by the product of acoustic pressure and the component of particle velocity perpendicular to the area. If all quantities are expressed in SI units (pressure amplitude or effective pressure amplitude in Pa, speed of sound in m/s, and density in kg/m^3), then the intensity will be in watts per square meter (W/m^2). *See also:* SOUND INTENSITY.

Because of the way the strength of a sound is perceived, it has become conventional to specify the intensity of sound in terms of a logarithmic scale with the (dimensionless) unit of the decibel (dB). An individual with unimpaired hearing has a threshold of perception near 10^{-12} W/m^2 between about 2 and 4 kHz, the frequency range of greatest sensitivity. As the intensity of a sound of fixed frequency is increased, the subjective evaluation of loudness also increases, but not proportionally. Rather, the listener tends to judge that every successive doubling of the acoustic intensity corresponds to the same increase in loudness.

The weakest sounds that can be perceived have an intensity level of 0 dB, normal conversational levels are around 60 dB, and hearing can be damaged if exposed even for short times to levels above about 120 dB. Every doubling of the intensity increases the intensity level by 3 dB. For sounds between about 500 Hz and 4 kHz, the loudness of the sound is doubled if the intensity level increases about 9 dB. This doubling of loudness corresponds to about an eightfold increase in intensity. For sounds lying higher than 4 kHz or lower than 500 Hz, the sensitivity of the ear is appreciably lessened. Sounds at these frequency extremes must have higher threshold intensity levels before they can be perceived, and doubling of the loudness requires smaller changes in the intensity with the result that at higher levels sounds of equal intensities tend to have more similar loudnesses. It is because of this characteristic that reducing the volume of recorded music causes it to sound thin or tinny, lacking both highs and lows of frequency. *See also:* DECIBEL; LOUDNESS.

Since most sound-measuring equipment detects acoustic pressure rather than intensity, it is convenient to define an equivalent scale in terms of the sound pressure level.

The intensity level and sound-pressure level are usually taken as identical, but this is not always true (these levels may not be equivalent for standing waves, for example).

Frequency and pitch

How “high” sound of a particular frequency appears to be is described by the sense of pitch. A few minutes with a frequency generator and a loudspeaker show that pitch is closely related to the frequency. Higher pitch corresponds to higher frequency, with small influences depending on loudness, duration, and the complexity of the waveform. For the pure tones (monofrequency sounds) encountered mainly in the laboratory, pitch and frequency are not found to be proportional. For the more complex waveforms usually encountered, however, the presence of harmonics favors a proportional relationship between pitch and frequency. *See also:* PITCH.

Consonance and dissonance

Two tones generated together cannot be distinguished from each other if their frequencies are the same. If their frequencies f_1 and (slightly higher) f_2 are nearly but not exactly identical, the ear will perceive a slow beating, hearing a single tone that is the average of the frequencies of the two individual tones and an amplitude that varies slowly according to the difference of the two frequencies. As f_2 increases more, the beating will quicken until it first becomes coarse and unpleasant (dissonant) and then resolves into two separate tones of different pitches. With still further increase, a sense of beating and dissonance will reappear, leading into a blending or consonance that then breaks again into beats and dissonance, and the whole cycle of events repeats. These islands of consonance surrounded by beating and dissonance are attained whenever the ratio of the two frequencies becomes that of small integers, $f_2/f_1 = 1/1, 2/1, 3/2, 4/3, \ldots$. The larger the integers in the ratio, the subtler the effects become. *See also:* BEAT.

Frequency spectrum and timbre

Sounds can be characterized by many subjective terms such as clean, nasal, edgy, brassy, or hollow. Each term attempts to describe the nature of a complex waveform that may be of very short or long duration and that consists of a superposition or combination of a number of pure tones. The sound of a person's whistling or of a flute played softly often has a pure, clean, but somewhat dull quality. These sounds consist mainly of a pure tone with few or no harmonics. As described above, complex repetitive waveforms are made up of a fundamental tone and a number of harmonics whose frequencies are integer multiples of the fundamental frequency. Blown or bowed instruments such as flute, bowed violin, oboe, and trumpet provide good examples. Other sounds are transient, or nonrepetitive, and usually consist of a fundamental plus a number of overtones whose frequencies are not integer multiples of the lowest. Piano, tympani, cymbals, and plucked violin generate these kinds of sounds.

An important factor is the way in which a sound commences. When a chime is struck, there is a clear sharp onset much like a hammer hitting an anvil; the higher overtones are quite short in duration, however, and quickly die out, leaving only a few nearly harmonic lower overtones that give a clear sensation of pitch. Plucking a guitar string near the bridge with a fingernail yields a similar effect. A gong gives a very complex impression because there are many nonconsonant overtones present, dying away at different rates, so that the sound seems to shift in pitch and timbre. It is the abundance of harmonics and overtones, the distribution of intensity among them, and how they preferentially die away in time that provide the subjective evaluation of the nature or timbre of the sound. *See also:* MUSICAL ACOUSTICS.

Propagation of sound

Plane waves are a considerable simplification of an actual sound field. The sound radiated from a source (such as a loudspeaker, a hand clap, or a voice) must spread outward much like the widening circles from a pebble thrown into a lake. A simple model of this more realistic case is a spherical source vibrating uniformly in all directions with a single frequency of motion. The sound field must be spherically symmetric with an amplitude that decreases with increasing distance from the source, and the fluid elements must have particle velocities that are directed radially.

Not all sources radiate their sound uniformly in all directions. When someone is speaking in an unconfined space, for example an open field, a listener circling the speaker hears the voice most well defined when the speaker is facing the listener. The voice loses definition when the speaker is facing away from the listener. Higher frequencies tend to be more pronounced in front of the speaker, whereas lower frequencies are perceived more or less uniformly around the speaker.

Diffraction

It is possible to hear but not see around the corner of a tall building. However, higher-frequency sound (with shorter wavelength) tends to bend or “spill” less around edges and corners than does sound of lower frequency. The ability of a wave to spread out after traveling through an opening and to bend around obstacles is termed diffraction. This diffraction is why it is often difficult to shield a listener, in a residence for example, from an undesired source of noise, such as traffic, by simply erecting a brick or concrete wall between source and receiver. *See also:* ACOUSTIC NOISE; DIFFRACTION.

Speed of sound

In fluids, the acoustic pressure and the density variation are related by Eq. (5),

$$p = \mathscr{R} s \tag{5}$$

where the condensation s is $(\rho - \rho_0)/\rho_0$ and $\mathscr{R}$ is a constant of proportionality. This is a three-dimensional Hooke’s law stating that stress and strain are proportional. The propagation of sound requires such rapid density changes that there is not enough time for thermal energy to flow from compressed (higher-temperature) elements to decompressed (lower-temperature) elements. Because there is little heat flow, the process is nearly adiabatic and $\mathscr{R}$ is the adiabatic bulk modulus (rather than the more familiar isothermal modulus relevant to constant-temperature processes). A derivation of the wave equation for a fluid reveals that the speed of sound is given by Eq. (6). Equations (4) and (5) can be combined to give Eq. (6). *See also:* ADIABATIC PROCESS; HOOKE'S LAW

$$c^2 = \frac{\mathscr{R}}{\rho_0} \tag{6}$$

$$p = \rho_0 c^2 s \tag{7}$$

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In most fluids, the equation of state is not known, and the speed of sound must be measured directly or inferred from experimental determinations of the bulk modulus. In distilled water the measured speed of sound in meters per second can be represented by a simplified equation (8),

$$c = 1403 + 4.9T - 0.05T^2 + 0.16\mathscr{P}_0 \tag{8}$$

where T is the temperature in degrees Celsius and $\mathscr{P}_0$ is the equilibrium pressure in bars. For most gases at reasonable pressures and temperatures, however, the equation of state is known to be very close to the perfect gas law, so a theoretical expression for the speed of sound in an ideal gas, is Eq. (9).

$$c = \sqrt{\gamma R T_K} \tag{9}$$

Thus, the speed of sound in an ideal gas depends on temperature, increasing as the square root of the absolute temperature. Because many applications of Eq. (9) are for gases around room temperature, it is convenient to re-express the formula in terms of degrees Celsius and the speed of sound c_0 at $T = 0°C$ (32°F), as in Eq. (10).

$$c = c_0\sqrt{1 + \frac{T}{273}} \tag{10}$$

This equation can be used to calculate the speed of sound for a perfect gas at any temperature in terms of the speed of sound in that gas at 0°C (32°F). In air, for example, $c_0 = 331$ m/s (1086 ft/s), and at 20°C (68°F) the speed of sound is calculated to be 343 m/s (1125 ft/s). *See also:* GAS; HEAT CAPACITY; UNDERWATER SOUND.

In solids, the sound speed depends on the transverse extent of the solid with respect to the wave. If the solid is rodlike, with transverse dimensions less than the acoustic wavelength, the solid can swell and contract transversely with relative ease, which tends to slow the wave down. For this case, the speed of sound is given by

Eq. (11)

$$c = \sqrt{\frac{\mathscr{Y}}{\rho_0}} \tag{11}$$

where $\mathscr{Y}$ is Young's modulus. If, in the other extreme, the solid has transverse dimensions much larger than the acoustic wavelength, then a longitudinal wave will travel with a greater speed of sound given by Eq. (12),

$$c = \sqrt{\frac{\mathscr{B} + 4\mathscr{G}/3}{\rho_0}} \tag{12}$$

where $\mathscr{G}$ is the shear modulus. These two different propagation speeds are often called bar and bulk sound speeds, respectively. *See also:* ELASTICITY; YOUNG'S MODULUS.

Reflection and transmission

If a sound wave traveling in one fluid strikes a boundary between the first fluid and a second, then there may be reflection and transmission of sound. For most cases, it is sufficient to consider the waves to be planar. The first fluid contains the incident wave of intensity I_i and reflected wave of intensity I_r, the second fluid, from which the sound is reflected, contains the transmitted wave of intensity I_t. The directions of the incident, reflected, and transmitted plane sound waves may be specified by the grazing angles measured between the respective directions of propagation and the plane of the reflecting surface. *See also:* REFLECTION OF SOUND.

Absorption

When sound propagates through a medium, there are a number of mechanisms by which the acoustic energy is converted to heat and the sound wave weakened until it is entirely dissipated. This absorption of acoustic energy is characterized by a spatial absorption coefficient α for traveling waves. For historical reasons, and to avoid ambiguity with other quantities, absorption is given in units of nepers per meter (Np/m), where the neper is a dimensionless label. Because of the use of sound pressure level in acoustics, spatial absorption can also be specified in terms of decibels per meter (dB/m). The temporal absorption coefficient β, given in nepers per second (Np/s), is related to α by $\beta = \alpha c$. *See also:* NEPER.

Classical mechanisms. One mechanism of absorption is shear viscosity, the analog of friction for fluids. Molecules traveling between fluid elements of differing speeds will transfer momentum between the elements through intermolecular collisions, diffusing the differences in collective motion into random (thermal) motion of the individual molecules. This loss of acoustic energy into heat is described by the absorption coefficient for viscosity $\alpha\upsilon$. *See also:* FRICTION; VISCOSITY.

Another mechanism arises from the thermal conductivity of the fluid. In a perfectly insulating fluid (zero thermal conductivity), cold regions could not conduct thermal energy away from hot regions. In real materials, small amounts of thermal energy can flow between these hotter and colder regions, tending to equalize the temperatures a little and converting acoustic energy into heat. This energy conversion is described by a thermal absorption coefficient α_t, which also increases with the square of the frequency. The losses from shear viscosity and thermal conductivity add together to give the classical thermoviscous absorption coefficient $\alpha_c = \alpha\upsilon + \alpha_t$. *See also:* HEAT CONDUCTION.

Structural relaxation. In certain liquids, including water, acetone, and alcohols, the observed absorption is significantly larger than that predicted by the classical absorption coefficient but has the same frequency dependence. A postulated mechanism is a structural relaxation, involving transitions between two preferred clusterings of nearest neighbors, one favored at lower density and the other at higher. When the sound wave travels through the fluid, the pressure and temperature fluctuations cause transitions between these two structural states. The net effect is to introduce a bulk viscosity coefficient additive to the shear viscosity. In water, the effect of bulk viscosity results in a measured absorption coefficient about three times the classical value. *See also:* ACETONE; ALCOHOL; WATER.

Thermal molecular relaxation. In some gases with polyatomic molecules, like air, thermal molecular relaxation is an important mechanism of absorption. When two gas molecules collide, in addition to simply rebounding from each other like two billiard balls, one or the other of the molecules may be excited into internal vibrations, thus removing energy from the collective acoustic motion. Once excited, the molecule may release this energy back into kinetic energy of motion during another collision, but this release is not coordinated with the acoustic wave and so appears at random, contributing to the thermal motion of the molecules. In air, collisions involving carbon dioxide with either nitrogen or oxygen, and oxygen with water vapor, are important in exciting internal energy states. The total absorption coefficient is a strong function of humidity and frequency throughout the audible range of frequencies. The effects are strong enough that the reverberation characteristics of a poorly ventilated concert hall can change during the course of a concert as the moisture exuded by the audience alters the humidity. *See also:* AIR; CARBON DIOXIDE; COLLISION (PHYSICS); HUMIDITY; NITROGEN; OXYGEN.

Chemical relaxation. In certain liquids, there can be chemical relaxations involving the concentrations of various chemical species and how they change with temperature. A sound wave passing through the liquid causes local temperature changes, and these in turn can cause changes in the ionization of dissolved salts. The basic mechanisms cause losses quite similar in effect to the molecular thermal relaxation described above. In seawater, chemical relaxations contribute appreciable additional absorption at frequencies below about 100 kHz for magnesium sulfate ($MgSO_4$) and below about 1 kHz for boric acid. *See also:* LIQUID; SEAWATER.

Alan B. Coppens

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