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Speed of sound

The **speed of sound** is the distance travelled per unit time by a sound wave as it propagates through an elastic medium. At 20 °C (68 °F), the speed of sound in air is about 343 metres per second (1,235 km/h; 1,125 ft/s; 767 mph; 667 kn), or a kilometre in 2.9 s or a mile in 4.7 s. It depends strongly on temperature, but also varies by several metres per second, depending on which gases exist in the medium through which a soundwave is propagating.

The speed of sound in an ideal gas depends only on its temperature and composition. The speed has a weak dependence on frequency and pressure in ordinary air, deviating slightly from ideal behavior.

In common everyday speech, *speed of sound* refers to the speed of sound waves in air. However, the speed of sound varies from substance to substance: sound travels most slowly in gases; it travels faster in liquids; and faster still in solids. For example, (as noted above), sound travels at 343 m/s in air; it travels at 1,480 m/s in water (4.3 times as fast as in air); and at 5,120 m/s in iron (about 15 times as fast as in air). In an exceptionally stiff material such as diamond, sound travels at 12,000 metres per second (39,000 ft/s)[1]—about 35 times as fast as in air—which is around the maximum speed that sound will travel under normal conditions.

Sound waves in solids are composed of compression waves (just as in gases and liquids), and a different type of sound wave called a shear wave, which occurs only in solids. Shear waves in solids usually travel at different speeds, as exhibited in seismology. The speed of compression waves in solids is determined by the medium's compressibility, shear modulus and density. The speed of shear waves is determined only by the solid material's shear modulus and density.

In fluid dynamics, the speed of sound in a fluid medium (gas or liquid) is used as a relative measure for the speed of an object moving through the medium. The ratio of the speed of an object to the speed of sound in the fluid is called the object's Mach number. Objects moving at speeds greater than *Mach 1* are said to be traveling at supersonic speeds.

Sound measurements	
Characteristic	Symbols
Sound pressure	p, SPL, L_{PA}
Particle velocity	v, SVL
Particle displacement	δ
Sound intensity	I, SIL
Sound power	P, SWL, L_{WA}
Sound energy	W
Sound energy density	w
Sound exposure	E, SEL
Acoustic impedance	Z
Speed of sound	c
Audio frequency	AF
Transmission loss	TL

Contents

History

Sir Isaac Newton computed the speed of sound in air as 979 feet per second (298 m/s), which is too low by about 15%.[2] Newton's analysis was good save for neglecting the (then unknown) effect of rapidly-fluctuating temperature in a sound wave (in modern terms, sound wave compression and expansion of air is an adiabatic process, not an isothermal process). This error was later rectified by Laplace.[3]

During the 17th century there were several attempts to measure the speed of sound accurately, including attempts by Marin Mersenne in 1630 (1,380 Parisian feet per second), Pierre Gassendi in 1635 (1,473 Parisian feet per second) and Robert Boyle (1,125 Parisian feet per second).[4]

In 1709, the Reverend William Derham, Rector of Upminster, published a more accurate measure of the speed of sound, at 1,072 Parisian feet per second.[4] Derham used a telescope from the tower of the church of St Laurence, Upminster to observe the flash of a distant shotgun being fired, and then measured the time until he heard the gunshot with a half-second pendulum. Measurements were made of gunshots from a number of local landmarks, including North Ockendon church. The distance was known by triangulation, and thus the speed that the sound had travelled was calculated.[5]

Basic concepts

The transmission of sound can be illustrated by using a model consisting of an array of spherical objects interconnected by springs.

In real material terms, the spheres represent the material's molecules and the springs represent the bonds between them. Sound passes through the system by compressing and expanding the springs, transmitting the acoustic energy to

neighboring spheres. This helps transmit the energy in-turn to the neighboring sphere's springs (bonds), and so on.

The speed of sound through the model depends on the stiffness/rigidity of the springs, and the mass of the spheres. As long as the spacing of the spheres remains constant, stiffer springs/bonds transmit energy quicker, while larger spheres transmit the energy slower.

In a real material, the stiffness of the springs is known as the "elastic modulus", and the mass corresponds to the material density. Given that all other things being equal (ceteris paribus), sound will travel slower in spongy materials, and faster in stiffer ones. Effects like dispersion and reflection can also be understood using this model.

For instance, sound will travel 1.59 times faster in nickel than in bronze, due to the greater stiffness of nickel at about the same density. Similarly, sound travels about 1.41 times faster in light hydrogen (protium) gas than in heavy hydrogen (deuterium) gas, since deuterium has similar properties but twice the density. At the same time, "compression-type" sound will travel faster in solids than in liquids, and faster in liquids than in gases, because the solids are more difficult to compress than liquids, while liquids in turn are more difficult to compress than gases.

Some textbooks mistakenly state that the speed of sound increases with density. This notion is illustrated by presenting data for three materials, such as air, water and steel, which also have vastly different compressibility, more which making up for the density differences. An illustrative example of the two effects is that sound travels only 4.3 times faster in water than air, despite enormous differences in compressibility of the two media. The reason is that the larger density of water, which works to *slow* sound in water relative to air, nearly makes up for the compressibility differences in the two media.
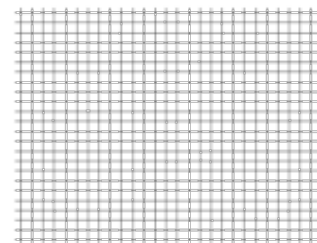
A practical example can be observed in Edinburgh when the "One o' Clock Gun" is fired at the eastern end of Edinburgh Castle. Standing at the base of the western end of the Castle Rock, the sound of the Gun can be heard through the rock, slightly before it arrives by the air route, partly delayed by the slightly longer route. It is particularly effective if a multi-gun salute such as for "The Queen's Birthday" is being fired.

Compression and shear waves

In a gas or liquid, sound consists of compression waves. In solids, waves propagate as two different types. A longitudinal wave is associated with compression and decompression in the direction of travel, and is the same process in gases and liquids, with an analogous compression-type wave in solids. Only compression waves are supported in gases and liquids. An additional type of wave, the transverse wave, also called a shear wave, occurs only in solids because only solids support elastic deformations. It is due to elastic deformation of the medium perpendicular to the direction of wave travel; the direction of shear-deformation is called the "polarization" of this type of wave. In general, transverse waves occur as a pair of orthogonal polarizations.

Pressure-pulse or compression-type wave (longitudinal wave) confined to a plane. This is the only type of sound wave that travels in fluids (gases and liquids). A pressure-type wave may also travel in solids, along with other types of waves (transverse waves, see below)

These different waves (compression waves and the different polarizations of shear waves) may have different speeds at the same frequency. Therefore, they arrive at an observer at different times, an extreme example being an earthquake, where sharp compression waves arrive first and rocking transverse waves seconds later.

The speed of a compression wave in a fluid is determined by the medium's compressibility and density. In solids, the compression waves are analogous to those in fluids, depending on compressibility and density, but with the additional

factor of shear modulus which affects compression waves due to off-axis elastic energies which are able to influence effective tension and relaxation in a compression. The speed of shear waves, which can occur only in solids, is determined simply by the solid material's shear modulus and density.

Equations

The speed of sound in mathematical notation is conventionally represented by *c*, from the Latin *celeritas* meaning "velocity".

For fluids in general, the speed of sound *c* is given by the Newton–Laplace equation:

$$c = \sqrt{\frac{K_s}{\rho}},$$

where

- K_s is a coefficient of stiffness, the isentropic bulk modulus (or the modulus of bulk elasticity for gases);
- ρ is the density.

Thus the speed of sound increases with the stiffness (the resistance of an elastic body to deformation by an applied force) of the material and decreases with an increase in density. For ideal gases, the bulk modulus *K* is simply the gas pressure multiplied by the dimensionless adiabatic index, which is about 1.4 for air under normal conditions of pressure and temperature.

For general equations of state, if classical mechanics is used, the speed of sound *c* is given by

$$c = \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s},$$
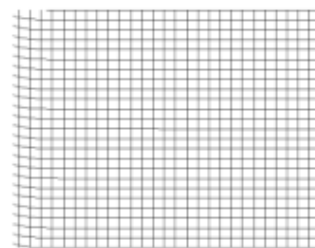
where

- *p* is the pressure;
- ρ is the density and the derivative is taken isentropically, that is, at constant entropy *s*.

If relativistic effects are important, the speed of sound is calculated from the relativistic Euler equations.

In a non-dispersive medium, the speed of sound is independent of sound frequency, so the speeds of energy transport and sound propagation are the same for all frequencies. Air, a mixture of oxygen and nitrogen, constitutes a non-dispersive medium. However, air does contain a small amount of CO_2 which *is* a dispersive medium, and causes dispersion to air at ultrasonic frequencies (> 28 kHz).[6]

In a dispersive medium, the speed of sound is a function of sound frequency, through the dispersion relation. Each frequency component propagates at its own speed, called the phase velocity, while the energy of the disturbance propagates at the group velocity. The same phenomenon occurs with light waves; see optical dispersion for a description.

Transverse wave affecting atoms initially confined to a plane. This additional type of sound wave (additional type of elastic wave) travels only in solids, for it requires a sideways shearing motion which is supported by the presence of elasticity in the solid. The sideways shearing motion may take place in **any** direction which is at right-angle to the direction of wave-travel (only one shear direction is shown here, at right angles to the plane). Furthermore, the right-angle shear direction may change over time and distance, resulting in different types of *polarization* of shear-waves

Dependence on the properties of the medium

The speed of sound is variable and depends on the properties of the substance through which the wave is travelling. In solids, the speed of transverse (or shear) waves depends on the shear deformation under shear stress (called the shear modulus), and the density of the medium. Longitudinal (or compression) waves in solids depend on the same two factors with the addition of a dependence on compressibility.

In fluids, only the medium's compressibility and density are the important factors, since fluids do not transmit shear stresses. In heterogeneous fluids, such as a liquid filled with gas bubbles, the density of the liquid and the compressibility of the gas affect the speed of sound in an additive manner, as demonstrated in the hot chocolate effect.

In gases, adiabatic compressibility is directly related to pressure through the heat capacity ratio (adiabatic index), while pressure and density are inversely related to the temperature and molecular weight, thus making only the completely independent properties of *temperature and molecular structure* important (heat capacity ratio may be determined by temperature and molecular structure, but simple molecular weight is not sufficient to determine it).

In low molecular weight gases such as helium, sound propagates faster as compared to heavier gases such as xenon. For monatomic gases, the speed of sound is about 75% of the mean speed that the atoms move in that gas.

For a given ideal gas the molecular composition is fixed, and thus the speed of sound depends only on its temperature. At a constant temperature, the gas pressure has no effect on the speed of sound, since the density will increase, and since pressure and density (also proportional to pressure) have equal but opposite effects on the speed of sound, and the two contributions cancel out exactly. In a similar way, compression waves in solids depend both on compressibility and density—just as in liquids—but in gases the density contributes to the compressibility in such a way that some part of each attribute factors out, leaving only a dependence on temperature, molecular weight, and heat capacity ratio which can be independently derived from temperature and molecular composition (see derivations below). Thus, for a single given gas (assuming the molecular weight does not change) and over a small temperature range (for which the heat capacity is relatively constant), the speed of sound becomes dependent on only the temperature of the gas.

In non-ideal gas behavior regimen, for which the van der Waals gas equation would be used, the proportionality is not exact, and there is a slight dependence of sound velocity on the gas pressure.

Humidity has a small but measurable effect on the speed of sound (causing it to increase by about 0.1%–0.6%), because oxygen and nitrogen molecules of the air are replaced by lighter molecules of water. This is a simple mixing effect.

Altitude variation and implications for atmospheric acoustics

In the Earth's atmosphere, the chief factor affecting the speed of sound is the temperature. For a given ideal gas with constant heat capacity and composition, the speed of sound is dependent *solely* upon temperature; see Details below. In such an ideal case, the effects of decreased density and decreased pressure of altitude cancel each other out, save for the residual effect of temperature.

Since temperature (and thus the speed of sound) decreases with increasing altitude up to 11 km, sound is refracted upward, away from listeners on the ground, creating an acoustic shadow at some distance from the source.[7] The decrease of the speed of sound with height is referred to as a negative sound speed gradient.

However, there are variations in this trend above 11 km. In particular, in the stratosphere above about 20 km, the speed of sound increases with height, due to an increase in temperature from heating within the ozone layer. This produces a positive speed of sound gradient in this region. Still another region of positive gradient occurs at very high altitudes, in the aptly-named thermosphere above 90 km.

Practical formula for dry air

The approximate speed of sound in dry (0% humidity) air, in metres per second, at temperatures near 0 °C, can be calculated from

$$c_{\text{air}} = (331.3 + 0.606 \cdot \vartheta) \ \ \text{m/s,}$$

where ϑ is the temperature in degrees Celsius (°C).

This equation is derived from the first two terms of the Taylor expansion of the following more accurate equation:

$$c_{\text{air}} = 331.3 \sqrt{1 + \frac{\vartheta}{273.15}} \ \ \text{m/s.}$$

Dividing the first part, and multiplying the second part, on the right hand side, by $\sqrt{273.15}$ gives the exactly equivalent form

$$c_{\text{air}} = 20.05 \sqrt{\vartheta + 273.15} \ \ \text{m/s.}$$

which can also be written as

$$c_{\text{air}} = 20.05 \sqrt{T/K} \ \ \text{m/s}$$

where T denotes the thermodynamic temperature.

The value of 331.3 m/s, which represents the speed at 0 °C (or 273.15 K), is based on theoretical (and some measured) values of the heat capacity ratio, γ, as well as on the fact that at 1 atm real air is very well described by the ideal gas approximation. Commonly found values for the speed of sound at 0 °C may vary from 331.2 to 331.6 due to the assumptions made when it is calculated. If ideal gas γ is assumed to be 7/5 = 1.4 exactly, the 0 °C speed is calculated (see section below) to be 331.3 m/s, the coefficient used above.

This equation is correct to a much wider temperature range, but still depends on the approximation of heat capacity ratio being independent of temperature, and for this reason will fail, particularly at higher temperatures. It gives good predictions in relatively dry, cold, low-pressure conditions, such as the Earth's stratosphere. The equation fails at extremely low pressures and short wavelengths, due to dependence on the assumption that the wavelength of the sound in the gas is much longer than the average mean free path between gas molecule collisions. A derivation of these equations will be given in the following section.

A graph comparing results of the two equations is at right, using the slightly different value of 331.5 m/s for the speed of sound at 0 °C.

Details
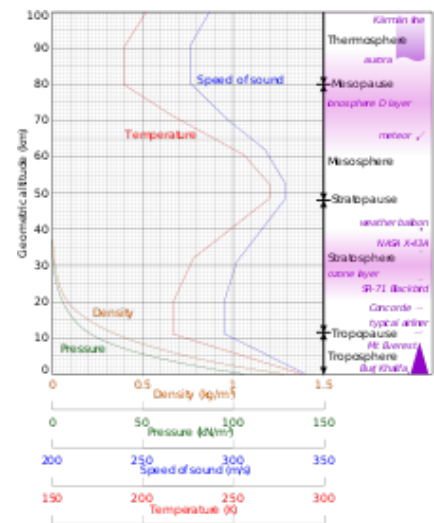
Density and pressure decrease smoothly with altitude, but temperature (red) does not. The speed of sound (blue) depends only on the complicated temperature variation at altitude and can be calculated from it since isolated density and pressure effects on the speed of sound cancel each other. The speed of sound increases with height in two regions of the stratosphere and thermosphere, due to heating effects in these regions.
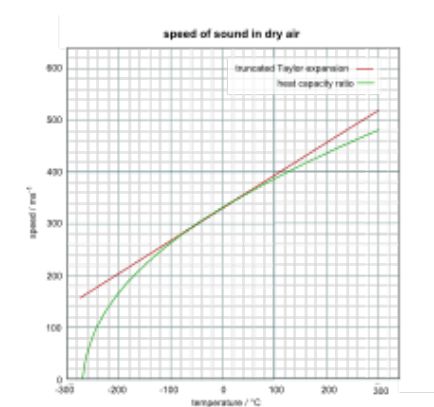
Approximation of the speed of sound in dry air based on the heat capacity ratio (in green) against the truncated Taylor expansion (in red).

Speed of sound in ideal gases and air

For an ideal gas, K (the bulk modulus in equations above, equivalent to C, the coefficient of stiffness in solids) is given by

$$K = \gamma \cdot p,$$

thus, from the Newton–Laplace equation above, the speed of sound in an ideal gas is given by

$$c = \sqrt{\gamma \cdot \frac{p}{\rho}},$$

where

- γ is the adiabatic index also known as the *isentropic expansion factor*. It is the ratio of specific heats of a gas at a constant-pressure to a gas at a constant-volume(C_p/C_v), and arises because a classical sound wave induces an adiabatic compression, in which the heat of the compression does not have enough time to escape the pressure pulse, and thus contributes to the pressure induced by the compression;
- p is the pressure;
- ρ is the density.

Using the ideal gas law to replace p with nRT/V, and replacing ρ with nM/V, the equation for an ideal gas becomes

$$c_{\text{ideal}} = \sqrt{\gamma \cdot \frac{p}{\rho}} = \sqrt{\frac{\gamma \cdot R \cdot T}{M}} = \sqrt{\frac{\gamma \cdot k \cdot T}{m}},$$

where

- c_{ideal} is the speed of sound in an ideal gas;
- R (approximately 8.314,5 J · mol^{-1} · K^{-1}) is the molar gas constant(universal gas constant);[8]
- k is the Boltzmann constant;
- γ (gamma) is the adiabatic index. At room temperature, where thermal energy is fully partitioned into rotation (rotations are fully excited) but quantum effects prevent excitation of vibrational modes, the value is 7/5 = 1.400 for diatomic molecules, according to kinetic theory. Gamma is actually experimentally measured over a range from 1.399,1 to 1.403 at 0 °C, for air. Gamma is exactly 5/3 = 1.6667 for monatomic gases such as noble gases and it is approxemately 1.3 for triatomic molecule gases;
- T is the absolute temperature;
- M is the molar mass of the gas. The mean molar mass for dry air is about 0.028,964,5 kg/mol;
- n is the number of moles;
- m is the mass of a single molecule.

This equation applies only when the sound wave is a small perturbation on the ambient condition, and the certain other noted conditions are fulfilled, as noted below. Calculated values for c_{air} have been found to vary slightly from experimentally determined values.[9]

Newton famously considered the speed of sound before most of the development of thermodynamics and so incorrectly used isothermal calculations instead of adiabatic. His result was missing the factor of γ but was otherwise correct.

Numerical substitution of the above values gives the ideal gas approximation of sound velocity for gases, which is accurate at relatively low gas pressures and densities (for air, this includes standard Earth sea-level conditions). Also, for diatomic gases the use of $\gamma = 1.4000$ requires that the gas exists in a temperature range high enough that rotational heat capacity is fully excited (i.e., molecular rotation is fully used as a heat energy "partition" or reservoir); but at the same time the temperature must be low enough that molecular vibrational modes contribute no heat capacity (i.e., insignificant heat goes into vibration, as all vibrational quantum modes above the minimum-energy-mode, have energies too high to be populated by a significant number of molecules at this temperature). For air, these conditions are fulfilled at room

temperature, and also temperatures considerably below room temperature (see tables below). See the section on gases in specific heat capacity for a more complete discussion of this phenomenon.

For air, we introduce the shorthand

$$R_* = R/M_{\text{air}}.$$

In addition, we switch to the Celsius temperature $\vartheta = T - 273.15$, which is useful to calculate air speed in the region near 0 °C (about 273 kelvin). Then, for dry air,

$$c_{\text{ideal}} = \sqrt{\gamma \cdot R_* \cdot T} = \sqrt{\gamma \cdot R_* \cdot (\vartheta + 273.15)},$$

$$c_{\text{ideal}} = \sqrt{\gamma \cdot R_* \cdot 273.15} \cdot \sqrt{1 + \frac{\vartheta}{273.15}},$$

where ϑ (theta) is the temperature in degrees Celsius(°C).

Substituting numerical values

$$R = 8.314\,510 \text{ J}/(\text{mol} \cdot \text{K})$$

for the molar gas constant in J/mole/Kelvin, and

$$M_{\text{air}} = 0.028\,964\,5 \text{ kg/mol}$$

for the mean molar mass of air, in kg; and using the ideal diatomic gas value of γ = 1.4000, we have

$$c_{\text{air}} = 331.3 \sqrt{1 + \frac{\vartheta}{273.15}} \quad \text{m/s.}$$

Finally, Taylor expansion of the remaining square root in ϑ yields

$$c_{\text{air}} = 331.3 \left(1 + \frac{\vartheta}{2 \cdot 273.15}\right) \quad \text{m/s,}$$

$$c_{\text{air}} = (331.3 + 0.606 \cdot \vartheta) \quad \text{m/s.}$$

The above derivation includes the first two equations given in the "Practical formula for dry air" section above.

Effects due to wind shear

The speed of sound varies with temperature. Since temperature and sound velocity normally decrease with increasing altitude, sound is refracted upward, away from listeners on the ground, creating an acoustic shadow at some distance from the source.[7] Wind shear of 4 m/(s · km) can produce refraction equal to a typical temperature lapse rate of 7.5 °C/km.[10] Higher values of wind gradient will refract sound downward toward the surface in the downwind direction,[11] eliminating the acoustic shadow on the downwind side. This will increase the audibility of sounds downwind. This downwind refraction effect occurs because there is a wind gradient; the sound is not being carried along by the wind.[12]

For sound propagation, the exponential variation of wind speed with height can be defined as follows:[13]

$$U(h) = U(0)h^\zeta,$$
$$\frac{dU}{dH}(h) = \zeta\frac{U(h)}{h},$$

where

- $U(h)$ is the speed of the wind at height h;
- ζ is the exponential coefficient based on ground surface roughness, typically between 0.08 and 0.52;
- $dU/dH(h)$ is the expected wind gradient at height h.

In the 1862 American Civil War Battle of Iuka, an acoustic shadow, believed to have been enhanced by a northeast wind, kept two divisions of Union soldiers out of the battle,[14] because they could not hear the sounds of battle only 10 km (six miles) downwind.[15]

Tables

In the standard atmosphere:

- T_0 is 273.15 K (= 0 °C = 32 °F), giving a theoretical value of 331.3 m/s (= 1086.9 ft/s = 1193 km/h = 741.1 mph = 644.0 kn). Values ranging from 331.3 to 331.6 m/s may be found in reference literature, however;
- T_{20} is 293.15 K (= 20 °C = 68 °F), giving a value of 343.2 m/s (= 1126.0 ft/s = 1236 km/h = 767.8 mph = 667.2 kn);
- T_{25} is 298.15 K (= 25 °C = 77 °F), giving a value of 346.1 m/s (= 1135.6 ft/s = 1246 km/h = 774.3 mph = 672.8 kn).

In fact, assuming an ideal gas, the speed of sound c depends on temperature only, **not on the pressure** or **density** (since these change in lockstep for a given temperature and cancel out). Air is almost an ideal gas. The temperature of the air varies with altitude, giving the following variations in the speed of sound using the standard atmosphere—*actual conditions may vary*.

Effect of temperature on properties of air

Temperature T (°C)	Speed of sound c (m/s)	Density of air ρ (kg/m^3)	Characteristic specific acoustic impedance z_0 (Pa·s/m)
35	351.88	1.1455	403.2
30	349.02	1.1644	406.5
25	346.13	1.1839	409.4
20	343.21	1.2041	413.3
15	340.27	1.2250	416.9
10	337.31	1.2466	420.5
5	334.32	1.2690	424.3
0	331.30	1.2922	428.0
−5	328.25	1.3163	432.1
−10	325.18	1.3413	436.1
−15	322.07	1.3673	440.3
−20	318.94	1.3943	444.6
−25	315.77	1.4224	449.1

Given normal atmospheric conditions, the temperature, and thus speed of sound, varies with altitude:

Altitude	Temperature	m/s	km/h	mph	kn
Sea level	15 °C (59 °F)	340	1,225	761	661
11,000 m–20,000 m (Cruising altitude of commercial jets, and first supersonic flight)	−57 °C (−70 °F)	295	1,062	660	573
29,000 m (Flight of X-43A)	−48 °C (−53 °F)	301	1,083	673	585

Effect of frequency and gas composition

General physical considerations

The medium in which a sound wave is travelling does not always respond adiabatically, and as a result, the speed of sound can vary with frequency.[16]

The limitations of the concept of speed of sound due to extreme attenuation are also of concern. The attenuation which exists at sea level for high frequencies applies to successively lower frequencies as atmospheric pressure decreases, or as the mean free path increases. For this reason, the concept of speed of sound (except for frequencies approaching zero) progressively loses its range of applicability at high altitudes.[9] The standard equations for the speed of sound apply with reasonable accuracy only to situations in which the wavelength of the soundwave is considerably longer than the mean free path of molecules in a gas.

The molecular composition of the gas contributes both as the mass (M) of the molecules, and their heat capacities, and so both have an influence on speed of sound. In general, at the same molecular mass, monatomic gases have slightly higher speed of sound (over 9% higher) because they have a higher γ (5/3 = 1.66...) than diatomics do (7/5 = 1.4). Thus, at the same molecular mass, the speed of sound of a monatomic gas goes up by a factor of

$$\frac{c_{\text{gas,monatomic}}}{c_{\text{gas,diatomic}}} = \sqrt{\frac{5/3}{7/5}} = \sqrt{\frac{25}{21}} = 1.091\ldots$$

This gives the 9% difference, and would be a typical ratio for speeds of sound at room temperature in helium vs. deuterium, each with a molecular weight of 4. Sound travels faster in helium than deuterium because adiabatic compression heats helium more since the helium molecules can store heat energy from compression only in translation, but not rotation. Thus helium molecules (monatomic molecules) travel faster in a sound wave and transmit sound faster. (Sound travels at about 70% of the mean molecular speed in gases; the figure is 75% in monatomic gases and 68% in diatomic gases).

Note that in this example we have assumed that temperature is low enough that heat capacities are not influenced by molecular vibration (see heat capacity). However, vibrational modes simply cause gammas which decrease toward 1, since vibration modes in a polyatomic gas give the gas additional ways to store heat which do not affect temperature, and thus do not affect molecular velocity and sound velocity. Thus, the effect of higher temperatures and vibrational heat capacity acts to increase the difference between the speed of sound in monatomic vs. polyatomic molecules, with the speed remaining greater in monatomics.

Practical application to air

By far the most important factor influencing the speed of sound in air is temperature. The speed is proportional to the

square root of the absolute temperature, giving an increase of about 0.6 m/s per degree Celsius. For this reason, the pitch of a musical wind instrument increases as its temperature increases.

The speed of sound is raised by humidity but decreased by carbon dioxide. The difference between 0% and 100% humidity is about 1.5 m/s at standard pressure and temperature, but the size of the humidity effect increases dramatically with temperature. The carbon dioxide content of air is not fixed, due to both carbon pollution and human breath (e.g., in the air blown through wind instruments).

The dependence on frequency and pressure are normally insignificant in practical applications. In dry air, the speed of sound increases by about 0.1 m/s as the frequency rises from 10 Hz to 100 Hz. For audible frequencies above 100 Hz it is relatively constant. Standard values of the speed of sound are quoted in the limit of low frequencies, where the wavelength is large compared to the mean free path.[17]

Mach number

Mach number, a useful quantity in aerodynamics, is the ratio of air speed to the local speed of sound. At altitude, for reasons explained, Mach number is a function of temperature. Aircraft flight instruments, however, operate using pressure differential to compute Mach number, not temperature. The assumption is that a particular pressure represents a particular altitude and, therefore, a standard temperature. Aircraft flight instruments need to operate this way because the stagnation pressure sensed by a Pitot tube is dependent on altitude as well as speed.

U.S. Navy F/A-18 traveling near the speed of sound. The white halo consists of condensed water droplets formed by the sudden drop in air pressure behind the shock cone around the aircraft (see Prandtl-Glauert singularity).[18]

Experimental methods

A range of different methods exist for the measurement of sound in air.

The earliest reasonably accurate estimate of the speed of sound in air was made by William Derham and acknowledged by Isaac Newton. Derham had a telescope at the top of the tower of the Church of St Laurence in Upminster, England. On a calm day, a synchronized pocket watch would be given to an assistant who would fire a shotgun at a pre-determined time from a conspicuous point some miles away, across the countryside. This could be confirmed by telescope. He then measured the interval between seeing gunsmoke and arrival of the sound using a half-second pendulum. The distance from where the gun was fired was found by triangulation, and simple division (distance/time) provided velocity. Lastly, by making many observations, using a range of different distances, the inaccuracy of the half-second pendulum could be averaged out, giving his final estimate of the speed of sound. Modern stopwatches enable this method to be used today over distances as short as 200–400 metres, and not needing something as loud as a shotgun.

Single-shot timing methods

The simplest concept is the measurement made using two microphones and a fast recording device such as a digital storage scope. This method uses the following idea.

If a sound source and two microphones are arranged in a straight line, with the sound source at one end, then the following can be measured:

  1. The distance between the microphones (x), called microphone basis.

2. The time of arrival between the signals (delay) reaching the different microphones (t).

Then $v = x/t$.

Other methods

In these methods, the time measurement has been replaced by a measurement of the inverse of time (frequency).

Kundt's tube is an example of an experiment which can be used to measure the speed of sound in a small volume. It has the advantage of being able to measure the speed of sound in any gas. This method uses a powder to make the nodes and antinodes visible to the human eye. This is an example of a compact experimental setup.

A tuning fork can be held near the mouth of a long pipe which is dipping into a barrel of water. In this system it is the case that the pipe can be brought to resonance if the length of the air column in the pipe is equal to *(1 + 2n)λ/4* where *n* is an integer. As the antinodal point for the pipe at the open end is slightly outside the mouth of the pipe it is best to find two or more points of resonance and then measure half a wavelength between these.

Here it is the case that $v = f\lambda$.

High-precision measurements in air

The effect of impurities can be significant when making high-precision measurements. Chemical desiccants can be used to dry the air, but will, in turn, contaminate the sample. The air can be dried cryogenically, but this has the effect of removing the carbon dioxide as well; therefore many high-precision measurements are performed with air free of carbon dioxide rather than with natural air. A 2002 review[19] found that a 1963 measurement by Smith and Harlow using a cylindrical resonator gave "the most probable value of the standard speed of sound to date." The experiment was done with air from which the carbon dioxide had been removed, but the result was then corrected for this effect so as to be applicable to real air. The experiments were done at 30 °C but corrected for temperature in order to report them at 0 °C. The result was 331.45 ± 0.01 m/s for dry air at STP, for frequencies from 93 Hz to 1,500 Hz.

Non-gaseous media

Speed of sound in solids

Three-dimensional solids

In a solid, there is a non-zero stiffness both for volumetric deformations and shear deformations. Hence, it is possible to generate sound waves with different velocities dependent on the deformation mode. Sound waves generating volumetric deformations (compression) and shear deformations (shearing) are called pressure waves (longitudinal waves) and shear waves (transverse waves), respectively. In earthquakes, the corresponding seismic waves are called P-waves (primary waves) and S-waves (secondary waves), respectively. The sound velocities of these two types of waves propagating in a homogeneous 3-dimensional solid are respectively given by[20]

$$c_{\text{solid,p}} = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}},$$

$$c_{\text{solid,s}} = \sqrt{\frac{G}{\rho}},$$

where

- K is the bulk modulus of the elastic materials;
- G is the shear modulus of the elastic materials;
- E is the Young's modulus;
- ρ is the density;
- v is Poisson's ratio.

The last quantity is not an independent one, as E = 3K(1 − 2v). Note that the speed of pressure waves depends both on the pressure and shear resistance properties of the material, while the speed of shear waves depends on the shear properties only.

Typically, pressure waves travel faster in materials than do shear waves, and in earthquakes this is the reason that the onset of an earthquake is often preceded by a quick upward-downward shock, before arrival of waves that produce a side-to-side motion. For example, for a typical steel alloy, K = 170 GPa, G = 80 GPa and ρ = 7,700 kg/m³, yielding a compressional speed $c_{\text{solid,p}}$ of 6,000 m/s.[20] This is in reasonable agreement with $c_{\text{solid,p}}$ measured experimentally at 5,930 m/s for a (possibly different) type of steel.[21] The shear speed $c_{\text{solid,s}}$ is estimated at 3,200 m/s using the same numbers.

One-dimensional solids

The speed of sound for pressure waves in stiff materials such as metals is sometimes given for "long rods" of the material in question, in which the speed is easier to measure. In rods where their diameter is shorter than a wavelength, the speed of pure pressure waves may be simplified and is given by:

$$c_{\text{solid}} = \sqrt{\frac{E}{\rho}},$$

where E is Young's modulus. This is similar to the expression for shear waves, save that Young's modulus replaces the shear modulus. This speed of sound for pressure waves in long rods will always be slightly less than the same speed in homogeneous 3-dimensional solids, and the ratio of the speeds in the two different types of objects depends on Poisson's ratio for the material.

Speed of sound in liquids

In a fluid, the only non-zero stiffness is to volumetric deformation (a fluid does not sustain shear forces).

Hence the speed of sound in a fluid is given by

$$c_{\text{fluid}} = \sqrt{\frac{K}{\rho}},$$

where K is the bulk modulus of the fluid.

Water

In fresh water, sound travels at about 1481 m/s at 20 °C (see the External Links section below for online calculators).[22] Applications of underwater sound can be found in sonar, acoustic communication and acoustical oceanography.

Seawater

In salt water that is free of air bubbles or suspended sediment, sound travels at about 1500 m/s (1500.235 m/s at 1000 kilopascals, 10 °C and 3% salinity by one method).[23] The speed of sound in seawater depends on pressure (hence depth), temperature (a change of 1 °C ~ 4 m/s), and salinity (a change of 1‰ ~ 1 m/s), and empirical equations have been derived to accurately calculate the speed of sound from these variables.[24][25] Other factors affecting the speed of sound are minor. Since in most ocean regions temperature decreases with depth, the profile of the speed of sound with depth decreases to a minimum at a depth of several hundred metres. Below the minimum, sound speed increases again, as the effect of increasing pressure overcomes the effect of decreasing temperature (right).[26] For more information see Dushaw et al.[27]

A simple empirical equation for the speed of sound in sea water with reasonable accuracy for the world's oceans is due to Mackenzie:[28]
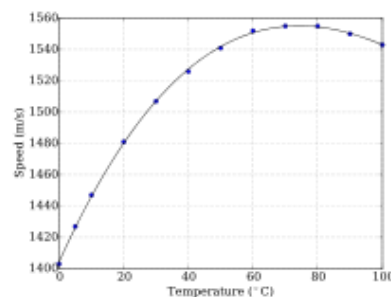
Speed of sound in water vs temperature.
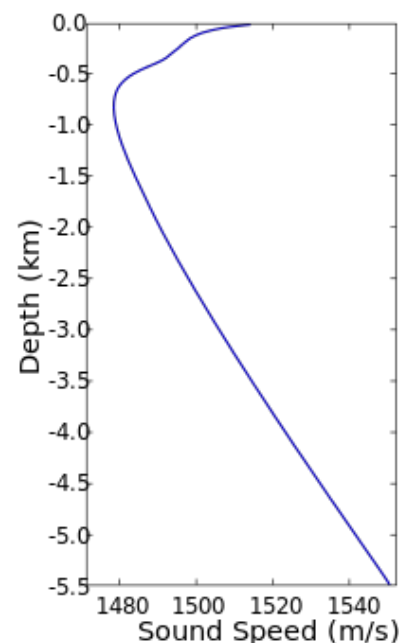
Speed of sound as a function of depth at a position north of Hawaii in the Pacific Ocean derived from the 2005 World Ocean Atlas. The SOFAR channel spans the minimum in the speed of sound at about 750-m depth.

$$c(T, S, z) = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 (S - 35) + a_6 z + a_7 z^2 + a_8 T(S - 35) + a_9 T z^3,$$

where

- T is the temperature in degrees Celsius;
- S is the salinity in parts per thousand;
- z is the depth in metres.

The constants $a_1, a_2, ..., a_9$ are

$$a_1 = 1,448.96, \qquad a_2 = 4.591, \qquad a_3 = -5.304 \times 10^{-2},$$
$$a_4 = 2.374 \times 10^{-4}, \qquad a_5 = 1.340, \qquad a_6 = 1.630 \times 10^{-2},$$
$$a_7 = 1.675 \times 10^{-7}, \qquad a_8 = -1.025 \times 10^{-2}, \qquad a_9 = -7.139 \times 10^{-13},$$

with check value 1550.744 m/s for T = 25 °C, S = 35 parts per thousand, z = 1,000 m. This equation has a standard error of 0.070 m/s for salinity between 25 and 40 ppt. See Technical Guides. Speed of Sound in Sea-Water (http://www.npl.co.uk/acoustics/techguides/soundseawater/) for an online calculator.

(Note: The Sound Speed vs. Depth graph does *not* correlate directly to the MacKenzie formula. This is due to the fact that the temperature and salinity varies at different depths. When T and S are held constant, the formula itself it always increasing.)

Other equations for the speed of sound in sea water are accurate over a wide range of conditions, but are far more complicated, e.g., that by V. A. Del Grosso[29] and the Chen-Millero-Li Equation.[27][30]

Speed of sound in plasma

The speed of sound in a plasma for the common case that the electrons are hotter than the ions (but not too much hotter) is given by the formula (see here)

$$c_s = (\gamma Z k T_e / m_i)^{1/2} = 9.79 \times 10^3 (\gamma Z T_e / \mu)^{1/2} \text{ m/s,}$$

where

- m_i is the ion mass;
- μ is the ratio of ion mass to proton mass $\mu = m_i/m_p$;
- T_e is the electron temperature;
- Z is the charge state;
- k is Boltzmann constant;
- γ is the adiabatic index.

In contrast to a gas, the pressure and the density are provided by separate species, the pressure by the electrons and the density by the ions. The two are coupled through a fluctuating electric field.

Gradients

When sound spreads out evenly in all directions in three dimensions, the intensity drops in proportion to the inverse square of the distance. However, in the ocean, there is a layer called the 'deep sound channel' or SOFAR channel which can confine sound waves at a particular depth.

In the SOFAR channel, the speed of sound is lower than that in the layers above and below. Just as light waves will refract towards a region of higher index, sound waves will refract towards a region where their speed is reduced. The result is that sound gets confined in the layer, much the way light can be confined to a sheet of glass or optical fiber. Thus, the sound is confined in essentially two dimensions. In two dimensions the intensity drops in proportion to only the inverse of the distance. This allows waves to travel much further before being undetectably faint.

A similar effect occurs in the atmosphere. Project Mogul successfully used this effect to detect a nuclear explosion at a considerable distance.

See also

- Acoustoelastic effect
- Elastic wave
- Second sound
- Sonic boom
- Sound barrier
- Speeds of sound of the elements
- Underwater acoustics
- Vibrations

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External links

- Calculation: Speed of Sound in Air and the Temperature (http://www.sengpielaudio.com/calculator-speedsound.htm)
- Speed of sound: Temperature Matters, Not Air Pressure (http://www.sengpielaudio.com/SpeedOfSoundPressure.pdf)
- Properties of the U.S. Standard Atmosphere 1976 (http://www.pdas.com/atmos.html)
- The Speed of Sound (http://www.mathpages.com/home/kmath109/kmath109.htm)
- How to Measure the Speed of Sound in a Laboratory (https://web.archive.org/web/20060429062028/http://www.bustertests.co.uk/answer/how-to-measure-the-speed-of-sound-in-a-laboratory/)
- Teaching Resource for 14-16 Years on Sound Including Speed of Sound (http://www.acoustics.salford.ac.uk/schools/index1.htm)
- Technical Guides. Speed of Sound in Pure Water (http://www.npl.co.uk/acoustics/techguides/soundpurewater/)
- Technical Guides. Speed of Sound in Sea-Water (http://www.npl.co.uk/acoustics/techguides/soundseawater/)
- Did Sound Once Travel at Light Speed? (https://www.newscientist.com/article/mg19826504.200-did-sound-once-travel-at-light-speed.html)
- Acoustic Properties of Various Materials Including the Speed of Sound (http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Reference%20Information/matproperties.htm)
- Technical Guides - Speed of Sound in Pure Water (http://www.npl.co.uk/acoustics/techguides/soundpurewater/) (provides a calculator for the speed in water)
- Discovery of Sound in the Sea (http://www.dosits.org/) (uses of sound by humans and other animals)

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