12

Acoustic Sensors

> *"Your ears will always lead you right,*
> *but you must know why."*
>
> —Anton von Webern

The fundamentals of acoustics are given in Section 3.10 of Chapter 3. Here, we will discuss the acoustic sensors for various frequency ranges. The audible range sensors are generally called the *microphones*; however, the name is often used even for the ultrasonic and infrasonic waves. In essence, a microphone is a pressure transducer adapted for the transduction of sound waves over a broad spectral range which generally excludes very low frequencies below a few hertz. The microphones differ by their sensitivity, directional characteristics, frequency bandwidth, dynamic range, sizes, and so forth. Also, their designs are quite different depending on the media from which sound waves are sensed. For example, for the perception of air waves or vibrations in solids, the sensor is called a *microphone*, whereas for the operation in liquids, it is called a *hydrophone* (even if the liquid is not water—from the Greek name of mythological water serpent Hydra). The main difference between a pressure sensor and an acoustic sensor is that latter does not need to measure constant or very slow-changing pressures. Its operating frequency range usually starts at several hertz (or as low as tens of millihertz for some applications), and the upper operating frequency limit is quite high—up to several megahertz for the ultrasonic applications and even gigahertz in the surface acoustic-wave device.

Because acoustic waves are mechanical pressure waves, any microphone or hydrophone has the same basic structure as a pressure sensor: it is composed of a moving diaphragm and a displacement transducer which converts the diaphragm's deflections into an electrical signal; that is, all microphones or hydrophones differ by the design of these two essential components. Also, they may include some additional parts such as mufflers, focusing reflectors or lenses, and so forth; however, in this chapter, we will review only the sensing parts of some of the most interesting, from our point of view, acoustic sensors.

12.1 Resistive Microphones

In the past, resistive pressure converters were used quite extensively in microphones. The converter consisted of a semiconductive powder (usually graphite) whose bulk resistivity was sensitive to pressure. Currently, we would say that the powder possessed piezoresistive properties. However, these early devices had quite a limited dynamic range, poor frequency response, and a high noise floor. Presently, the same piezoresistive principle can be employed in the micromachined sensors, where stress-sensitive resistors are the integral parts of a silicon diaphragm (Section 10.5 of Chapter 10).

12.2 Condenser Microphones

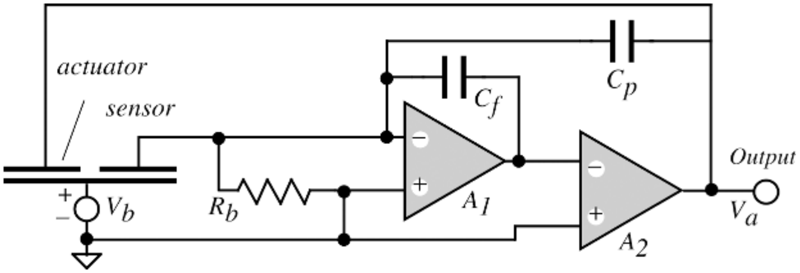
If a parallel-plate capacitor is given an electric charge q, the voltage across its plates is governed by Eq. (3.19 of Chapter 3). On the other hand, according to Eq. (3.20 of Chapter 3) the capacitance depends on distance d between the plates. Thus, solving these two equations for voltage, we arrive at

$$V = q\frac{d}{\varepsilon_0 A}, \tag{12.1}$$

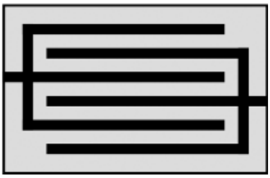
where $\varepsilon_0 = 8.8542 \times 10^{-12}\ \mathrm{C^2/N\,m^2}$ is the permitivity constant (Section 3.1 of Chapter 3). Equation (12.1) is the basis for operation of the *condenser* microphones, which is another way to say "capacitive" microphones. Thus, a capacitive microphone linearly converts a distance between the plates into electrical voltage which can be further amplified. The device essentially requires a source of an electric charge q whose magnitude directly determines the microphone sensitivity. The charge can be provided either from an external power supply having a voltage in the range from 20 to 200 V or from an internal source capable of producing such a charge. This is accomplished by a built-in electret layer which is a polarized dielectric crystal.

Presently, many condenser microphones are fabricated with silicon diaphragms, which serve two purposes: to convert acoustic pressure into displacement and to act as a moving plate of a capacitor. Some promising designs are described in Refs. [1–3]. To achieve high sensitivity, a bias voltage should be as large as possible, resulting in a large static deflection of the diaphragm, which may result in reduced shock resistivity and lower dynamic range. In addition, if the air gap between the diaphragm and the backplate is very small, the acoustic resistance of the air gap will reduce the mechanical sensitivity of the microphone at higher frequencies. For instance, at an air gap of 2 μm, an upper cutoff frequency of only 2 kHz has been measured [1].

One way to improve the characteristics of a condenser microphone is to use a mechanical feedback from the output of the amplifier to the diaphragm [4]. Figure 12.1A shows a circuit diagram and Fig. 12.1B is a drawing of interdigitized electrodes of the microphone. The electrodes serve different purposes: One is for the conversion of a diaphragm displacement into voltage at the input of the amplifier A_1 and the other electrode is for converting feedback voltage V_a into a mechanical deflection by means of electrostatic force. The mechanical feedback clearly improves the linearity and the frequency range of the microphone; however, it significantly reduces the deflection, which results in a lower sensitivity.



(A)



(B)

Fig. 12.1. Condenser microphone with a mechanical feedback: (A) a circuit diagram; (B) interdigitized electrodes on the diaphragm. (Adapted from Ref. [4].)

For further reading on condenser microphones an excellent book edited by Wong and Embleton is recommended [5].

12.3 Fiber-Optic Microphone

Direct acoustic measurements in hostile environments, such as in turbojets or rocket engines, require sensors which can withstand high heat and strong vibrations. The acoustic measurements under such hard conditions are required for computational fluid dynamics (CFD) code validation, structural acoustic tests, and jet noise abatement. For such applications, a fiber-optic interferometric microphone can be quite suitable. One such design [6] is composed of a single-mode temperature insensitive Michelson interferometer and a reflective plate diaphragm. The interferometer monitors the plate deflection, which is directly related to the acoustic pressure. The sensor is water cooled to provide thermal protection for the optical materials and to stabilize the mechanical properties of the diaphragm.

To provide an effect of interference between the incoming and outgoing light beams, two fibers are fused together and cleaved at the minimum tapered region (Fig. 12.2). The fibers are incorporated into a stainless-steel tube, which is water cooled. The internal space in the tube is filled with epoxy, and the end of the tube is polished until the optical fibers are observed. Next, aluminum is selectively deposited at one of the fused fiber core ends to make its surface mirror reflective. This fiber serves as a reference arm of the microphone. The other fiber core is left open and serves as the sensing arm. Temperature insensitivity is obtained by the close proximity of the reference and sensing arms of the assembly.

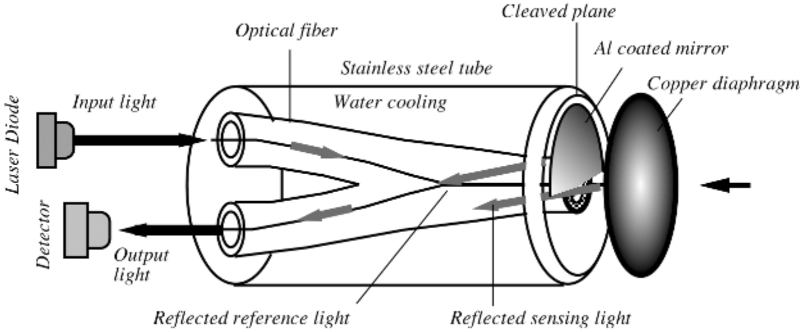


Fig. 12.2. Fiber-optic interferometric microphone. Movement of the copper diaphragm is converted into light intensity in the detector.

Light from a laser source (a laser diode operating near 1.3 μm wavelength) enters one of the cores and propagates toward the fused end, where it is coupled to the other fiber core. When reaching the end of the core, light in the reference core is reflected from the aluminum mirror toward the input and output sides of the sensor. The portion of light which goes toward the input is lost and has no effect on the measurement, whereas the portion which goes to the output strikes the detector's surface. That portion of light which travels to the right in the sensing core, exits the fiber, and strikes the copper diaphragm. Part of the light is reflected from the diaphragm back toward the sensing fiber and propagates to the output end, along with the reference light. Depending on the position of the diaphragm, the phase of the reflected light will vary, thus becoming different from the phase of the reference light.

While traveling together to the output detector, the reference and sensing lights interfere with one another, resulting in the light-intensity modulation. Therefore, the microphone converts the diaphragm displacement into a light intensity. Theoretically, the signal-to-noise ratio in such a sensor is obtainable on the order of 70–80 dB, thus resulting in an average minimum detectable diaphragm displacement of 1 Å (10^{-10} m).

Figure 12.3 shows a typical plot of the optical intensity in the detector versus the phase for the interference patterns. To assure a linear transfer function, the operating

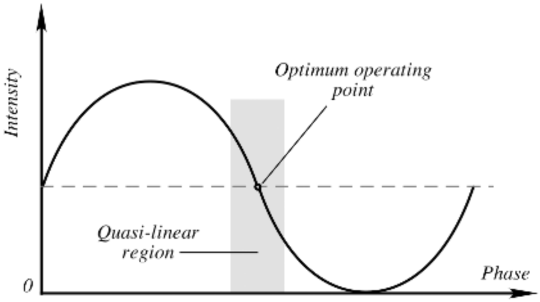


Fig. 12.3. Intensity plot as function of a reflected light phase.

point should be selected near the middle of the intensity, where the slope is the highest and the linearity is the best. The slope and the operating point may be changed by adjusting the wavelength of the laser diode. It is important for the deflection to stay within one-quarter of the operating wavelength to maintain a proportional input.

The diaphragm is fabricated from a 0.05-mm foil with a 1.25-mm diameter. Copper is selected for the diaphragm because of its good thermal conductivity and relatively low modulus of elasticity. The latter feature allows us to use a thicker diaphragm, which provides better heat removal while maintaining a usable natural frequency and deflection. A pressure of 1.4 kPa produces a maximum center deflection of 39 nm (390 AA), which is well within a one-quarter of the operating wavelength (1300 nm). The maximum acoustic frequency which can be transferred with the optical microphone is limited to about 100 kHz, which is well above the desired working range needed for the structural acoustic testing.

12.4 Piezoelectric Microphones

The piezoelectric effect can be used for the design of simple microphones. A piezoelectric crystal is a direct converter of a mechanical stress into an electric charge. The most frequently used material for the sensor is a piezoelectric ceramic, which can operate up to a very high frequency limit. This is the reason why piezoelectric sensors are used for the transduction of ultrasonic waves (Section 7.6 of Chapter 7). Still, even for the audible range, the piezoelectric microphones are used quite extensively. Typical applications are voice-activated devices and blood pressure measurement apparatuses where the arterial Korotkoff sounds have to be detected. For such acoustically non-demanding applications, the piezoelectric microphone design is quite simple (Fig. 12.4). It consists of a piezoelectric ceramic disk with two electrodes deposited on each side. The electrodes are connected to wires either by electrically conductive epoxy or by soldering. Because the output impedance of such a microphone is very large, a high-input-impedance amplifier is required.

Piezoelectric films [polyvinylidene fluoride (PVDF) and copolymers] were used for many years as very efficient acoustic pickups in musical instruments [7]. One of the first applications for piezoelectric film was as an acoustic pickup for a violin. Later, the

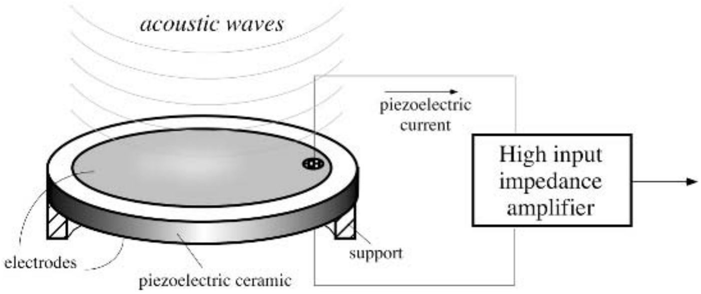


Fig. 12.4. Piezoelectric microphone.

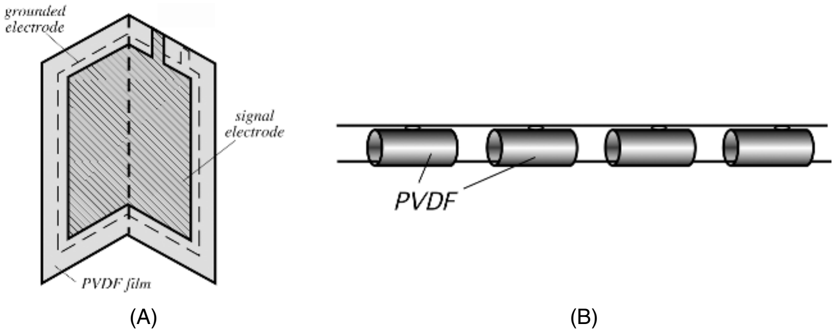


Fig. 12.5. Foldover piezoelectric acoustic pickup (A) and arrangement of a piezoelectric film hydrophone (B).

film was introduced for a line of acoustic guitars as a saddle-mounted bridge pickup, mounted in the bridge. The very high fidelity of the pickup led the way to a family of vibration-sensing and accelerometer applications: in one guitar pickup, a thick-film, compressive (under the saddle) design; another is a low-cost accelerometer, and another is an after-market pickup design that is taped to the instrument. Because of the low Q of the material, these transducers do not have the self-resonance of hard ceramic pickups. Shielding can be achieved by a foldover design as shown in Fig. 12.5A. The sensing side is the slightly narrower electrode on the inside of the fold. The foldover technique provides a more sensitive pickup than alternative shielding methods because the shield is formed by one of the electrodes. For application in water, the film can be rolled in tubes, and many of such tubes can be connected in parallel (Fig. 12.5B).

12.5 Electret Microphones

An electret is a close relative of piezoelectric and pyroelectric materials. In effect, they are all electrets with either enhanced piezoelectric or pyroelectric properties. An electret is a permanently electrically polarized crystalline dielectric material. The first application of electrets to microphones and earphones where described in 1928 [8]. An electret microphone is an electrostatic transducer consisting of a metallized electret and backplate separated from the diaphragm by an air gap (Fig. 12.6).

The upper metallization and a metal backplate are connected through a resistor R's voltage V across which it can be amplified and used as an output signal. Because the electret is a permanently electrically polarized dielectric, the charge density σ_1 on its surface is constant and sets an electric field E_1 in the air gap. When an acoustic wave impinges on the diaphragm, the latter deflects downward, reducing the air gap thickness s_1 for a value of Δs. Under open-circuit conditions, the amplitude of a variable portion of the output voltage becomes

$$V = \frac{s\Delta s}{\varepsilon_0(s+\varepsilon s_1)}. \tag{12.2}$$

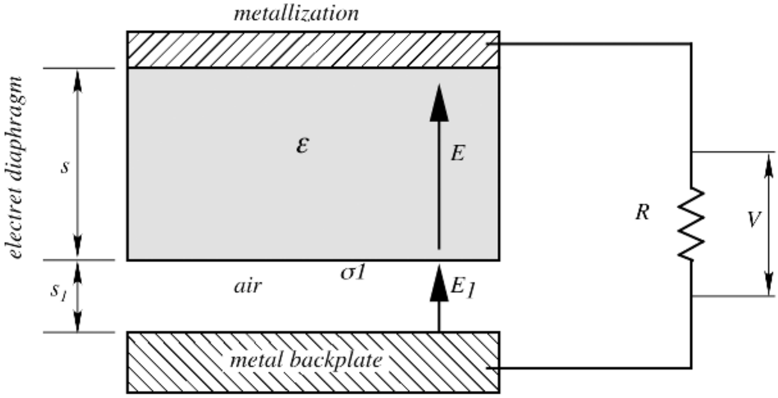


Fig. 12.6. General structure of an electret microphone. The thicknesses of layers are exaggerated for clarity. (After Ref. [9].)

Thus, the deflected diaphragm generates voltage across the electrodes. That voltage is in phase with the diaphragm deflection. If the sensor has a capacitance C, Eq. (12.2) should be written

$$V = \frac{s\Delta s}{\varepsilon_0(s+\varepsilon s_1)} \frac{2\pi f RC}{\sqrt{1+(2\pi f RC)^2}}, \tag{12.3}$$

where f is the frequency of sonic waves.

If the restoring forces are due to the elasticity of the air cavities behind the diaphragm (effective thickness is s_0) and the tension T of the membrane, its displacement Δs to a sound pressure Δp assuming negligible losses is given by [10]

$$\Delta s = \frac{\Delta p}{(\gamma p_0/s_0)+(8\pi T/A)}, \tag{12.4}$$

where γ is the specific heat ratio, p_0 is the atmospheric pressure, and A is the membrane area. If we define the electret microphone sensitivity as $\delta_m = \Delta V/\Delta p$, then below resonance it can be expressed as [9]

$$\delta_m = \frac{s s_0 \sigma_1}{\varepsilon_0(s+\varepsilon s_1)\gamma p_0}. \tag{12.5}$$

It is seen that the sensitivity does not depend on area. If the mass of the membrane is M, then the resonant frequency is defined by

$$fr = \frac{1}{2\pi}\sqrt{\frac{p_0}{s_0 M}}. \tag{12.6}$$

This frequency should be selected well above the upper frequency of the microphone's operating range.

The electret microphone differs from other similar detectors in the sense that it does not require a dc bias voltage. For comparable design dimensions and sensitivity, a condenser microphone would require well over 100 V bias. The mechanical tension of the membrane is generally kept at a relatively low value (about 10 N m^{-1}), so that the restoring force is determined by the air-gap compressibility. A membrane may be fabricated of Teflon FEP (Fluorinated Ethylene Propylene), which is permanently charged by an electron beam to give it electret properties. The temperature coefficient of sensitivity of the electret microphones are in the range of 0.03 dB/°C in the temperature range from -10 to $+50$°C [11].

Foil-electret (diaphragm) microphones have more desirable features than any other microphone type. Among them is very wide frequency range from 10^{-3}Hz and up to hundreds of megahertz. They also feature a flat frequency response (within ± 1 dB), low harmonic distortion, low vibration sensitivity, good impulse response, and insensitivity to magnetic fields. Sensitivities of electret microphones are in the range of few millivolts per microbar.

For operation in the infrasonic range, an electret microphone requires a miniature pressure equalization hole on the backplate. When used in the ultrasonic range, the electret is often given an additional bias (like a condenser microphone) in addition to its own polarization.

Electret microphones are high-impedance sensors and thus require high-input-impedance interface electronics. A JFET transistor has been the input of choice for many years. However, recently monolithic amplifiers gained popularity. An example is the LMV1014 (National Semiconductors), which is an audio amplifier with very low current consumption (38 μA) that may operate from a small battery power supply ranging from 1.7 to 5 V.

12.6 Solid-State Acoustic Detectors

Currently, use of the acoustic sensors is broader than detecting sound. In particular, they became increasingly popular for detecting mechanical vibrations in a solid for the fabrication of such sensors as microbalances and surface acoustic-wave (SAW) devices. Applications range over measuring displacement, concentration of compounds, stress, force, temperature, and so forth. All such sensors are based on elastic motions in solid parts of the sensor and their major use is serving as parts in other, more complex sensors, (e.g., in chemical detectors, accelerometers, pressure sensors, etc.). In chemical and biological sensors, the acoustic path, where mechanical waves propagate, may be coated with chemically selective compound which interact only with the stimulus of interest.

An excitation device (usually of a piezoelectric nature) forces atoms of the solid into vibratory motions about their equilibrium position. The neighboring atoms then produce a restoring force tending to bring the displaced atoms back to their original positions. In the acoustic sensors, vibratory characteristics, such as phase velocity and/or the attenuation coefficient, are affected by the stimulus. Thus, in acoustic sensors, external stimuli, such as mechanical strain in the sensor's solid, increase the propagating speed of sound. In other sensors, which are called gravimetric, sorption of molecules or attachment of bacteria cause a reduction of acoustic-wave velocity.

In another detector, called the acoustic viscosity sensors, viscous liquid contacts the active region of an elastic-wave sensor and the wave is attenuated.

Acoustic waves propagating in solids have been used quite extensively in electronic devices such as electric filters, delay lines, microactuators, and so forth. The major advantage of the acoustic waves as compared with electromagnetic waves is their low velocity. Typical velocities in solids range from 1.5×10^3 to 12×10^3 m/s, and the practical SAWs utilize the range between 3.8×10^3 and 4.2×10^3 m/s [12], that is, acoustic velocities are five orders of magnitude smaller than those of electromagnetic waves. This allows for the fabrication of miniature sensors operating with frequencies up to 5 GHz.

When the solid-state acoustic sensor is fabricated, it is essential to couple the electronic circuit to its mechanical structure where the waves propagate. The most convenient effect to employ is the piezoelectric effect. The effect is reversible (Section 3.6 of Chapter 3), which means that it works in both directions: The mechanical stress induces electrical polarization charge, and the applied electric field stresses the piezoelectric crystal. Thus, the sensor generally has two piezoelectric transducers at each end: one at the transmitting end, for the generation of acoustic waves, and the other at the receiving end, for conversion of acoustic waves into an electrical signal.

Because silicon does not possess piezoelectric effect, additional piezoelectric material must be deposited on the silicon waver in the form of a thin film [12]. Typical piezoelectric materials used for this purpose are zinc oxide (ZnO), aluminum nitride (AlN), and the so-called solid-solution system of lead–zirconite–titanium oxides $Pb(Zr,Ti)O_3$ known as PZT ceramic. When depositing thin films on the semiconductor material, several major properties must be taken into account:

1. Quality of the adhesion to the substrate
2. Resistance to the external factors (such as fluids which interact with the sensing surface during its operations)
3. Environmental stability (humidity, temperature, mechanical shock, and vibration)
4. Value of electromechanical coupling with the substrate
5. Ease of processing by the available technologies
6. Cost

The strength of the piezoelectric effect in elastic-wave devices depends on the configuration of the transducting electrodes. Depending on the sensor design, for the bulk excitation (when the waves must propagate through the cross-sectional thickness of the sensor), the electrodes are positioned on the opposite sides and their area is quite large. For the SAW, the excitation electrodes are interdigitized.

Several configurations for the solid-state acoustic sensors are known. They differ by the mode the waves propagate through the material. Figure 12.7 shows two of the most common versions: a sensor with a flextural plate mode (Fig. 12.7A) and with the acoustic plate mode (Fig. 12.7B). In the former case, a very thin membrane is flexed by the left pair of the interdigitized electrodes and its vertical deflection induces response in the right pair of the electrodes. As a rule, the membrane thickness is substantially less than the wavelength of the oscillation. In the latter case, the waves are formed on

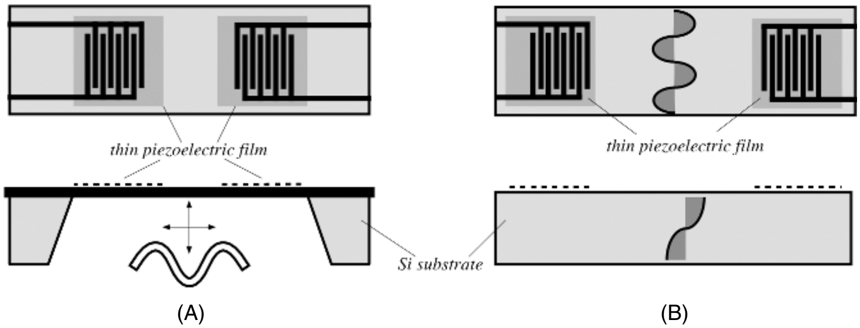


Fig. 12.7. Flextural-plate mode sensor (A) and surface acoustic plate mode (B) sensors.

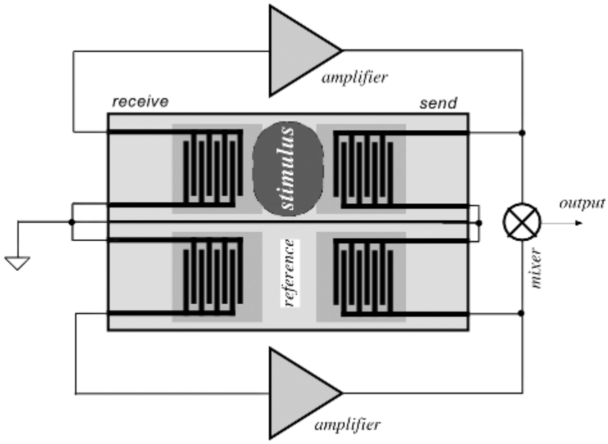


Fig. 12.8. Differential SAW sensor.

the surface of a relatively thick plate. In either case, the space between the left and right pairs of the electrodes is used for interaction with the external stimulus, such as pressure, viscous fluid, gaseous molecules, or microscopic particles.

A typical application circuit for a SAW includes a SAW plate as a time-keeping device of a frequency oscillator. Because many internal and external factors may contribute to the propagation of an acoustic wave and, subsequently, to change in frequency of oscillation, the determination of change in stimulus may be ambiguous and contain errors. An obvious solution is to use a differential technique, where two identical SAW devices are employed: One device is for sensing the stimulus and the other is reference (Fig. 12.8). The reference device is shielded from stimulus, but subjected to common factors, such as temperature, aging, and so forth. The difference of the frequency changes of both oscillators is sensitive only to variations in the stimulus, thus canceling the effects of spurious factors.

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3.10 Sound Waves

Alternate physical compression and expansion of medium (solids, liquids, and gases) with certain frequencies are called sound waves. The medium contents oscillate in the direction of wave propagation; hence, these waves are called longitudinal mechanical waves. The name *sound* is associated with the hearing range of a human ear, which is approximately from 20 to 20,000 Hz. Longitudinal mechanical waves below 20 Hz are called *infrasound* and above 20,000 Hz (20 kHz), they are called *ultrasound.* If the classification were made by other animals, like dogs, the range of sound waves surely would be wider.

Detection of infrasound is of interest with respect to analysis of building structures, earthquake prediction, and other geometrically large sources. When infrasound is of a relatively strong magnitude, it can be, if not heard, at least felt by humans, producing quite irritating psychological effects (panic, fear, etc.). Audible waves are produced by vibrating strings (string music instruments), vibrating air columns (wind music instruments), and vibrating plates (some percussion instruments, vocal cords, loudspeaker). Whenever sound is produced, air is alternatively compressed and rarefied. These disturbances propagate outwardly. A spectrum of waves may be quite different—from a simple monochromatic sounds from a metronome or an organ pipe, to a reach violin music. Noise may have a very broad spectrum. It may be of a uniform distribution of density or it may be "colored" with predominant harmonics at some of its portions.

When a medium is compressed, its volume changes from V to $V - \Delta V$. The ratio of change in pressure, Δp, to relative change in volume is called the bulk modulus of elasticity of medium:

$$B = -\frac{\Delta p}{\Delta V/V} = \rho_0 v^2, \tag{3.97}$$

where ρ_0 is the density outside the compression zone and v is the speed of sound in the medium. Then, the speed of sound can be defined as

$$v = \sqrt{\frac{B}{\rho_0}}. \tag{3.98}$$

Hence, the speed of sound depends on the elastic (B) and inertia (ρ_0) properties of the medium. Because both variables are functions of temperature, the speed of sound also depends on temperature. This feature forms a basis for operation of the acoustic thermometers (Section 16.5 of Chapter 16). For solids, longitudinal velocity can be defined through its Young's modulus E and Poisson ratio ν:

$$v = \sqrt{\frac{E(1-\nu)}{\rho_0(1+\nu)(1-2\nu)}}. \tag{3.99}$$

Table A.15 (Appendix) provides the speeds of longitudinal waves in some media. It should be noted that the speed depends on temperature, which always must be considered for the practical purposes.

If we consider the propagation of a sound wave in an organ tube, each small volume element of air oscillates about its equilibrium position. For a pure harmonic tone, the displacement of a particle from the equilibrium position may be represented by

$$y = y_m \cos\frac{2\pi}{\lambda}(x - vt), \tag{3.100}$$

where x is the equilibrium position of a particle and y is a displacement from the equilibrium position, y_m is the amplitude, and λ is the wavelength. In practice, it is more convenient to deal with pressure variations in sound waves rather than with displacements of the particles. It can be shown that the pressure exerted by the sound wave is

$$p = (k\rho_0 v^2 y_m)\sin(kx - \omega t), \tag{3.101}$$

where $k = 2\pi/\lambda$ is a wave number, ω is angular frequency, and the terms in the first parentheses represent an amplitude, p_m, of the sound pressure. Therefore, a sound wave may be considered a pressure wave. It should be noted that sin and cos in Eqs. (3.100) and (3.101) indicate that the displacement wave is 90° out of phase with the pressure wave.

Pressure at any given point in media is not constant and changes continuously, and the difference between the instantaneous and the average pressure is called the *acoustic pressure* P. During the wave propagation, vibrating particles oscillate near a stationary position with the instantaneous velocity ξ. The ratio of the acoustic pressure and the instantaneous velocity (do not confuse it with a wave velocity) is called the acoustic impedance:

$$Z = \frac{P}{\xi}, \tag{3.102}$$

which is a complex quantity, characterized by an amplitude and a phase. For an idealized media (no loss), $\boldsymbol{Z}$ is real and is related to the wave velocity as

$$Z = \rho_0 v. \tag{3.103}$$

We can define the intensity I of a sound wave as the power transferred per unit area. Also, it can be expressed through the acoustic impedance:

$$I = P\xi = \frac{P^2}{Z}. \tag{3.104}$$

It is common, however, to specify sound not by intensity but rather by a related parameter β, called the sound level and defined with respect to a reference intensity $I_0 = 10^{-12}$ W/m^2

$$\beta = 10\log_{10}\left(\frac{I}{I_0}\right) \tag{3.105}$$

The magnitude of I_0 was chosen because it represents the lowest hearing ability of a human ear. The unit of β is a decibel (dB), named after Alexander Graham Bell. If $I = I_0$, $\beta = 0$.

Table 3.3. Sound Levels (β) Referenced to I_0 at 1000 Hz

Sound Source	dB
Rocket engine at 50 m	200
Supersonic boom	160
Hydraulic press at 1 m	130
Threshold of pain	120
10-W Hi-Fi speaker at 3 m	110
Unmuffled motorcycle	110
Rock-n-roll band	100
Subway train at 5 m	100
Pneumatic drill at 3 m	90
Niagara Falls	85
Heavy traffic	80
Automobiles at 5 m	75
Dishwashers	70
Conversation at 1 m	60
Accounting office	50
City street (no traffic)	30
Whisper at 1 m	20
Rustle of leaves	10
Threshold of hearing	0

Pressure levels also may be expressed in decibels as

$$\Pi = 20\log_{10}\left(\frac{p}{p_0}\right), \tag{3.106}$$

where $p_0 = 2\times10^{-5}$ N/m^2 (0.0002 µbar)=2.9×10^{-9} psi.

Examples of some sound levels are given in Table 3.3. Because the response of a human ear is not the same at all frequencies, sound levels are usually referenced to I_0 at 1 kHz, at which the ear is most sensitive.

3.11 Temperature and Thermal Properties of Materials

Our bodies have a sense of temperature which by no means is an accurate method to measure outside heat. Human senses are not only nonlinear, but relative with respect to our previous experience. Nevertheless, we can easily tell the difference between warmer and cooler objects. Then, what is going on with these objects that they produce different perceptions?

Every single particle in this universe exists in perpetual motion. Temperature, in the simplest way, can be described as a measure of kinetic energy of vibrating particles. The stronger the movement, the higher the temperature of that particle. Of course, molecules and atoms in a given volume of material do not move with