Chapter 16
Audio Transducers

Audio is the marriage of acoustics and electronics. Audio is used in three major ways: as sound recording and reproduction, as sound reinforcement in rooms or public address, and in broadcasting. In each case, a sound wave is turned into an electrical equivalent (i.e., an electrical analog) and processed in some way as an electrical signal. Then it is turned back into a sound wave. The devices that make the transformation, from acoustical to electrical and back to acoustical, are transducers.

To understand transducers you need to know a little about electricity, and that is where this chapter begins. It introduces the topics of electrical charge, voltage, current, and magnetism.

16.1 Basic Definitions

- *Charge:* Everything in the world is made up of atoms. In the center of an atom is a nucleus that contains protons (positively charged). All round the nucleus are clouds of electrons (negatively charged). In a neutral atom the number of electrons is just equal to the number of protons, and the positive and negative charges cancel. The net charge is zero (neutral). For instance, an atom of copper has 29 protons—that is why it is copper. A neutral copper atom then has 29 electrons too. A neutral atom of aluminum has 13 protons and 13 electrons. Figure 16.1 shows an aluminum atom.

Because of the positive and negative charges, atoms are chock full of forces. (A force is a push or a pull.) These forces are ultimately what gives electricity its prodigious powers. The electrons are attracted to the protons because opposite charges experience a force of attraction. That is why most of the electrons do not wander off into space but stay in the vicinity of the positive nucleus. However, in a material like copper or aluminum, it is possible to separate *some* electrons from their atoms. Some electrons are free to move around throughout the material.

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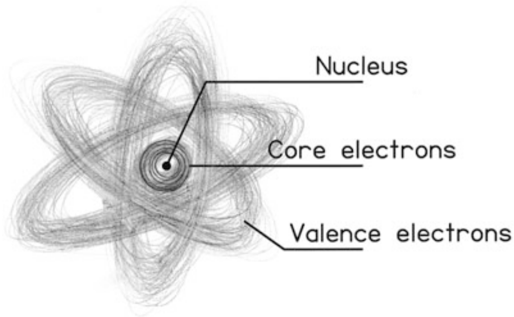

Fig. 16.1 The nucleus of an aluminum atom contains 13 protons, which gives the nucleus a strong positive charge. Around the nucleus are several clouds of electrons. One cloud (the core) is strongly bound to the nucleus. The other cloud (valence electrons) is more spread out. In the aluminum atom there are three valence electrons in this cloud. When atoms of aluminum are put together to make a metallic solid these three electrons are free to move around and to conduct electrical current through the metal

Such materials are called "metals" and they can conduct electrical currents. Electron currents move audio information through wires.

- *Voltage:* Because charges of opposite sign attract one another, a force field is set up when positive and negative charges are caused to be separated. This field of force has an effect on still other charges in the vicinity, and it is known as a voltage. A voltage is measured in volts. For instance, the chemical reaction that separates electrical charges in a flashlight battery leads to a voltage of 1.5 V. These electrical forces, or voltages, can be added together. The basic flashlight contains a stack of two batteries, one on top of the other, leading to a voltage of 3.0 V. The standard 9-V battery is made from six such cells, stacked together in a little rectangular package with snaps on top. You can measure the voltage of a battery by using a voltmeter. It gives a steady reading. Electrical signals, like speech or music in electronic form, consist of voltages that change rapidly with time. You can measure a voltage that changes with time by using an oscilloscope.

- *Current:* Fundamentally, current is the motion of electrical charge. Electrons in a metal are always in motion. All things being equal, they move in random directions—any one direction as much as any other. An electrical current occurs when electrons are caused to move preferentially in one direction, for instance from one end of a copper wire toward the other end. They are caused to move by the force of a voltage. If there is no voltage no current will flow. With a voltage present, either steady from a battery or alternating from an electrical signal, a current flows. For instance, Fig. 16.2 shows voltage from a battery driving a current through a light bulb.

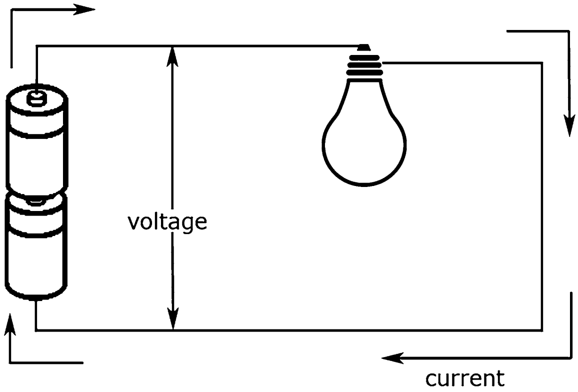

Fig. 16.2 The simple circuit that is used in a flashlight. The two batteries are added together to create a voltage of 3 V. This voltage motivates a current that flows through the light bulb creating light

Electrical current in a wire is analogous to the flow of water in a pipe. You can measure the flow of water in a pipe in units of gallons per minute. You can measure the flow of electrons in a wire in units of electrons per second. A more common unit for current is amperes (abbreviation: amps). If you go to the basement of your house and look at the circuit breaker box you will find breakers rated at 15 A. That means that the circuit can safely carry electrical current at a rate of 15 A.

- *Magnetism:* Magnetism is intimately connected with electricity. In fact, every time there is an electrical current there is also a magnetic field. It's a law of nature; it's unavoidable. The reverse is true as well. Every magnetic field owes its existence to some form of electrical current somewhere. (By the way, magnetism is completely unrelated to gravity. People are often confused on this point because our Earth has both a magnetic field and a gravitational field, but these two forces, magnetic and gravitational, have nothing to do with one another, as far as we know.) The relationship between magnetism and electricity leads to the first of three principles of electromagnetism.

16.2 The Current and Magnetism Principle

The current–magnetism principle is:

1. *An electrical current in a wire creates a magnetic field around the wire. If the current changes, the magnetic field changes in the same way.*

There are two kinds of magnets, temporary and permanent. An electrical current from a battery creates a temporary magnetic field. When the circuit is switched off, the current stops and the field disappears.

Permanent magnets exist because there are certain materials, especially materials that contain iron, that can be made to have a magnetic field because of electrical currents within the atoms themselves. These atomic currents are in a state of perpetual

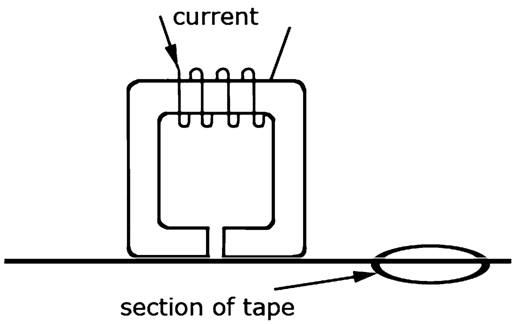

Fig. 16.3 Current in the coil of the record head makes a magnetic field in the gap. This magnetic field puts permanent magnetism on the tape, which is moving from *left* to *right*. The magnetic field stored at a particular spot on the tape is analogous to the signal in the coil a at particular instant of time

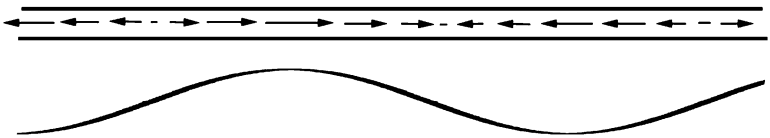

Fig. 16.4 A close up of the section of tape from the image above. The *sine wave* represents the input signal, and the *arrows* represent the corresponding magnetic fields that are analogous to the input signal

motion. They never stop. Therefore, permanent magnets can be permanent. You are probably familiar with permanent magnets as compass needles. You can turn a piece of steel (contains iron) into a permanent magnet by putting the steel in a magnetic field, either temporary or permanent. Just being in a strong magnetic field is enough to magnetize a piece of steel—a screwdriver, for example.

16.2.1 Application of the Current–Magnetism Principle

The current–magnetism principle applies to the recording of a sound on magnetic tape. Magnetic tape consists of a mylar backing and a coating (contains iron) that can be magnetized. The coating can be given a permanent magnetic field, just like a screwdriver can be magnetized.

Here's how the recording process works. The acoustical wave is first converted to an electrical signal by a microphone. The electrical signal is amplified and sent to a coil that produces a magnetic field in the record head, because of the current–magnetism principle. As shown in Fig. 16.3, the record head is a solid ring of magnetic material that has a narrow gap where some magnetic field can leak out. As the tape moves from one reel to the other, it makes contact with the record head, right at the gap. The magnetic field in the gap leaves a remnant field on the tape, a permanent record of the signal at a particular instant in time as shown in Fig. 16.4. This is how an audio tape recorder works. This is how a tape camcorder or a VCR works.

16.3 The Analog Concept

The process of recording on magnetic tape, as described above, is an analog process. The signal starts out as a pressure wave in air, and in the recording process it undergoes a number of transformations. It is first converted to a voltage by the microphone, which leads to a current through the wires in the coil of the record head. Then the signal is transformed into a magnetic field in the gap of the record head, and finally it ends up as a remnant magnetism on the tape. The analog concept says that if the process is working correctly then information about the shape of the waveform is preserved in every transformation. If the original pressure wave has a positive bump at some time, then the electrical voltage has an analogous feature at that time, and the magnetism on the tape has an analogous feature at the place on the tape corresponding to the time of the original pressure bump. If the equipment is not working perfectly so that the shape information of the pressure wave is not preserved during the recording transformations then the signal is said to be "distorted." You can hear the difference.

16.4 The Generator Principle

You know what an electrical generator does. It starts with mechanical energy (gasoline engine, steam turbine, waterfall, wind power, etc.) and transforms it into electrical energy. At the basis of that transformation is the generator principle:

2. *If there is relative motion between a wire and a magnetic field, a voltage is induced in the wire.*

Note that the key point is *relative* motion. It doesn't matter whether the wire moves or the magnetic field moves, just so long as one moves with respect to the other. If there is no relative motion there is no voltage.

The generator principle describes the process of playing back a magnetic tape. There is a playback head, very similar in construction to the record head. As the magnetized tape moves past the gap in the playback head, it creates a changing magnetic field in the head. The changing magnetic field passes through a coil wrapped on the head and a voltage is induced in the wire of the coil. This voltage is analogous to the magnetic field on the tape.

The generator principle also describes the operation of microphones of the kind called "dynamic." As shown in Fig. 16.5, the microphone has a diaphragm that is caused to move by the air pressure variations in a sound. A coil of wire is attached to the diaphragm, and so the coil moves with the acoustical wave. The coil is surrounded by a permanent magnet. When the coil moves in the magnetic field, a voltage is created in the coil, and it is this voltage that is the output of the microphone. Positive air pressure causes the diaphragm to move inward, and this creates a positive voltage. Negative air pressure (the small partial vacuum in sound

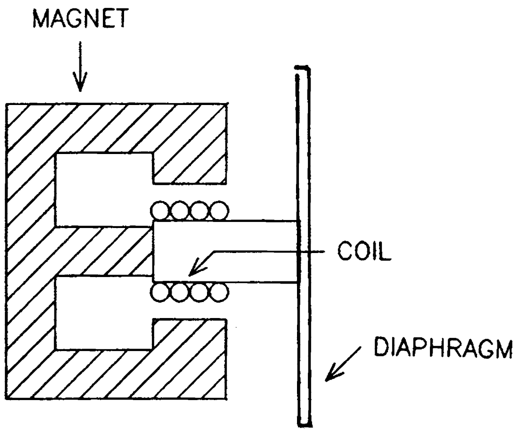

Fig. 16.5 A dynamic microphone works according to the generator principle. Motion of the diaphragm, caused by the pressure in an acoustical wave, causes a coil to move in a magnetic field. This relative motion causes a voltage to be induced in the coil

waves) causes the diaphragm to move outward, and this change makes a negative voltage. The voltage can be amplified and used for recording or public address or broadcasting.

The generator principle also is responsible for the operation of a phonograph cartridge, used to play vinyl records. The grooves in the record cause a needle in the cartridge to vibrate. The motion of the needle causes relative motion of a coil and a magnetic field. In this way the cartridge acts as a generator, producing an output voltage.

16.5 The Motor Principle

An electric motor has electrical energy as an input and mechanical energy as an output. It operates according to the motor principle:

3. *If a wire carries a current through an external magnetic field, there is a force on the wire.*

Loudspeakers and headphones operate according to the motor principle. This is true of almost 100% of the loudspeakers of the world, and the great majority of the headphones. We begin with the loudspeaker. A loudspeaker consists of an enclosure—perhaps a rectangular wood box, perhaps the plastic case of a boom box—and sound producing elements called "drivers." We are interested in the drivers.

As shown in Fig. 16.6, a loudspeaker driver has a cone that is attached to a coil of wire. The coil of wire is suspended inside a steel permanent magnet (That is why loudspeakers are heavy.) A power amplifier drives electrical current through the coil and, because of the motor principle, this generates a force on the cone. The force causes the cone to move, and the cone motion moves the air, causing a sound

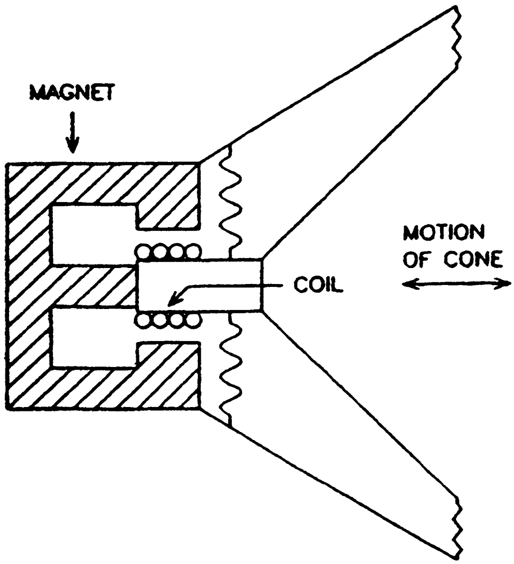

Fig. 16.6 A loudspeaker driver works according to the motor principle. The interaction of a current (in the coil) with a magnetic field (from the permanent magnet) leads to a force on the coil. This causes the coil to move forward or backward. The coil is connected to the cone which then compresses or expands the air in front of the speaker. You may notice that this figure rather resembles Fig. 16.5 for the microphone. That is not an accident. See Exercise 8 below

wave. When the current moves in a positive direction, the cone moves outwards, compressing the air in front. When the current is negative, the cone moves inward—into the loudspeaker cabinet—and this creates a partial vacuum. In this way, an alternating electrical signal can create an alternating pressure wave that we hear as sound.

16.6 Electrostatic Devices

Although most audio transducers operate according to the three electromagnetic principles above, some operate according to electrostatic principles. These principles were introduced in the sections above called *Charge* and *Voltage*. There are two principles.

The **fundamental electrostatic** principle:

1. *Like charges repel each other, unlike charges attract.*

The fundamental electrostatic principle says that two objects with electrical charge will exert a force on one another. Two positive charges repel one another. Two negative charges repel one another. A positive and negative charge attract one another. The electrostatic force has a convenient duality. It can be attractive or repulsive. Therefore, this force can create positive or negative motion (compression or expansion) to make a sound wave in the air.

Electrostatic headphones work according to this principle. Electrostatic headphones are known for their very good high-frequency response because they do not need the heavy magnet and coil that are needed in the usual electromagnetic headphones. However, electrostatic headphones do require a high polarizing voltage—about 100 V. Therefore, these headphones are not so portable. The user has to be close to the supply for polarizing voltage.

The second electrostatic principle is the **capacitor** principle:

2. *Separating electrical charges leads to a voltage. The bigger the separation, the bigger the voltage.*

The capacitor principle obviously creates an opportunity to build a microphone. A moveable diaphragm carries one charge and a fixed frame in the microphone carries the opposite charge. As sound waves cause the diaphragm to move, the charges are separated by more or less and this makes more or less voltage. The world's best microphones as well as the world's cheapest microphones operate according to this capacitor (sometimes called "condenser") principle. The best microphones are used in recording studios; the cheapest microphones are used in telephones and cell phones and for speech input to computer sound cards. The best microphones require a polarizing voltage, normally supplied in recording studios by the preamplifier that amplifies the microphone output voltage. The cheapest microphones are *electret* microphones where the polarizing voltage comes from special materials that have a fixed charge, which creates a fixed electrostatic field much as a permanent magnet creates a fixed magnetic field. (The word "electret" resembles the word "magnet.") Both produce permanent fields, but electrostatic fields and electromagnetic fields are very different. Electromagnetic fields require charges in motion. Electrostatic fields come from charges that are . . . well . . . static.

16.7 Electro-Optical Transducers

Electro-optical transducers convert electrical current into light or convert light into an electrical voltage. Electro-optical audio techniques were the first used in putting sound tracks on movie film. The alternative was to separate the sound track from the film images, but the problem of synchronizing sound and pictures in the early days of movie sound made it evident that putting the sound track on the same film with the pictures was the way to go. The sound track was played back by shining a light through the track. The light was then captured by a photosensitive element which created, or modulated, a voltage when struck by the light. The voltage became the audio signal to be played to the audience. The sound track itself was made to pass more or less light by varying its optical density on the film or by varying the width of the track. Analog sound tracks made in this way never worked very well. They were noisy, generated tons of distortion, and had limited dynamic range. The technology of film sound was considerably improved by digitizing the sound tracks.

Electro-optical transducers made from semiconducting materials are now used to play back compact discs and DVDs. They are also used to transmit information along optical fibers. For example, in a compact disc (CD) player, a semiconducting laser (similar to a light-emitting diode) shines a highly focused light beam on the rotating CD. Music is encoded on the surface of the CD in the form of small pits in the surface. When the light beam hits a pit, interference causes the reflected light to be very dim. When the light beam hits a "land" (flat area between the pits) the beam is reflected brightly. The beam, dim or bright, is reflected to a photodiode, which is a semiconducting device that passes current when stimulated by light. Thus, the music, encoded by pits and lands on the CD, causes electrical current to be off and on respectively. The information from the CD is now in electronic form, and that is the most flexible and useful form of all.

These modern optical transducers are different from the other transducers described in this chapter because they do not work on analog principles. Although information is retrieved from a compact disc by modulating a beam of light, there is nothing in the beam of light or the current in the photodiode that is analogous to the music being retrieved. Instead, the compact disc and the modulated light beam convey digital information, a series of ones and zeros. With this technology there is little concern about distortion. Imagine, for instance that a reflected light beam is transmitting a signal that is supposed to be a "one." Suppose there is distortion and the beam transmits the analog equivalent of 0.8. That discrepancy corresponds to a distortion of 20%—intolerably huge for an analog system. Nevertheless, that signal is much closer to 1 than it is to 0, and therefore, the signal will be correctly read as "one." Thus no information is lost by the distortion. More on digital recording appears in Chap. 20.

Exercises

Exercise 1, Basic definitions

Define electrical charge, voltage, and current.

Exercise 2, It's not the size, it's the principle

How is a dynamic microphone like an electrical power generator?

Exercise 3, The origin of magnetism

Is it possible to have magnetism without electrical current in some form?

Exercise 4, Loudspeaker drivers

The motor principle involves a current and a magnetic field. The combination is said to produce a force. This principle applies to loudspeakers. Where does the current come from? Where does the magnetic field come from? What experiences the force?

Exercise 5, Warped images

Putting loudspeakers next to a TV can distortion the TV picture! Why should this happen? [Hint: This is an unintended consequence of the motor principle. Think about the CRT described in the chapter on Instrumentation. Do you see a current

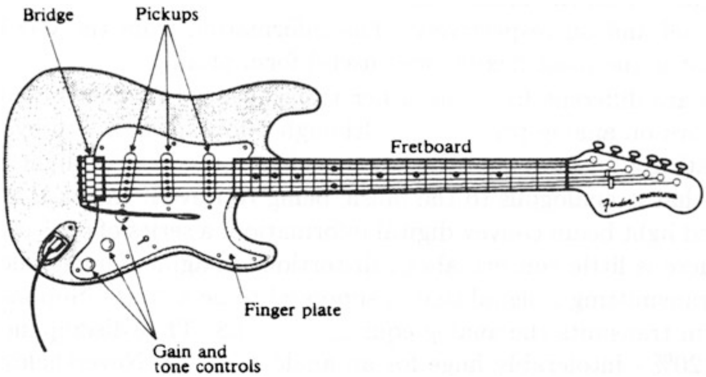

Fig. 16.7 This electric guitar has three pickups—three buttons—for each string

there? Think about loudspeaker drivers. Do you see a magnetic field there? Then there is the force. What experiences the force?

Exercise 6, Where's the motion?

If you look closely at a rock guitar, you will see one or more sets of buttons below each string as shown in Fig 16.7. The buttons are "pickups" that create an electrical current analogous to the motion of the strings. A pickup uses the generator principle to do this. The guitar pickup consists of a coil of wire wrapped around a magnet. How is there relative motion between a this coil of wire and a magnetic field? [Hint: Strings used on an electric guitar are steel, and steel is magnetic.]

Exercise 7, Design a microphone

In a dynamic microphone, the motion of a diaphragm causes relative motion between a coil and a magnetic field. If you had to design a microphone, which would you attach to the diaphragm—the coil or the permanent magnet?

Exercise 8, Motors and generators

It is sometimes said that a generator is simply a motor operated in reverse. (a) Explain how this is true in terms of fundamental ideas of mechanical motion and force and electrical current and voltage. (b) Do you suppose that you could use a loudspeaker driver as a microphone?

Exercise 9, Burned out drivers

The electrical current in the voice coil of a loudspeaker driver, which is necessary to make the cone move, has an unintended consequence. It creates heat. If there is too much current the wire in the voice coil will become so hot that the wire melts. What effect do you expect this to have on the operation of the driver?

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