Technology Brief 22
Noise-Cancellation Headphones

Noise-cancellation headphones are a class of devices that use ***active noise-control*** technology to reduce the level of environmental noise reaching a listener's ear. They were invented by Amar Bose in 1978, based on concepts developed in the mid-20th century (most notably by Paul Lueg, who developed a system for cancelling noise in air ducts using loudspeakers). The primary advantage of such systems is the ability to selectively reduce noise without having to use heavy and expensive sound padding. Beyond hearing aids and the commercial headphones used by airline passengers, specialized active noise-control systems have been in use by pilots and heavy equipment operators for several decades. In small enclosed environments, active noise-control systems can employ microphone and speaker arrays to lower the amount of ambient noise experienced by the listener. Examples of this include noise-cancellation systems used to dampen engine noise in cockpits, active mufflers for industrial exhaust stacks, noise reduction around large fans and, recently, systems for reducing road and traffic noise in automobile interiors.

Active Noise Control

In its most basic form, active noise control consists of measuring the sound levels at certain points in the environment and then using that data to emit noise from speakers whose frequency, phase shift, and amplitude are selected in order to cancel out the incoming environmental noise (**Fig. TF22-1**). In noise-cancellation headphones, small microphones outside the headphones measure the incoming ambient noise, and the measured signal is then fed to circuitry that produces output noise in the headset that cancels out the ambient sound (**Fig. TF22-2**). The general phenomenon whereby one waveform is added to another to cancel it out is called ***destructive interference***. The basic idea is to add a replica of the environmental noise signal, but shifted in phase by 180°, which is equivalent to multiplying the added signal waveform by (-1). Consider a vibrating wave traveling along a one-dimensional string (**Fig. TF22-3**), which is analogous to a sound pressure wave moving through the air. If we superimpose a second traveling wave onto the string (perhaps by waving the end up and down with a second hand), the two waves will overlap and the result will be the sum of the two individual waves (superposition). If we precisely time the second wave so

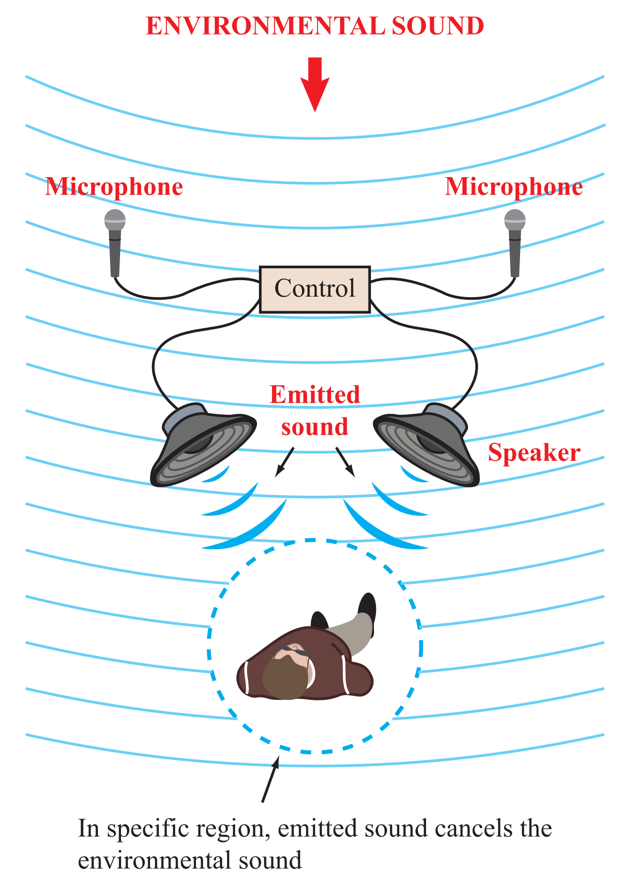

Figure TF22-1: Active noise control. A basic active noise-control system uses a set of microphones to sense incoming ambient sound; the microphone signals are fed into control circuits which drive a set of speakers. The control circuit generates exactly the signals required to cancel out the incoming ambient sound in a specific region.

that it is the exact mirror of the first (i.e., it is phase-shifted by 180° from the first wave), the two waves will cancel out exactly, and the string will not vibrate. This (in principle) is what active noise control aims to do, even though (in reality) the technology faces a number of limitations.

Limitations

In order to truly cancel out all ambient noise, the emitted noise would have to exactly match the ambient noise in both space and time for all audible frequencies across a three-dimensional volume (such as the interior of a car or an airplane cabin). This is very difficult to accomplish in real environments. High frequencies are the hardest

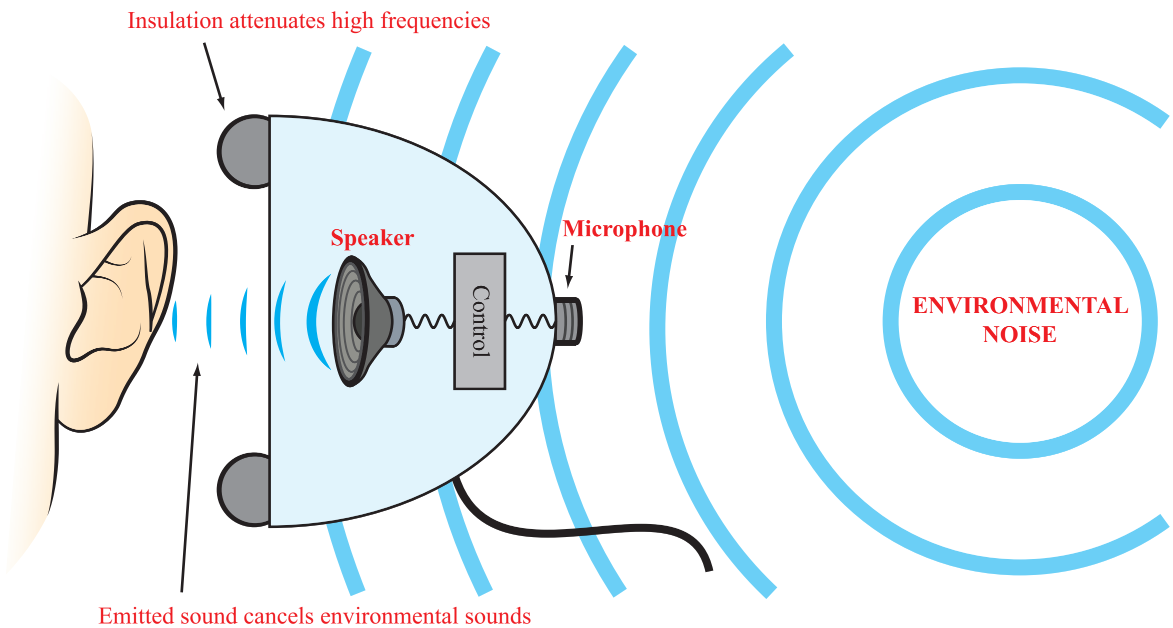

Figure TF22-2: Noise-cancellation headphones employ the active noise-control principle to eliminate noise around the ear. Sound insulation is used commonly to remove high-frequency noise signals, while the active system removes low-frequency sound.

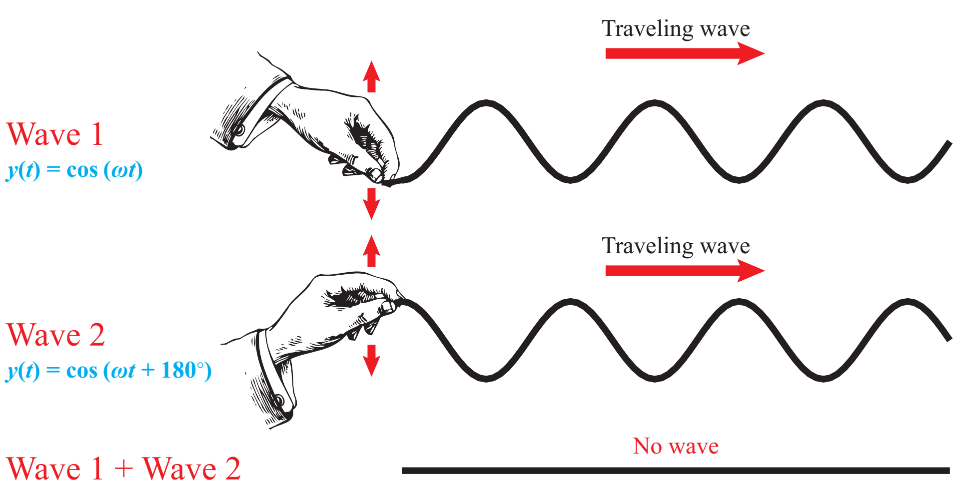

Figure TF22-3: Destructive interference via the superposition of two waves. A string can be agitated so as to generate traveling waves along its length. In order to cancel out a wave traveling along the string (Wave 1), we simultaneously can generate a second wave of the same amplitude and frequency with a 180° phase shift (Wave 2). Because the vibration of the string will be the result of the two waves superimposed, the two waves cancel out, and no vibration occurs. This is analogous to what active control systems do: Microphones sense ambient waves that are then canceled out by emitting an appropriately phase-shifted wave from the speakers.

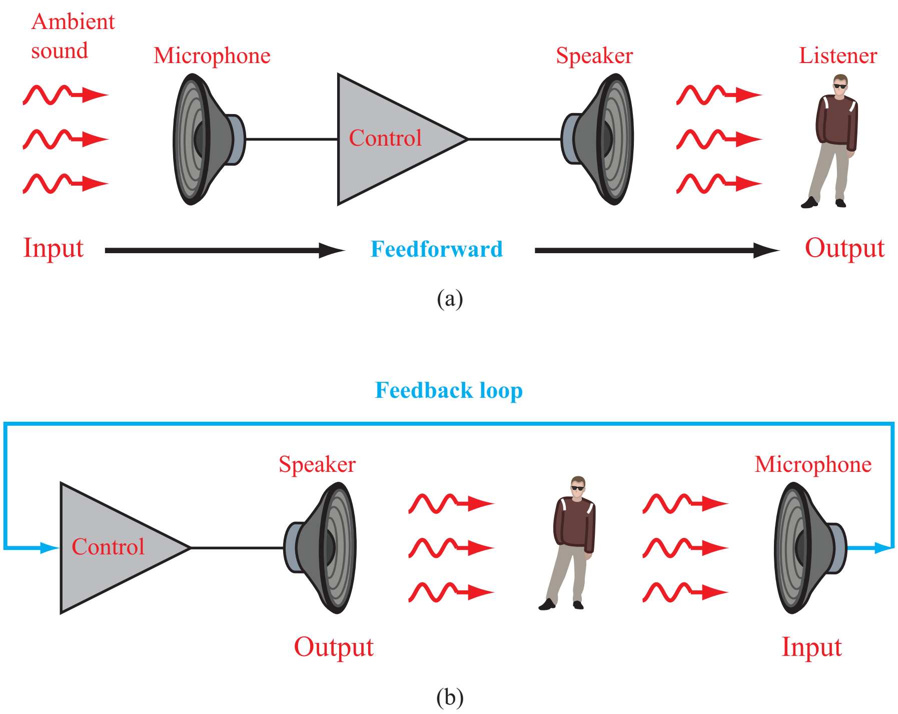

Figure TF22-4: Comparison between (a) an active noise-control system in a feedforward configuration, and (b) in a feedback configuration.

to match, because to correctly cancel them, the system would need to employ large arrays of microphones and speakers. Moreover, objects within the environment will reflect, absorb, and emit sound—further complicating the signals required to cancel the ambient sound. The situation is somewhat easier for headphones, as the area of interest is simply the user's ear (a much smaller physical region). However, most commercial noise-cancellation headphones do not attempt to cancel high frequencies. Padding and passive layers are instead used to absorb the high frequencies and the system actively cancels out only the lower frequencies (e.g., the airplane engine hum). In general, noise cancellation only works well for sound that is periodic. Noise that is random or has very fast changes is very hard to mask, because the system cannot compute what the interfering signal should be instantaneously.

Feedforward versus Feedback Control

Active noise-control systems provide an interesting comparison between feedback control (which we examined in Chapter 4) and feedforward control (**Fig. TF22-4**). Consider again **Fig. TF22-1**. If the microphones of this system are positioned relatively far away from the speakers, they sample the incoming ambient sound signal and send it ahead to the control circuit, which then drives the speakers. There is no microphone at the speaker location and thus no way to measure the "output" of the system (i.e., there is no microphone that measures how well the system is canceling the sound at the listener). This is an example of ***feedforward*** control. If we were to move the microphones very close to the speakers (or, better yet right next to the listener), the microphones would continuously report how well the speakers were canceling the sound. If the control system is doing poorly, the microphones will detect some sound, and the control circuit can attempt to correct for this. In such a configuration, the system is operating with ***feedback*** control. **Figure TF22-4** illustrates both of these control configurations. Some sophisticated active noise-control systems use both modes simultaneously: They have distant microphones as well as microphones near the listener. In general, feedforward systems are less practical to implement in consumer systems, and feedback systems tend to be less stable.