Dynamic and Electrostatic Headphones

Howard Souther*

WHILE THE SUBJECT of this discourse concerns listening through headphones, to understand the subjective significance of their performance we must employ comparisons with the perception of musical sounds in real existence. Further, we will help this effort by contrasting headphones perception to that obtained from loudspeakers. Additionally, we will elaborate on the differences between the listening modes—monaural, binaural, stereo and, yes, even four-channel "surround" sound.

The earliest reproducer was a single earpiece, which included a small electomagnet consisting of a coil of wire and an iron core with a 2- or 3-inch steel plate suspended over the end of it. The electrical counterpart of the signal passing through the coil winding induced varying amounts of magnetism in the core. This in turn vibrated the suspended steel plate, moving the air and making sound. The quality of these early phones was poor because the musical range was quite restricted. However, these phones served in communications work for many years, the present telephone receiver being a not so improved version.

Monaural Sound

The sound from early phones was characterized as *monaural*, and even when two earpieces were combined into a headset, the sound had no dimension nor depth. The best description of the effect would be that of listening to the music through a window, or, perhaps, listening with one ear at the microphone location.

Binaural Sound

When two microphones are employed, spaced and separated as are one's ears and each microphone feeds its own headphone, a tremendous effect of realism is obtained, although the sound seems to be realized "in the middle of the head" and slightly above the median line of the ears. The effect is pleasing, although reality is not duplicated, since there is no movement of the head permitted relative to the sound source.

Ordinarily, recordings are not made with this microphone spacing, for to achieve dramatic spatial effects with loudspeaker playback, a different pickup technique must be invoked.

Stereo

In stereo recordings microphones are widely spaced to favor instrument groups. Stereo listening through speakers is as different from "binaural" as binaural is from real life listening.

The finest loudspeakers reproduce about 8½ octaves of the musical range out of a possible 10. When one speaker is placed to the right and the other to the left, the directional effects of the concert field are simulated in the living room. Even the sound emanating from the center of the field is synthesized by the blending of the sound from two speakers.

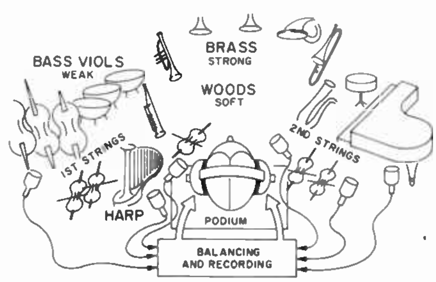
A cross-referencing center in the brain of the listener evaluates the intensity, quality, and arrival time of the sound from two sources in an instantaneous, composite and unconscious function. This allows him to determine that the sounds come from the left, the center, or the right. According to the loudness and reverberant quality, the listener also perceives whether the sounds are from the near distance or from far away. These things give three dimensions to the music and place the listener in the same position as the audience to produce a powerful effect of realism.

The art and science of acoustics provides tools and techniques which can enhance reality. It was Leopold Stowkowski who once said, "If I had a thousand bass viols, I could use them all." This points up one of the many limitations of real existence—and now we suggest something better.

The exclusion of distracting sounds, coupled with the proximity of the musical information received is only a part of the improvement over speakers and, yes, over real life listening too.

The plan (Figure 1) shows that however preferential his listening position, the conductor is too close to some instruments and too far from others, so that he must interpret, rather than hear, the actual musical balance. He compensates partially by bringing the soft playing harp in close, so that he can detect the delicate plucking. The inefficient violins are adjacent, with the concertmaster only arm's length away. Not so the bass viols. Their physical size and number demand a distant situation, in spite of their weak, but important low, grave tones.

The best efforts of the most famous maestro are vastly improved upon by the recording engineer when the phonograph record is produced. The recordist, using individual microphones placed in each orchestral section, augments and monitors the dim harp. He moderates the over-intensity of the clamorous



FINER THAN REAL LIFE

Fig. 1—This diagram illustrates the manner in which the headphone listener receives balanced sound levels from all parts of the orchestra.

*Vice President-Engineering, Koss Corporation brass. He increases the normally deficient bass section, thus accomplishing a musically balanced performance almost impossible to achieve in real life.

Through stereophones we gain the finest listening position, that of the conductor himself, and through disc recordings bypass his problem of interpreting proper balance of the instruments over near and far distances.

Here, then, through stereophones, and the scientific wizardry of the acoustics engineer, is the means of appreciating music far beyond the composer's most impossible desire.

Four-Channel Sound

Currently there is extreme interest, not to mention controversy, in *four-channel sound*, where left, right, left rear, and right rear signals are recorded and played back from the four corners of the room. Peculiarly, if the listener faces the center front and holds his head very still, there is no certainty that sound comes from the rear, although the ambience effect has been enhanced, perhaps because the two extra speakers have assisted high frequency dispersion. Movement of the head, of course, permits rear directional effects. The illustration may disclose why increased "surround sound" effects are achieved with speakers, and suggest that maybe headphone stereo listening has had the "surround" effect right along.

Observe in the illustration (Figure 2) that if the listener is blindfolded and faces the center between two speakers while the head is held steady, the virtual sound originating 20 degrees to the right cannot be differentiated from sound at 167 degrees, or from *behind the listener!* (1)

If, while listening to four channels with four speakers the head is moved 30 to 40 degrees to the right, the right rear channel becomes the "right" channel, and the left rear channel the right rear channel. Thus, a new localization of the sound to the front is achieved, but the origin of the *rear* sounds remain in question. It may be interpreted that in real life a visual clue is required to determine front and rear sounds unless the head is rotated. It has also been shown that visual clues are required for determining "up" and "down" sounds. While the two ears do a creditable job of establishing left, center, and right, and the brain evaluates intensity and reverberation to determine near and far distances, to hear rear sounds (without head movement), and to hear sound from "up" or "down," we may need a total of six ears situated on each plane of the head!

Because the headphones turn with the head, movement does not assist in determining "rear" sounds. However, the superior ambience effects, which lend so much to pleasing listening, have always been present in headphones with two channel recordings and now show possibilities of enhancement with the ambience added by four channel techniques.

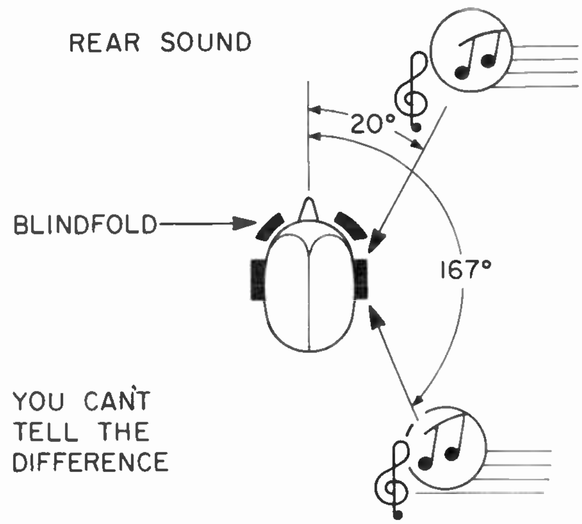


Fig. 2—When a blindfolded listener holds his head steady, rear sounds cannot be differentiated from front sounds. In this case a source 20 degrees off the axis also may be localized at 167 degrees.

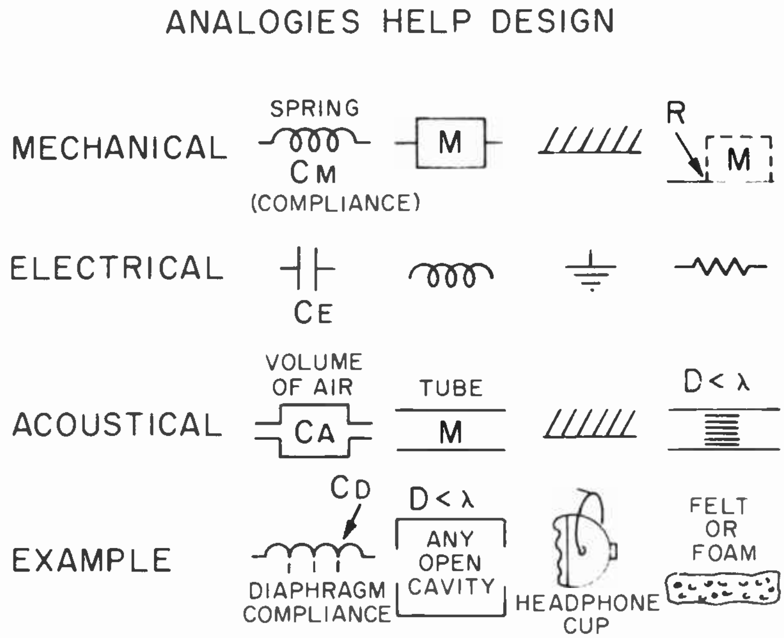


Fig. 3—Mechanical, electrical, and acoustical analogies. *Mass* is the mechanical element which opposes a change in velocity. *Inductance* is the element which opposes a change in current. *Resistance* is the electrical dissipative element. *Friction* is the mechanical dissipative element. *Capacitance* is the electrical element which opposes a change in the applied force. *Compliance* is the mechanical element which opposes a change in the applied force. It should be noted that in a mechanical or acoustical system, the capacitive element always must have one side grounded.

Tools for Design

The design of headphones is as much an art as it is a science. However, the art is ably assisted by the body of knowledge in mechanics and electricity. If this exposition serves as intended, the reader can become an expert and himself execute a good headphone design. Using as a tool the table of analogies illustrated in Figure 3 and by employing the considerations to follow as a base, a creditable headphone will result.

Before designing a headphone we must choose the method of operation. There are two of these, velocity and pressure, and we will explain the advantages of both. (See Fig. 4.)

The velocity design is light in weight, and defined as "supra-aural," which means that it rests *on* the ear. This class of phone is smooth in response and gives good sound. It does not exclude outside sounds, and thus lacks the virtue of complete involvement with the performance because of the inclusion of ambient noise.

The *pressure* operated headphone is "circum-aural." This means that the headphone cushion surrounds and seals the aural cavity. It rests on the head around the ear and scarcely touches the sensitive "pinna" or cartilagenous parts of the external ear. The circum-aural feature excludes outside noise and is very comfortable, although it makes for a somewhat heavier headset than the velocity type. The response range of pressure phones can be very wide, and for this reason they may be preferred.

How Velocity Phones Work

It is a nature of all physical things to vibrate at a fundamental frequency more easily than at any other. For example, a 3-inch disc of aluminum, 2 mils thick, suspended from a string in free space, if struck a sharp blow will resonate at about 1 kHz. (See Fig. 5). The mass, or inductance, and the compliance, which is analogous to electrical capacity, forms a resonant circuit resulting in high efficiency. If the disc were infinitely light and infinitely stiff (the "ideal" loudspeaker membrane operating in free space), the response would be weak at low frequencies (zero capacity or compliance) and increase at 6 dB per octave without limit as the frequency went up (zero inductance or mass). Under these circumstances, the sound would be shrill, just like that of a magnetic or velocity phonograph cartridge plugged into the auxiliary amplifier input instead of the velocity equalized cartridge input. The remedy in a velocity design is to apply mechanical equalization to our headphone to offset the shrill sound. Here is the way we go about it:

First, we select a diaphragm of the proper thickness, say 2 mils, and introduce thereby a certain amount of mass, or inductance. This mass behaves just like a coil of wire in an electrical circuit and rolls off the shrill high end. Next, we make our diaphragm compliant by having previously selected a limp material, like polyvinyl chloride, so that we add "capacity" to our equivalent electrical circuit. If we make this selection judiciously, the diaphragm will resonate where we lacked energy, or be very efficient at 200 Hz. By using foam

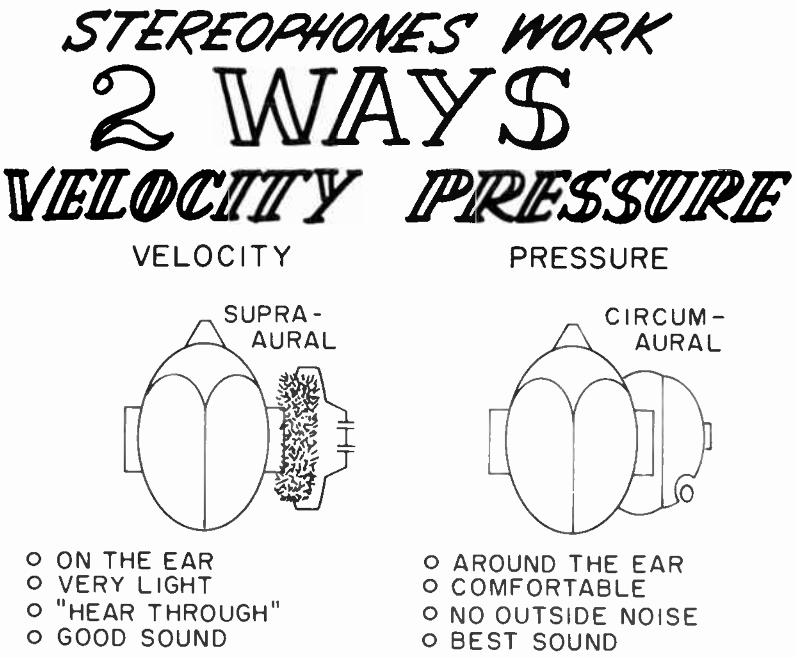


Fig. 4—Comparison of the main features of velocity and pressure type headphones.

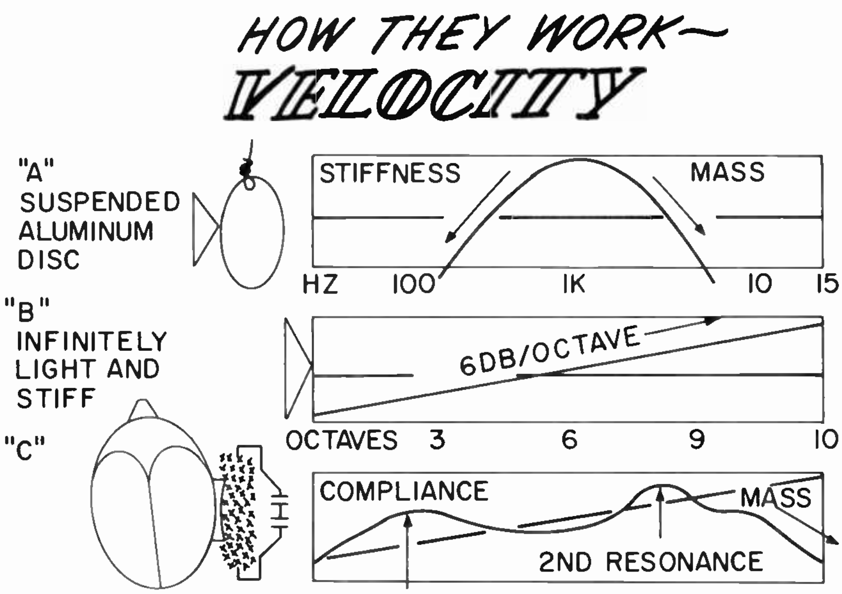


Fig. 5—A, The response of a 2-mil aluminum disc in free space when struck. **B,** The "ideal" diaphragm is infinitely light and infinitely stiff. **C,** The mass and compliance of a velocity headphone are chosen so that a large primary resonance occurs at about 200 Hz.

on the frontal area of the earpiece, we introduce resistance which lowers the height of the resonant 200 Hz "hump" and controls it. This foam, or felt, distributes the pressure on the ear and gives comfort, too.

The diameter of the diaphragm determines the frequency of the reflection from the rim back to the center. Generally this causes a reinforcement in the treble range and is designated as the *second resonance* in the diagram. If a major reflection returns to the center out of phase, a bad cancellation of the signal energy can take place.

At this point in the design, art enters in and science leaves the scene. The physicist would say simply that you can't make a phone that will work well in these circumstances. But the engineer, by judicious employment of felt, foam, plastic, and wire, and despite humps and suckouts in the mid-range, smooths the response, struggles to get widest range and finally achieves a pleasing musical balance by minimizing the weak energy in the first three octaves and the effects of too much mass roll-off of the high end.

Pressure Type Phone

The ideal environment for propagating bass sounds is a closed cavity. Here the pressure mode of operation excells, for the circum-aural cushion seals the headphone diaphragm against the cavity of the ear. It can be predicted that response will be flat below the 400 or 500 Hz primary resonance of the system. Under these conditions we achieve linear response all the way to dc. This is a situation that can be used to help in other ways. The diaphragm can be much stiffer than in velocity phones, promoting an extension of the high end. The stiffness of 2 mil mylar, for instance, offsets the high frequency limiting mass of the material to give full energy level as high as 24 kHz.

The Glitch

We mentioned earlier that the reflection from the rim often causes a cancellation, the frequency of which depends on the diameter. This cancellation can be especially violent in a closed cavity. Referring to our chart of analogies, we find that acoustic resistance in the form of foam can eliminate peaks simply by knocking them off, or lowering the Q of the circuit. It can and does lower efficiency, too. Cone drivers common to lower cost headphones have bass efficiency to spare, but the acoustical resistance is difficult to apply, so most low cost headphones have a violent dip, or glitch, an octave or more wide in the midrange. (See Fig. 6.) This causes a displeasing hollow sound. If the glitch is more than 12 dB deep, it causes an actual physical discomfort because the brain is overstrained to supply the missing frequencies. The cone has another serious deficiency too. Not only does the mass of the cone roll off the higher frequencies, but the compliance of the very large trapped air volume shunts the high frequencies to the acoustic ground, consisting of the hard bones around the head and the headphone case.

The Fix

By using a smaller, flatter diaphragm, say two inches in diameter and mounting it close to the ear, high frequency-destroying mass and compliance (the trapped air volume in the apex of the relatively large and heavy cone) can be reduced. This reduction gives extended highs at good efficiency. The diameter glitch is still there, however, and defies almost all countermeasures.

Instead of raising the bridge we must lower the river. Removal of the glitch

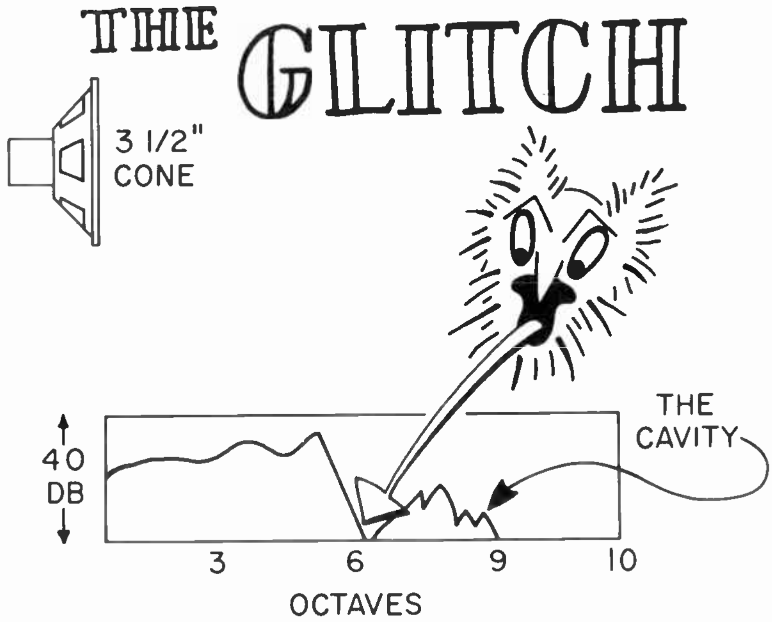


Fig. 6—The low energy output of cone type drivers is very high with a 3½-in. diameter cone, but is not easily damped. Operating as a pressure device in a sealed cavity, a violent cancellation is shown about 2000 Hz.

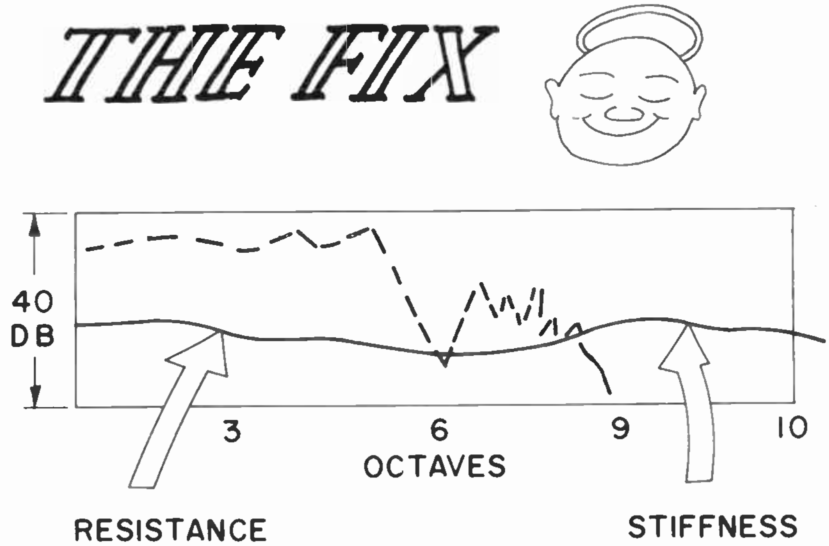


Fig. 7—With a 2-in. flat diaphragm acoustic resistance lowers the bass efficiency to the bottom of the "glitch." Increased stiffness and lower mass extends the high end.

is accomplished at the expense of the unneeded bass efficiency by applying a very high acoustical resistance to the area back of but not touching the diaphram. This works almost entirely at the low end to reduce all bass level to the bottom of the glitch, effectively banishing it. By compressing the felt used as a resistance the bass level can be adjusted for pleasing balance, or accented to appeal to the younger listeners. If physicists would only think of compromises like this there would be no need for engineers!

Exploiting the Pressure Design

The cutaway illustration of the new PRO-4AA headphone (Fig. 8) shows how the preceding considerations have resulted in a practical design which performs well. The felt washer is adjustably clamped to damp the bass range. A 1 inch very light weight self-supporting voice coil operates in a gap saturated with flux from the magnet structure. This coil is attached to a 2-mil mylar diaphragm that is actually sandwiched between 2 conforming plastic members. In this way high acoustical stiffness is achieved because the trapped air volumes are kept exceedingly small, thus giving extended 24 kHz response at full level. Note the plastic dome beneath the diaphragm which greatly minimizes the trapped air volume.

The conforming liquid filled ear cushion effects an almost perfect seal against the head with comfort, thus insuring linear bass response to the electrical limits of the supporting amplifier.

A collateral, but important benefit of the unique acoustical loading is that the plastic of the "sandwich" supports the mylar diaphragm uniformly against destructive excursions from all but the most severe overloads, making the element virtually blow-out proof.

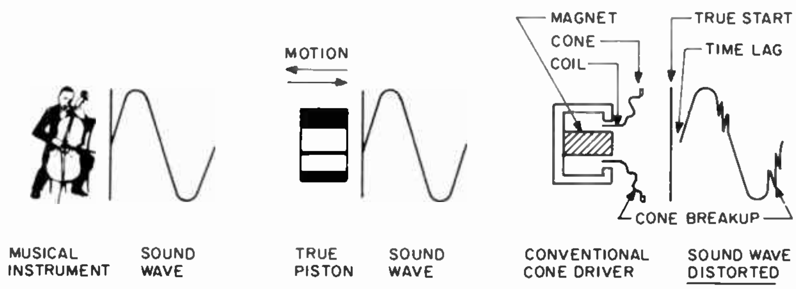


Fig. 9—Ideal piston operation and cone breakup.

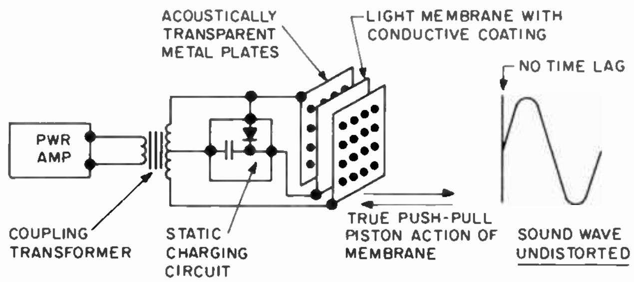


Fig. 10—Operation of the electrostatic driver. The charging circuit may be self-energized as shown, or be separately energized from a power supply, as with the Koss ESP-9.

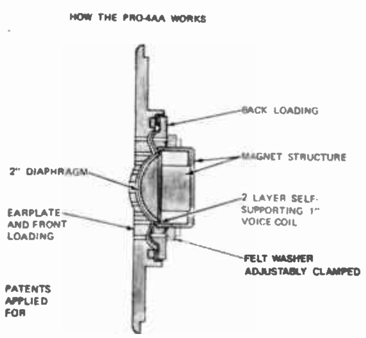


Fig. 8—Cross section of the Koss Pro—4AA with 2-in. element.

ELECTROSTATICS

The illustration (Fig.9) shows a cone loudspeaker and an electrical signal in the form of pure sine wave. Lacking high stiffness, the cone vibrates not only at the frequency of excitation, but breaks up and vibrates at frequencies other than the fundamental. This is a form of distortion which is present in greater or lesser degree in all dynamic drivers because only the central portion of the cone adjacent to the voice coil is under perfect control.

In the search for flattest, most extended response range and lowest distortion, the electrostatic principle overcomes many disadvantages of the dynamic units and offers several important improvements.

The moving diaphragm can be very thin, say ½ mil mylar, weighing less than a ⅜ inch layer of air adjacent. While the ideal of "infinite stiffness" may seem distant, it is closer than we might first surmise.

In a dynamic driver the magnet structure provides an intense field. This field changes the condition of space around the voice coil so that current flowing through the coil causes it to move and transmit its motion, indirectly, to the diaphragm. In electrostatic transducers a static charge on the membrane also changes the condition of space. When the diaphragm is mounted between two acoustically transparent plates, and the signal is impressed across the plates, the entire diaphragm is electrically controlled, *or stiffened*, and force is exerted *directly* over the entire area, causing it to move without breakup as an ideal piston.

The resonance of the pressure operated electrostatic driver is in the region of 2 kHz because of its low mass. This means that below this point we predict, and obtain, virtually linear response. Aided by the high electrical stiffness as well as the low mass, extended high response is obtained, and attention to proper coupling to the ear results in excellent flatness. True push-pull action, not attained in dynamic designs, cancels all second harmonic distortion.

The effect of the performance of a good electrostatic headphone is immediate, vivid and compelling. The bio-acoustic benefits of very low distortion require study, but electrostatics have a cleanliness of reproduction not approached by any other form of reproducer. There is a satisfying, unstrained quality form the extended, flatter response that surveys an unparalleled emotional experience.

In electrostatic headphones we can find the happy blend of art and science. Try listening to them—and we think you'll agree that here is modern acoustical engineering in its highest, most sustained flight. Æ

(1) *Journal of the SMPTE* Vol. 61, September, 1953, Physical Factors in Auditory Perspective, J.C. Stienberg and W.B. Snow.

The "OPEN-AIRE" Principle in High Fidelity Headphones

Friedrich Warning*

During the last decade, stereo headphones have become increasingly popular. Everyone who experiences headphone sound for the first time is amazed at the almost unbelievable difference in sound quality as compared to loudspeaker reproduction.

However, early headphone designs were not without their drawbacks. Conventional units, for example, required an airtight seal between phone and ear to achieve good low-frequency reproduction, for with the slightest leak, bass tones seemed to "drain" from program content. While the seal produced some possibly desirable effects, such as isolating the listener from his surroundings, some side effects made this a mixed blessing.

For one thing, the sense of isolation, except in special applications, often proved uncomfortable. To see why, one only need hold up a glass or cup to the ear. After a relatively short period of time, the constant pressure and lack of airflow generally proves annoying. Another problem is that the seal prevents ever-present body heat and moisture, as well as bass energy, from escaping, producing a warm and often humid environment that can quickly become uncomfortable, particularly on sticky days.

The headphone construction techniques required for this type of design also had some drawbacks; as some manufacturers produced increasingly heavy and more soundproof enclosures, some headphones became rather monstrous in size and weight. For the majority of listening situations, smaller size and weight are of definite importance, particularly for prolonged periods of time.

*Sennheiser Electronic

Getting Back to Basics

Because the "open-aire" approach to headphone design depends on a number of basic transducer phenomena, it might be well to review some of the principles originally discovered in loudspeaker research. Figure 1 shows the cone of an ordinary loudspeaker suspended in free air.

Early loudspeaker designers found that, at normal listening distances (A and beyond, Figure 1A), free-standing speakers are relatively inefficient at low frequencies. This is, of course, because sound waves generated by the *rear* of the speaker arrive at the ear

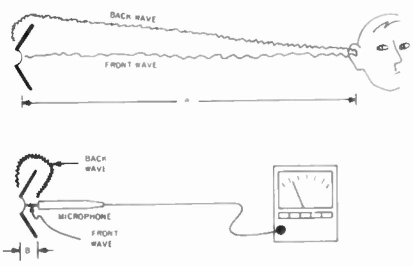


Fig. 1—Close to the speaker, phase cancellation is minimal, even at low frequencies.

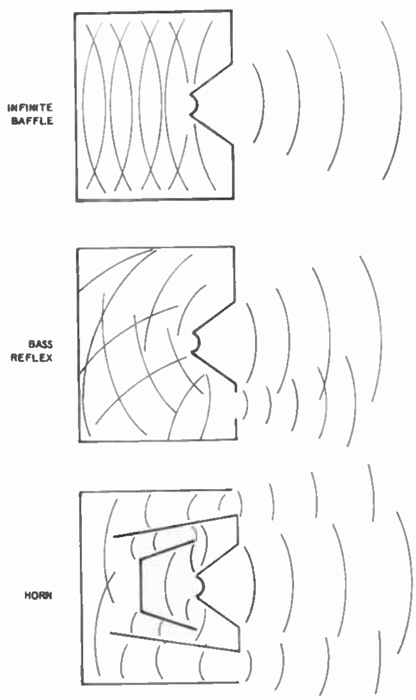


Fig. 2—Various speaker enclosures which eliminate, attenuate, or rephase back waves.

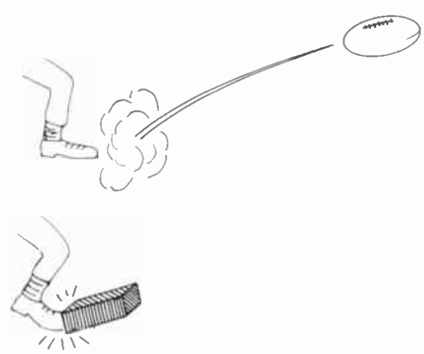


Fig. 3—An object with low mass moves easier and further when a force is applied.

with amplitudes nearly equal to those arriving from the *front* of the speaker. Since, at low frequencies, the wavelengths are relatively long, sound energy from the rear of the speaker arrives almost perfectly out of phase with energy from the front of the speaker, resulting in a high degree of cancellation and poor or nonexistant bass.

However, when the speaker's response is measured at distance B, which is close to the front side of the cone (actually, a distance less than the cone's diameter), much better bass response is measured. This is because, while the front wave travels a very short distance, the back wave's path is, relatively speaking, much longer. And when you consider that sound, like any form of energy, dissipates in intensity with the *square* of the distance between source and listener, the cancellation produced at B between front wave and back wave is negligible.

Of course, with a speaker system, it is impractical to move the listener to point B. To get around this problem, various types of enclosures were developed—infinite baffle, bass reflex, horn, etc. But all utilized the same basic principle, attenuate or eliminate the speaker's back wave (see Fig. 2). As the many excellent speakers on the market demonstrate, this has been successfully achieved.

But this was not done, however, without some compromise. Restricting the air-flow behind a speaker generally raises its resonance point which is not especially critical in a speaker system (since transducers may be readily made large and heavy enough to have low resonances even when enclosed), but quite another situation occurs when transducers are small, as in headphones.

When headphones are enclosed at the rear of the diaphragm, substantial increases must often be made in diaphragm size and/or mass, to reattain low resonance frequency. Unfortunately, as moving mass increases, so does inertia. This can have detrimental effects on transient response, since higher masses require greater forces to move them (or longer time to get moving with equal applied force—see Fig. 3). Thus, with conventional headphone designs, it may be necessary to trade off transient response for better bass response (or vice versa).

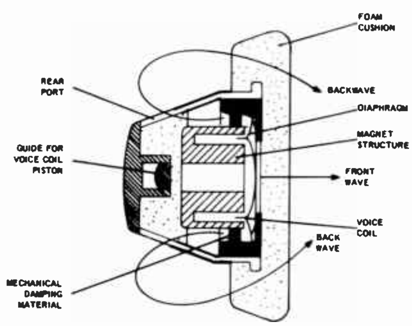


Fig. 4—Cross-section of "open-aire" headphone.

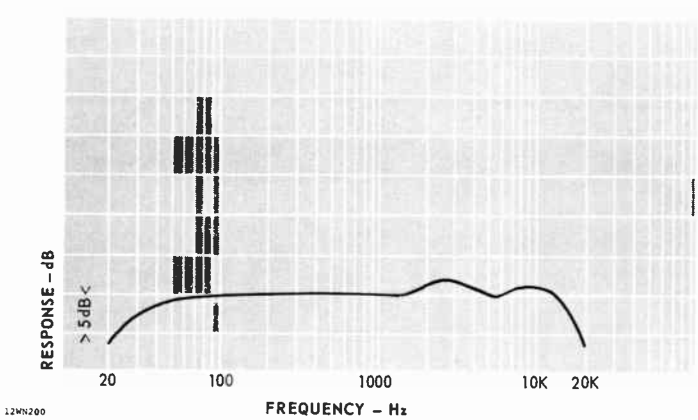


Fig. 5—Response of Sennheiser HD 414 "open-aire" headphones.

The "Open-Aire" Design

Going back to Fig. 1B, we see that there are few response problems if the listener is relatively close to the speaker diaphragm. In fact, if distance "B" is less than the diameter of the cone (or diaphragm), we can *ignore the nullifying effect* of the back waves for all practical purposes. And if this is achievable, there is no longer any need to "bottle up" or attenuate the back wave, with associated resonance and transient response problems.

Now consider, for a moment, the ear's location with respect to the diaphragm of a headphone. You see the point—without resorting to a huge diaphragm, the ear is still less than half-a-diameter away from the diaphragm. It is precisely this "free-air" principle that is responsible for the excellent frequency and transient response of the "open-aire" design.

Figure 4 illustrates the cross-section of an "open-aire" headphone. A moving coil system is coupled to a diaphragm in the normal way. However, the housing at the rear of the driver element is perforated, to allow unrestricted passage of the sound generated by the rear of the moving diaphragm. There is no trapped air behind the diaphragm to raise resonance or inhibit transient response. So, with a diaphragm of proper weight, elasticity, and diameter, it is possible to obtain good low-frequency response combined with excellent performance in tone-burst tests.

Ear as a Resonant Cavity

Even though "open-aire" headphones do not seal the *rear* of the transducer, they could be constructed in a manner that eliminates all outside sounds by providing the *front* of the diaphragm with an airtight coupling to the ear cavity. However, besides the comfort problems raised earlier, two acoustic problems could result.

First, a sealed cavity in *front* of the diaphragm would have precisely the same injurious effects on frequency and transient response as one behind it, raised resonance and all its results.

Second, tests have shown that several disturbing resonances can occur between the outer ear and a flat surface close to it—a phenomenon not uncommon with conventional headphones. In the "open-aire" design, a soft, lightweight cushion of porous foam spans the opening of the outer ear. The damping effect of this cellular material prevents dips and peaks in the frequency response. Figure 5 illustrates the response of a typical "open-aire" headphone, the Sennheiser Model HD 414. The intentional response rise at 2.5 KHz corresponds to the natural increase in sound pressure at this frequency caused by the dimensional properties of the head of an average person.

Psychological Factors

While our discussion of the "open-aire" design is primarily an acoustical one, it would be incomplete without mentioning some relevant psychological factors. As the intentional response peak mentioned above indicates, our consideration of creating "optimum" sound has gone beyond the restricted environment between diaphragm and ear because any reproducing transducer should not aim at some theoretical norm (e.g., idealized "headphone" sound, "speaker" sound, etc.), but rather at verisimilitude, a lifelike-as-possible recreation of the original performance.

Thus, we have included a response peak, to duplicate the apparent sound perceived by the *ear* in an open-air listening environment.

For similar reasons, tests have shown the "free-space" feeling of the "open-aire" design are critical to the "naturalness" of using headphones. Some subjects, in fact, reported that at mid and high frequencies, the sound actually seemed to be coming from "beyond" the headphones: a fact which later tests determined was due to the *positive* effects of miniscule. backwave leakage that occurred at these frequencies.

Also, many subjects indicated a preference for the relative lack of isolation from outside sounds provided by the headphones. Responses ranged from the practical ("I know if the phone is ringing or the baby crying") to the musically-oriented ("I feel like I'm at a live performance rather than in an artificial environment"). However, objective tests revealed that, even though the headphones cannot be "heard" well by nearby individuals (even when played at high levels), wearers could achieve a feeling of total isolation, when desired, simply by advancing the volume control. Æ