TECHNOLOGICAL REPORT

An "acoustically invisible" hearing aid

By Mead C. Killion, PhD

For roughly a dozen years, the writer has been pursuing the goal of creating a high fidelity hearing aid. This paper is a progress report on a K-AMP custom integrated circuit amplifier designed to make such a hearing instrument possible. The "automatic signal processing" built into this amplifier differs from common practice. The first section of this paper explains the rationale for the new approach.

The second section of this paper reviews the author's earlier fidelity rating experiments. Using experimental "unity gain" hearing aids, it was demonstrated that subminiature microphones and receivers could deliver high fidelity sound according to the most stringent listening-test standards.

Finally, the input-output characteristics of traditional hearing aid amplifiers are reviewed in order to compare them to the new approach.

Rationale: Who needs it?

Despite decades of research, still not enough is known about hearing impairment to define the optimum hearing aid characteristics for many individuals. This is certainly true for the person with severe to profound hearing loss.

The person who claims: "I don't need a hearing aid most of the time," however, appears to present a problem for which a solution can be defined without further research. As argued below, such an individual probably has a mild hearing loss that is restricted to a loss of sensitivity for quiet sounds, with normal or near-normal hearing for louder sounds.

Nixon[6] reported in 1945 that "hearing loss measurements were made on a number of engineers, program producers and musicians at NBC some years ago to attempt to correlate hearing loss with ability to judge program quality. In a few cases where hearing was impaired to the extent of 40 dB at frequencies of 4000 cycles (Hz) and higher, the particular individuals were actually among the most competent of those concerned with exercising judgment of program quality." This author's more recent observation of musicians and colleagues with mild hearing impairment leads to the same conclusions: they show absolutely no indication of any abnormality in hearing for high-level sounds, even though a mild or mild-to-moderate hearing loss at threshold is measurable at the speech frequencies and is noticeable when someone talks too quietly.

As an illustration, the audiograms in Fig. 1 show the extensive regions of presumably normal hearing, inferred from the experimental complete-recruitment data of Barfod,[1] for two hypothetical subjects with mild hearing loss.

When to do nothing

Following the old adage "If it ain't broke, don't fix it," the ideal hearing instrument for someone who "doesn't need a hearing aid most of the time" appears self evident. It should do absolutely *nothing* most of the time. When no hearing assistance is required, the hearing instrument should be so acoustically transparent that it subjectively disappears; it should be acoustically "invisible." Stated another way, if an individual has normal hearing for loud sounds, the hearing instrument should, for loud sounds, neither stand in the way of the wearer's normal hearing nor give amplification the wearer does not need.

Of course, this principle is nothing more than an application in the *amplitude* domain of a principle that every dispenser applies in the *frequency* domain: Don't amplify in a region of normal hearing. The great success of the open-canal fitting for those with normal, low frequency hearing is an obvious example of the latter. But the same principle generally has not been applied in the amplitude (loudness) domain.

The prime example is in the hearing-impaired person trying to make out individual voices around a conference table. In this case, amplification tends to magnify everything, including making loud sounds too loud. What appears to be needed in this case is a hearing instrument with such fidelity that it subjectively disappears for louder sounds when it is (automatically) set to provide 0 dB acoustic gain (no gain, no loss) for louder sounds. The instrument should, of course, provide gain for the quiet sounds this person is missing. In the same way, the typical, older person with sloping, high frequency hearing loss needs more gain for high frequency sounds than for low frequency sounds, so that a substantial treble boost also is required for quiet sounds.

High fidelity transducers

A decade ago, it was popular to proclaim that the main problem with hearing aids was the "inherently low fidelity of the microphones and earphones." Partly in answer to such claims, this author demonstrated that it was possible to design BTE and ITE hearing aids which would reproduce speech and music with a fidelity comparable to that of expensive studio monitor loudspeakers.[2,4]

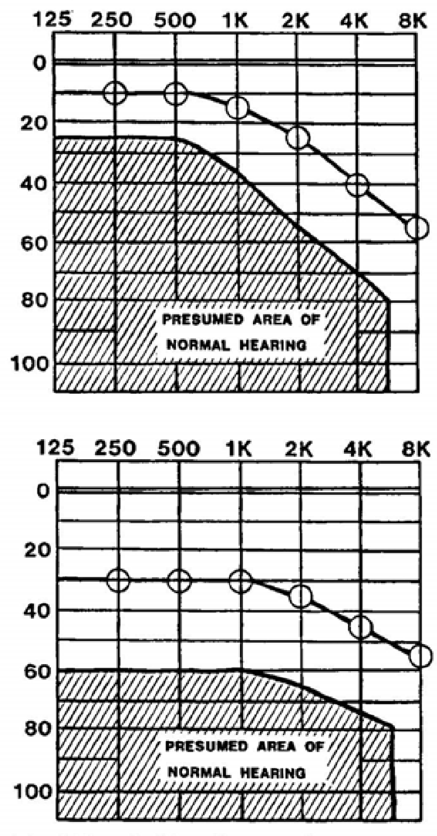

Fig. 1. Threshold audiograms for two hypothetical subjects, with areas of presumed normal hearing based on Barfod's data (reprinted with permission from Killion 1988[5]).

Fig. 2 shows a few of the results from those extensive fidelity rating experi-

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Mead C. Killion, PhD, is president of Etymotic Research, Elk Grove Village, IL.

ments. Experimental hearing aids were compared to popular stereo headphones such as the Koss PRO4AA, stereo loudspeakers such as the ElectroVoice Sentry V studio monitors and a speech audiometer (which was often referred to as "high fidelity" in the audiological literature). Three types of listening panels were used: Golden Ears (five high fidelity experts, the most famous of which were Julian Hirsch, who makes his living rating high fidelity systems; Hugh Knowles, who as "Mr. Loudspeaker" in the 1940s coined the term "Bass Reflex"; and Edgar Villchur, who in the 1950s developed the acoustic suspension woofers and dome tweeters); Trained Listeners (Elmer Carlson, Richard Peters, Daniel Queen, Eugene Ring, Robert Schulein and Frederic Wightman); and Untrained Listeners (12 males and 12 females aged 20 to 60), chosen to represent "man on the street" type of listeners. All three panels gave essentially similar results. Available transducers (Knowles BT- and EA-series microphones and BP-series earphones) permitted the reproduction of full-orchestra and jazz-trio selections, at original concert levels, with a fidelity equal to high-quality stereo systems.

Further evidence that the transducers are not "the problem" is the fact that a modified version of one hearing aid microphone, which the author helped design, is regularly used in broadcast and recording studios. In addition, the same basic receiver (Knowles ED-series) that is used in many hearing aids also is used in some of the highest-fidelity stereo earphones presently available. The main problem left to be solved then is one of amplifier design.

The traditional amplifier

Most hearing instruments provide amplification for all sounds, even loud sounds, up to the level that peak clipping, input or output compression limiting or ASP circuits set in to reduce the gain. Many of these modern compression circuits are designed now to prevent the sounds some older hearing instruments made when driven into overload. Properly adjusted, all prevent sounds from becoming uncomfortably loud, however, only a few wide-dynamic-range-compression circuits amplify sounds up until they are *almost* at the point of being uncomfortably loud. Slightly loud normal conversational speech generally is considered to be at a hearing level of 60-70 dB, corresponding to an SPL of 75-85 dB. Such speech may not be *really* uncomfortable when amplified to 90-100 dB SPL, but it is getting there. The well-known result is that the hearing instrument wearer often turns the volume control down and consequently misses some of the

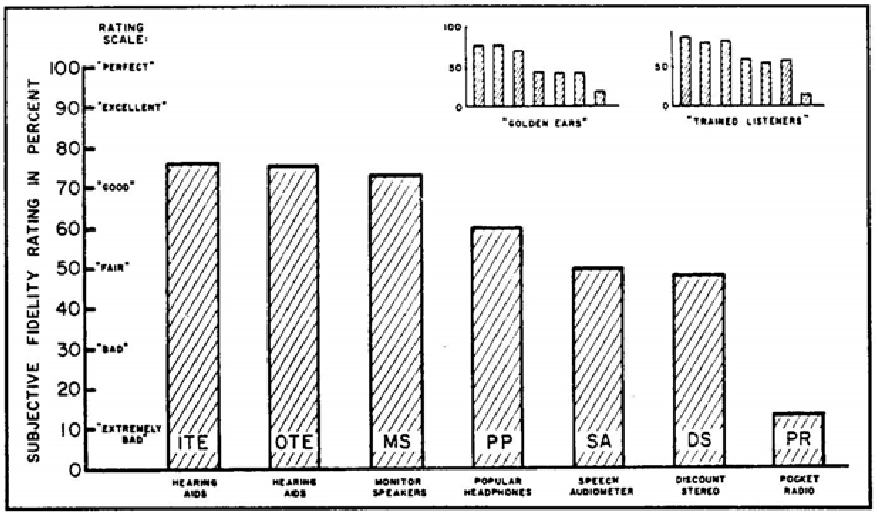

Fig. 2. Average fidelity ratings obtained for several sound reproduction systems (reprinted with permission from Killion 1988[5]):
Experimental ITE binaural hearing aids (ITE);
Experimental OTE binaural hearing aids (OTE);
ElectroVoice Sentry V studio Monitor Speakers (MS);
Koss PRO4AA Popular Phones (PP);
Simulated speech audiometer with TDH-39 earphones (SA);
K-MART special $69.95 "High Fidelity" Discount Stereo (DS);
GE $4.95 pocket radio in peak-clipping overload (PR);

quieter sounds.

The relationships described above are shown graphically in Fig. 3, which shows the gain and input-output characteristics of a hearing instrument with maximum output controlled by limiting (whether peak clipping or any-named compression with high compression threshold and high compression ratio). Note that such an instrument acts as a linear amplifier with constant gain until limiting sets in. Below the limiting level, both loud and quiet sounds are amplified by the same amount.

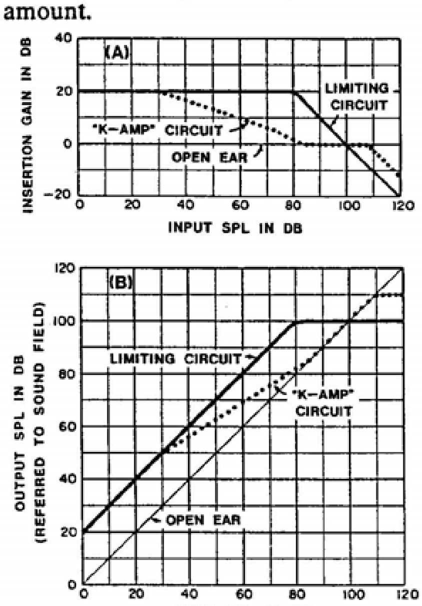

Fig. 3. Hearing instrument gain (A) and output (B) vs. input for conventional "limiting" type of amplifier (_____) and for the new amplifier design (. . . . .), both set for a maximum gain of 20 dB. NOTE: The unaided open ear has neither gain nor loss "0 dB gain" for all inputs.

The new amplifier

During his PhD research, this author designed a "four-stage compression amplifier" to eliminate the problems described above.[3] This circuitry is called the K-AMP. It is designed to provide:

1. Substantial gain for quiet sounds;
2. Decreasing gain for moderate-level sounds;
3. No gain (but no loss) for loud sounds;
4. Compression limiting for the loudests sounds, to prevent output amplifier overload (peak clipping) with its attendant rasping, raucous, unpleasant sound.

AUTHOR'S NOTE: *With the high quality sound reproduction available in audio devices today, only an experienced hearing instrument wearer would be expected to tolerate the grating sound of peak clipping on a prolonged basis; although in all fairness to peak clipping circuits, some wearers get quite used to it and accept it.*

The type of input-output characteristic that results with the new approach also is shown graphically in Fig. 3. The new amplifier provides the same gain as a traditional amplifier for quiet sounds. For loud sounds, however, the new amplifier allows the hearing aid to "do nothing" (provide neither gain nor loss). For intermediate sounds, an intermediate amount of gain is provided. Combined with proper transducers and acoustic coupling and venting, the result can be a hearing instrument that comes close to being "acoustically invisible."

Note especially that the traditional discomfort-preventing output limiting is no longer needed in most cases, because loud sounds are not amplified.

With the K-AMP circuitry, intense sounds should be no more uncomfortable with the hearing instrument on than if it were removed. Only if the wearer needed hearing protection in his or her daily routine would output limiting be required for that purpose.

The need for greater gain at high frequencies, in the case of sloping high frequency loss, can be accommodated by requiring the frequency response, as well as the gain, to change with level.[7] Fig. 4 shows the frequency response characteristics, with level as a parameter, of a prototype version of the K-AMP with suitable level-dependent, high frequency emphasis. No high frequency emphasis is provided for loud sounds, because the typical individual with mild, sensorineural hearing loss does not appear to have a high frequency hearing loss for loud sounds, only for quiet sounds (recall Fig. 1).

Antifeedback bonus

There is an additional advantage to the new design approach. Feedback squeal is an all-too-common problem which sometimes can occur even with a reasonably well-fit earmold when the wearer is eating. For most wearers, the only practical solution to date has been to turn down the gain of the hearing instrument during such times. This "turn-it-down" occurs automatically with the K-AMP circuit. As soon as feedback squeal starts to build up, but while it still is very quiet, the increasing signal at the microphone causes the gain

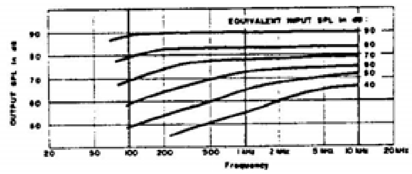

Fig. 4. Output vs. frequency of prototype amplifier adjusted for an individual who has a sloping high-frequency hearing loss for quiet sounds with normal hearing for loud sounds (reprinted with permission from Killion 1988[5]).

to drop until the hearing instrument is just on the verge of squealback. In nearly every case, this will occur at a relatively low output level, so that instead of hearing a loud squeal with each chew, the wearer hears only a quiet, almost breathy, whistle that generally will be inaudible to others around the table.

What's next

As exciting as it is to see the approaching completion of a 12-year project, the real test is still ahead. When it is finished, this K-AMP circuit will be made available to manufacturers. The ultimate test of this amplifier design will be the degree of its acceptance by hearing-impaired wearers. □

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Address further inquiries to: Mead C. Killion, PhD, Etymotic Research, 61 Martin Lane, Elk Grove Village, IL 60007.
