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HIGH FIDELITY AND HEARING AIDS

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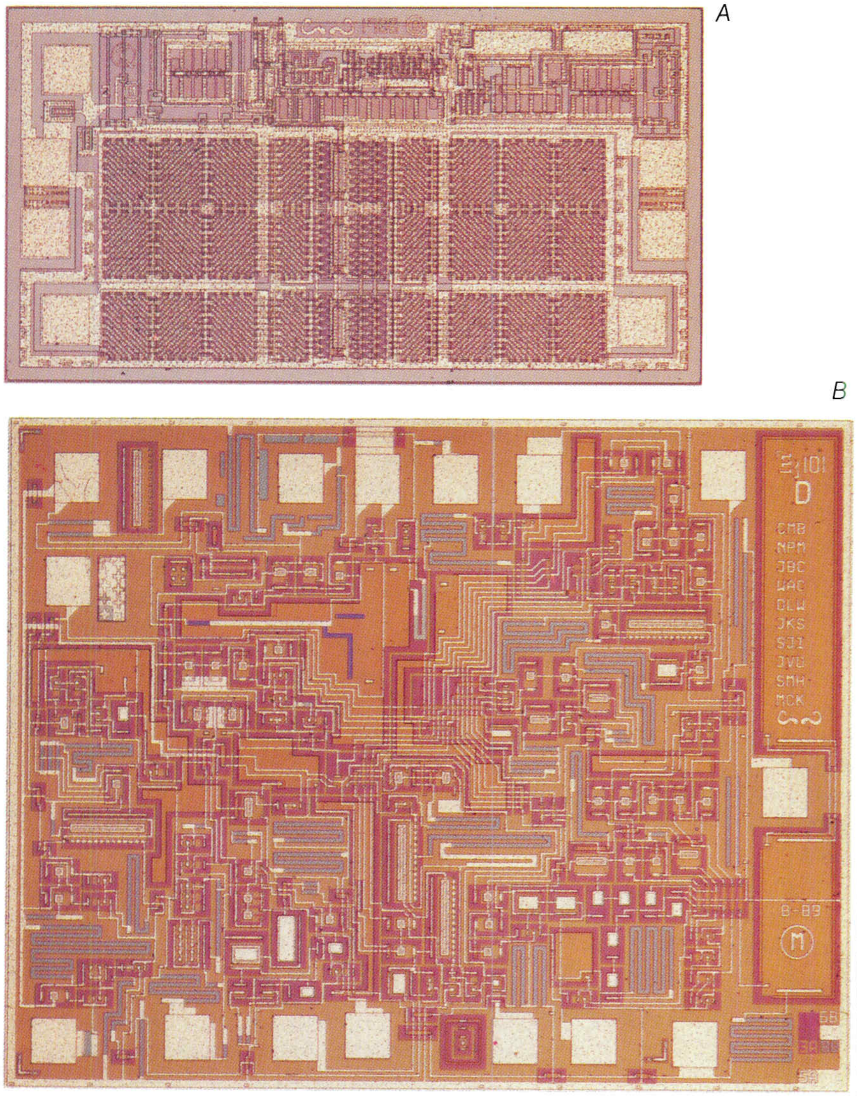

Fig. 1—A magnified view of two high-fidelity hearing-aid ICs, a C-MOS Class-D power amplifier (A) and the K-Amp bipolar input amplifier (B).

The quest for a high-fidelity hearing aid began with the design of hearing-aid sized microphones that were used in recording and broadcast studios in the late 1970s [1]. It continued with the development of damped acoustic coupling systems for hearing-aid receivers [2].

Listening tests which I conducted at Northwestern University back in the late '70s verified that complete hearing aids could be assembled with both objective frequency response accuracy and subjective fidelity ratings comparable to those of highly regarded loudspeaker systems. These aids could be substantially superior to the most popular stereo headphone of the time [3]. Hearing-aid microphones and earphones were available with smooth frequency responses over a bandwidth of 20 Hz to 16 kHz.

Two things were missing, however: A low-distortion power amplifier small enough and with a low enough battery drain to be practical for use in the smaller hearing aids, and a broadcast-quality input amplifier that could handle loud voices and live orchestra concerts without distortion. Both amplifiers are now a reality in the tiny integrated circuit chips shown in Fig. 1.

Figure 1A shows a high-fidelity Class-D power amplifier chip that is included *inside the receiver case* of several of the Knowles Electronics hearing-aid receiver models [4]. The Model EP-3074 receiver, for example, has the same transducer mechanism used in the Etymotic Research ER-1 high-fidelity insert earphones. It will produce 110 to 115 dB maximum undistorted output, yet its internal Class-D amplifier idles at about 0.17 mA, a small fraction of the idling current of a typical hearing-aid power amplifier. Even so, the entire EP-3074 package would easily hide inside an ordinary pencil eraser.

High fidelity for the hearing impaired is not the same as high fidelity for normal listeners. Developed with the help of a $500,000 grant from the National Institute on Aging, the Etymotic Research K-Amp input amplifier chip (Fig. 1B) has a unique feature: *It only amplifies quiet sounds*. An automatic circuit operates an electronic volume control to make quiet sounds audible and a tone control to provide treble boost for quiet sounds. Loud sounds that present a problem for most hearing-aid wearers (dishes clattering, paper crunching, wind howling, people shouting) pass through without amplification just as if the hearing aid weren't there [5]. Amplification for loud sounds is *available* to the user if he or she chooses to use it, but it will generally not be required.

Undistorted amplification of intense sound is a very important part of the performance of a high-fidelity hearing aid. Strong vocalization, piano playing, live symphony orchestra concerts, wind noise, a spoon dropped onto a plate, etc. can all generate sounds peaking between 95 and 105 dB SPL on the sound-level meter. These meter readings correspond to instantaneous oscilloscope peaks of 103 to 118 dB SPL, equivalent to sine-wave inputs of 100 to 115 dB SPL. Many hearing-aid circuits, however, are designed to op-

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Distortion makes intense sounds even more annoying, so undistorted headroom is vital in high-fidelity hearing aids.

erate without distortion only up to inputs of 90 dB SPL, even at minimum volume-control setting. Distortion often makes intense sounds seem even louder—and thus more annoying—than they would otherwise be, so the input circuit of the K-Amp is designed to operate distortion-free for inputs up to 110 to 115 dB SPL. In many hours of listening tests (including live symphony, choral, and jazz concerts), the only times distortion has been detected have been when car keys were jangled next to the hearing-aid microphone inlet or piano keys were banged when the listener's head was inside the grand piano. Distortion was detected only on clearly unreasonable tests.

The most familiar automatic signal processing (ASP) circuits for hearing aids reduce low-frequency gain as input level increases. This type of ASP is intended for wearers who frequently find themselves in noisy environments, especially environments where low-frequency noise predominates. Existing ASP circuits are primarily designed to filter out low frequencies, which until recently were presumed to contain most of the troublesome noise energy, although the better designs include a broadband reduction of gain at the highest input levels to reduce distortion. Recent indications are that the success of these circuits may relate more to their ability to reduce hearing-aid distortion than to their level-dependent frequency response characteristic. The latter acts to increase the relative *low*-frequency gain of the hearing aid for quiet sounds. This BILL (Bass Increases at Low Levels) type of level-dependent frequency response effectively gives the most *treble* emphasis for *loud* sounds.

The K-Amp type of ASP works in just the opposite way, giving the most treble emphasis for *quiet* sounds. This type of ASP is intended for wearers with high-frequency hearing loss. They typically need more gain for quiet sounds, particularly at high frequencies, than they do for loud sounds (a phenomenon known as recruitment). An amount of high-frequency gain that might produce a harsh or shrill sound in a linear hearing aid may become quite acceptable if the treble boost is automatically reduced for high-level inputs. This typical operation of the K-Amp circuit is illustrated in Fig. 2, where curves of gain versus frequency are shown for different input levels. Figure 3 shows corresponding curves of output versus frequency for various input SPLs, based on KEMAR measurements in a diffuse sound field.

Rather than attempting to reject the noise by filtering it out (which also filters out part of the speech), the K-Amp approach attempts to maximize the clarity of speech by making all speech cues audible [6]. This is accomplished by automatically selecting the appropriate gain and treble boost for each listening level so that all speech sounds *will* be made audible for the hearing-impaired listener. For users with high-frequency hearing loss, this TILL (Treble Increases at Low Levels) form of ASP, combined with the wide bandwidth and low distortion provided by the K-Amp hearing aid, should provide the best intelligibility in noise and the most natural frequency response in the greatest number of real-world listening conditions.

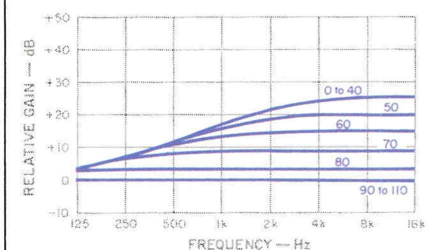

Fig. 2—Relative gain of the K-Amp for different input levels. Loud sounds pass through unchanged, while quiet sounds receive up to 25 dB of treble boost.

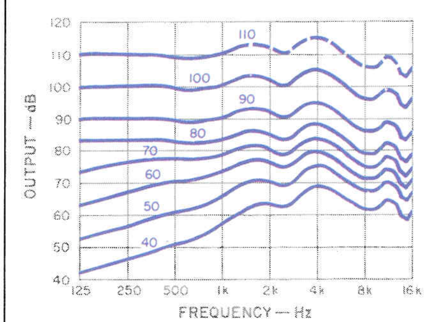

Fig. 3—Output to the ear of a complete K-Amp hearing aid, referenced to a diffuse sound field. In this model, suitable for individuals with mild to moderate high-frequency hearing loss, sounds above 90 dB SPL are passed through unamplified, while progressively greater gain and treble boost are applied as level is reduced below that point. The dashed portion of the 110-dB curve represents high-frequency levels which would overload the amplifier as sine-wave inputs but which do not occur in normal speech and music.

Thus, while the real-ear frequency response of the complete K-Amp hearing aid for *loud* sounds is essentially flat, the frequency response for *quiet* sounds will be high fidelity only as perceived by the hearing-impaired listener. To restore the audibility that has been lost by someone with a high-frequency hearing loss—the most common loss due to aging or exposure to noise—the automatic gain and tone-control circuit will provide 20 dB or more of treble boost for quiet sounds.

The K-Amp integrated circuit from Etymotic Research and high-fidelity microphones and Class-D amplifiers from Knowles Electronics are small enough to be incorporated into custom in-the-ear hearing aids. Such aids offer true high fidelity and can now be obtained from several manufacturers.

References

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