RI 9506

REPORT OF INVESTIGATIONS/1994

Active Noise Cancellation—Performance in a Hearing Protector Under Ideal and Degraded Conditions

By Roy C. Bartholomae

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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International Standard Serial Number
ISSN 1066-5552

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	kHz	kilohertz
dBA	decibel (A-weighted)	pct	percent
ft^3	cubic foot	s	second
Hz	hertz	W	watt

ACTIVE NOISE CANCELLATION—PERFORMANCE IN A HEARING PROTECTOR UNDER IDEAL AND DEGRADED CONDITIONS

By Roy C. Bartholomae[1]

ABSTRACT

This U.S. Bureau of Mines study found that the performance of the active noise cancellation hearing protector in a reverberant field was mixed. The performance varied when the conditions changed from ideal to nonideal. The active noise cancellation (ANC) component provided substantial additional noise reduction from 125 to 500 Hz for all testing conditions (broadband noise or pure tones both with and without safety glasses). While the ANC under ideal conditions provided additional attenuation from 500 Hz and below, under nonideal pink noise conditions the ANC amplified noise below the 125-Hz third octave band. There was a middle band of frequencies at which the ANC amplified noise levels ranging from 630 to 4,000 Hz. The results for pure tones showed that attenuations were higher but that they followed the same general trend.

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INTRODUCTION

MINING OCCUPATIONAL NOISE PROBLEM

Noise is often regarded as a nuisance rather than as an occupational hazard. However, overexposure to noise can cause serious hearing loss. The problem is especially severe in the mining industry. A 1976 study by the National Institute of Occupational Safety and Health (NIOSH) (*1*)[2] found that underground coal miners had measurably worse hearing than the national average. For example, at age 60, over 70 pct of miners had a hearing loss of more than 25 dB, and about 25 pct had a hearing loss of more than 40 dB (*2*).[3]

Miners experience greater hearing impairment than most other industrial workers because of their work-related overexposure to noise. Moreover, noise-induced hearing loss is debilitating and cannot be cured by hearing aids.[4] Because this hearing loss occurs gradually over many years, the individual is usually not aware of it until he or she notices difficulties in communicating with other people or an inability to hear safety signals in the workplace.

Historically, the noise levels of the mining workplace have shown an upward trend, due primarily to the steady increase in the power of mechanized mining machines. Increased power is the key to more efficient mineral extraction. As the industry continues to seek greater productivity, mining machines will continue to become more powerful, and the workplace noise levels will continue to increase.

ACTIVE NOISE CANCELLATION

The arbitrary mixing of acoustical waves results in constructive and destructive interference. This causes increases and decreases in the sound field at various locations. The concept of active noise cancellation (ANC) involves generating a sound field that, when mixed with the acoustical "noise" to be canceled, results in destructive interference and thus "cancels" the noise. ANC is in general a very difficult, and in some cases an impossible, task. An analogous "simplified" two-dimensional situation would be to continuously throw handfuls of stones into a lake and then somehow drop other stones at exactly the correct time and place such that the waves in the lake would exactly cancel each other.

Unlike two-dimensional waves in water, acoustical waves radiate in three dimensions. Also, as an acoustical wave travels, its frequency spectrum and amplitude change. These changes are brought on by numerous factors including physical properties of noise that vary with frequency. These frequency-dependent properties include the absorption, reflection, diffusion, vibration modes, radiation efficiencies, etc. of the surfaces the traveling noise waves encounter, as well as the frequency-dependent absorption of the air itself.

In ANC, loudspeakers are used to generate "anti-noise," which is ideally an acoustical field that at every point in space is exactly equal in amplitude and spectrum to the noise being canceled; the only difference is that the anti-noise is exactly 180° out of phase with the noise. The general case of actively canceling nonpredictable varying noise in a three-dimensional space is impossible. Loudspeakers have fixed, three-dimensional radiation patterns and, therefore, cannot cancel nonpredictable varying three-dimensional noise fields. In fact, even if two exactly identical loudspeakers could be built, it would be impossible to totally cancel the noise from one with the other loudspeaker. This is because the only way to have the loudspeakers exactly cancel each other would be to have their fixed radiation patterns exactly overlay. This is impossible because both loudspeakers would have to occupy the same space.

There is no way of using a number of loudspeakers to totally cancel noise. Thus, ANC is not a panacea for all noise control problems.

Another technical hurdle to overcome with ANC is predicting what the sound field will be in the future. This is needed because time is required before the anti-noise field can be generated. Historically, the concept of an ANC system emerged in the initial stages of the electronics revolution when the commercial application of the vacuum tube amplifier was being developed into radio, television, talking pictures, etc. U.S. Patent No. 2,043,416, entitled "Process of Silencing Sound Oscillations," was awarded in 1936 to Paul Lueg. Although this patent showed the basic concept of ANC in ducts, the electronics and basic theories were not developed sufficiently for decades (*3*).

Only in the 1980's were systems for very special applications developed with varying success. These special applications include specialized noise cancellation systems for low-frequency noise, typically in confined spaces.

This report focuses on investigating the performance of a prototype commercial ANC system developed for personal hearing protection devices. The research objective was to study the performance of the ANC system under controlled ideal and degraded laboratory conditions and to assess how the performance of the system would change.

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

[3]The American Academy of Ophthalmology and Otolaryngology recognizes that individuals with 25-dB hearing losses have a hearing handicap.

[4]For a detailed discussion on hearing loss, see the "Federal Occupational Safety and Health Administration Regulation on Occupational Noise Hearing Conservation Programs" (49 FR.4078, Jan. 16, 1981).

The work was done as part of a U.S. Bureau of Mines (USBM) program to reduce the exposure of miners to health risks.

The experimental setup discussed below was not designed to study the absolute attenuation of earmuffs as they would be worn by miners. Previous research by the USBM (*4-5*) has shown that even under ideal laboratory conditions, purely physical measurements of earmuff attenuation on human subjects do not always correlate well to psychophysical earmuff attenuations at higher frequencies. In addition, this study was conducted on a manikin under controlled laboratory conditions. The actual attenuations provided to workers were not addressed in this study.

ACTIVE NOISE CANCELLATION HEARING PROTECTOR

Figure 1 shows the frequency and sound pressure range for typical sounds and the range of the ear's response (*6*). Figure 2 shows a cross section of the ear. The ear is composed of three parts: the external ear, the middle ear, and the inner ear. The external ear includes the auricle and the ear canal. The auricle directs sound into the ear canal, which helps to determine whether the sound is coming from front, behind, or side. Sound waves are thus directed along the ear canal to the eardrum, which is vibrationally excited. Between the external ear and the inner ear is an air-filled space, the middle ear, that contains three tiny bones. These bones act like levers to couple the vibrations from the eardrum to the middle ear. The eustachian tube connects the middle ear to the back of the throat and allows atmospheric pressure to reach the middle ear chamber, so that air pressure is the same on both sides of the eardrum. The inner ear is completely surrounded by bone. It is shaped like a snail shell at one end; at the other end are three loops known as the semicircular canals. Sound is coupled to the inner ear by a middle ear bone, whose base fits into the small opening called the oval window. The oval window is covered by a thin membrane that keeps fluid within the middle ear. The ear thus has very complicated acoustical and vibrational impedance paths.

The ear canal normally opens into a very large space (e.g., a room or the out-of-doors). When an earmuff is placed on an individual, the acoustical impedance of the ear is changed. Figure 3 shows an individual wearing an earmuff hearing protector. When an earmuff hearing protector is added, the ear canal is now opened only to the small volume inside the earmuff. Figure 4 is a graphical cross section of an earmuff earcup on an individual's head. The earmuff greatly distorts and simplifies the sound field entering the ear canal. Noise can now only enter the ear via acoustical leaks in the cushion air seals or vibrations in the earcup set up by the noise field.[5]

Assuming that the cushion air seal is good, the majority of the noise entering the ear is from the noise-induced vibrations in the earcup. The earcup vibrations then produce a sound field under the earcup that enters the ear canal.

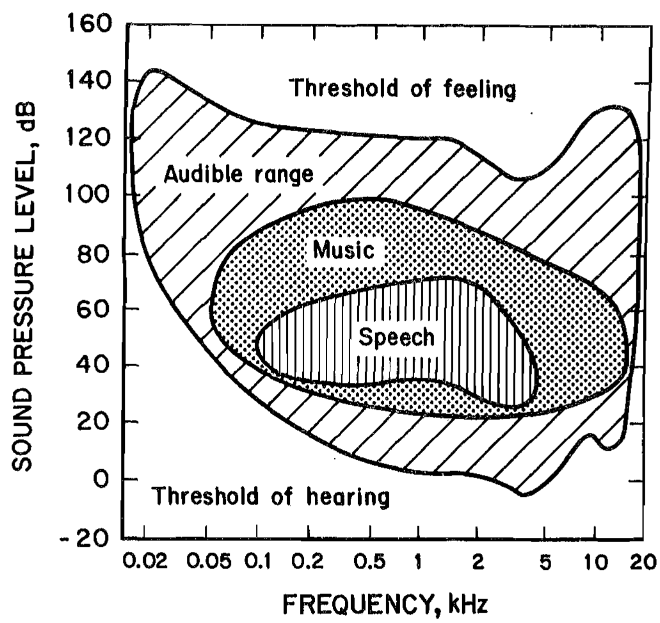

Figure 1.—Typical range of hearing and sounds.

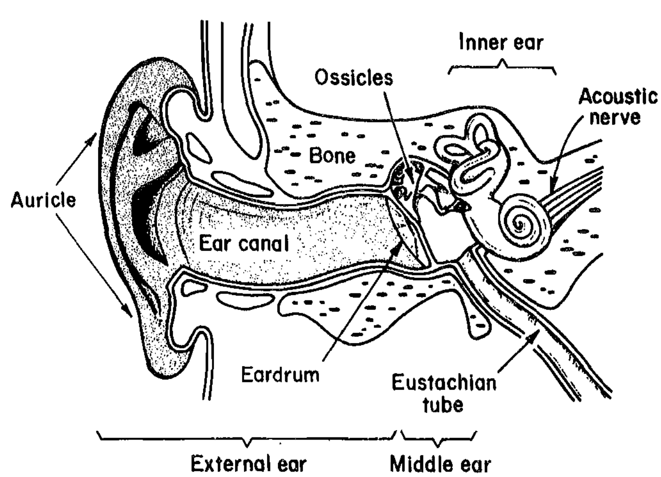

Figure 2.—Cross section of human ear.

[5]Noise and vibration can also reach the middle and inner ear via bone conduction, but this path is so highly attenuated that for this discussion the effect is negligible.

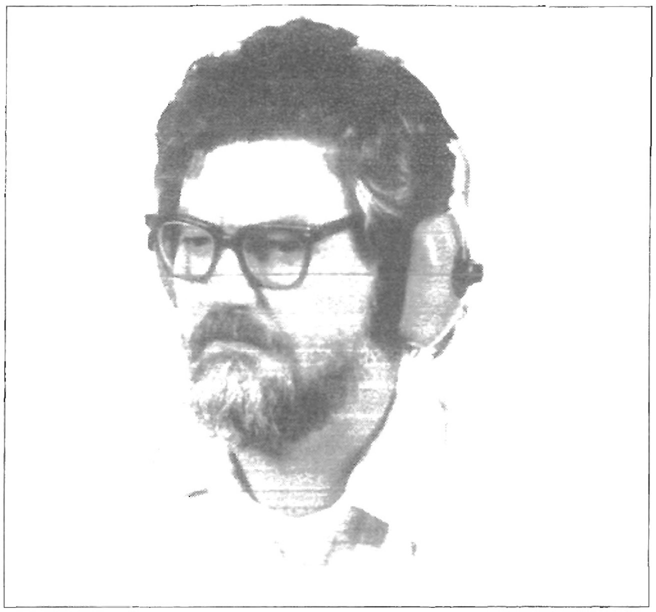

Figure 3.—Individual wearing typical earmuff hearing protector.

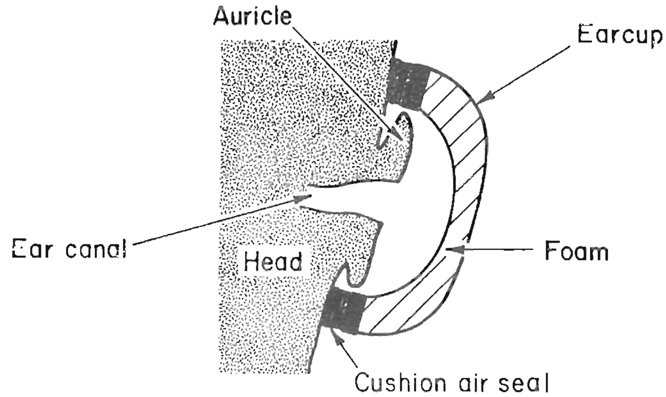

Figure 4.—Schematic cross section of standard hearing protector earcup on individual's head.

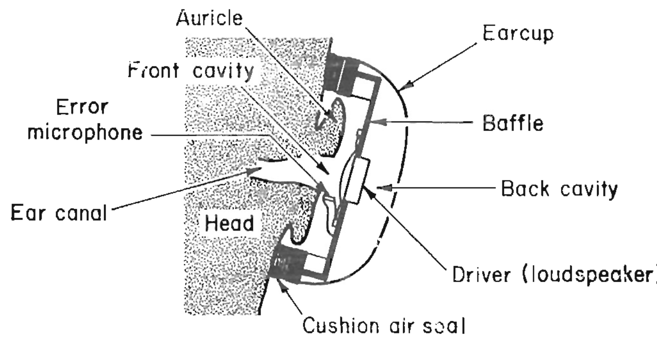

Figure 5.—Schematic cross section of ANCHP on individual's head.

Normally sound enters the ear from varying directions in varying patterns. But, as discussed above, when an earmuff with properly fitted cushion air seals is put on, the majority of the noise entering the ear is produced from vibrations in the earcup. The earcup is in a fixed position in relation to the ear.

The ear canal perceives the earcup as a fixed concave acoustical radiating surface (fig. 4). An acoustical analogy of this is a loudspeaker (the earcup) directed down a duct or pipe (the ear canal). This "simplified" acoustical environment lends itself to ANC by placing the noise canceling loudspeaker inside the earcup. The ANC loudspeaker system is thus operating inside a fixed-volume closed system of the hearing protector and ear canal.

The active noise cancellation hearing protector (ANCHP) being tested[6] is claimed to actively cancel noise at frequencies below 1,000 Hz. Figure 5 is a schematic cross section of the ANCHP earcup on an individual's head. In principal, the only difference between a regular hearing protector earcup (fig. 4) and an ANCHP earcup (fig. 5) is the addition of the loudspeaker and the error microphone. The error microphone is located as close as possible to the opening in the ear to detect what "noise cancellation" signal is needed from the loudspeaker. The electronics are located in a separate box. At low frequencies the electronic feedback signal works fast enough to generate the appropriate noise cancellation signal. The objective of this research project is to assess how effectively this system functions in diffuse sound fields.

EXPERIMENTAL SETUP

The experiment involves studying the effect of the ANC component of an ANCHP in a broadband, reverberant, random noise field, and pure tone, reverberant, sound fields at 125, 250, 500, 1,000, and 4,000 Hz.

The ANCHP electronics can be switched on and off. With the electronics switched off the ANCHP is essentially a standard hearing protector. Investigation of the ANCHP's performance with the electronics switched on and off was used to analyze the functioning of the ANC component of the system. The experiments were conducted in the USBM's Mining Noise Laboratory Reverberation Chamber (MNLRC) with broadband, pink random, and pure tone noise. The reverberation chamber has a volume of approximately 45,000 ft^3 and meets the

[6]The device investigated is a prototype production device developed by the Bose Corp.

requirements of ANSI 51.31-1908 (ISO 3741) (7).[7] All broadband random noise tests conducted in the chamber were at noise levels in each one-third octave band that were 20 dB higher than the background noise levels. In addition, all pure tone tests were conducted with the tone in excess of 90 dBA.

All experiments were conducted using a Kemar manikin[8] (fig. 6), which is a standard manikin for testing hearing protectors and hearing aids. The manikin has an ear canal and eardrum simulator. A precision microphone (Bruel & Kjaer (B&K) Model 3134) was mounted inside the manikin head to pick up the simulated eardrum noise levels. The microphone was connected to a B&K Model 2131 analyzer. All noise measurements were made with a 32-s averaging time. A Zwislocki coupler was used to simulate the impedance of a human ear. The measurement of a hearing protector's attenuation on the Kemar manikin involved the following steps.

- For broadband random noise: First, a broadband, constant level, pink random, reverberant noise field was established in the reverberation chamber. This was done using a pink noise generator driving an 800-W Altec high-intensity noise generating system. The simulated eardrum noise level of the Kemar manikin was measured in each third octave band from 31.5 Hz to 10,000 Hz. Next, the ANCHP was fitted onto the manikin and the one-third octave simulated eardrum measurements were repeated. Subtracting the second measurement from the first for each one-third octave band gives the Kemar attenuation for the hearing protector.
- For pure tone measurements: The same procedure was followed, except in this case pure tones were established in the reverberation chamber and measurements were only made in the third octave band that corresponded to the pure tone frequency.

[7]The reverberation chamber was also appropriate in this case for pure tone studies because the sound source and manikin were kept in fixed positions during each test. In the one-third octave bands from 31.5 Hz to 10 kHz, the background noise levels in the reverberation chamber were below 47 dB.

[8]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

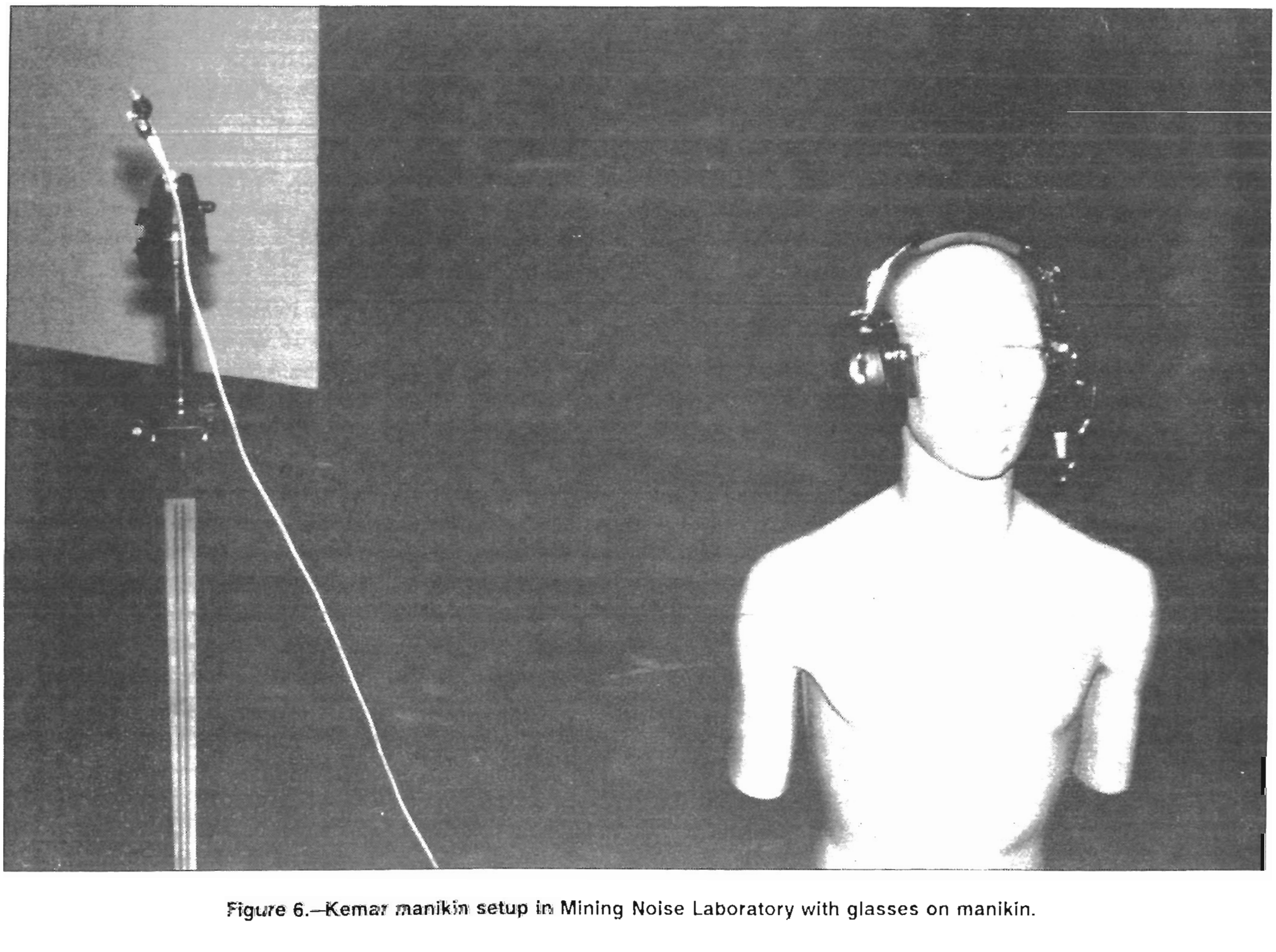

Figure 6.—Kemar manikin setup in Mining Noise Laboratory with glasses on manikin.

DISCUSSION

The experiments were conducted as follows in four series of tests for the "ideal" laboratory and "nonideal" simulated real world condition.

The first series of ANCHP tests were conducted for the ideal laboratory case with the broadband, random, diffuse, pink noise source established in the MNLRC. Three separate measurements of the noise in the Kemar manikin simulated ear without hearing protectors were made and averaged to establish the baseline noise levels. The standard deviation in each one-third octave for these and all subsequent averages reported below were within 0.5 dB.

The ANCHP was then placed on the Kemar manikin with the ANC turned off. The Kemar ear sound pressure level was monitored, and the ANCHP was physically adjusted until the lowest overall noise level was achieved. Measurements were then taken without further disturbing the system using the B&K 2131 analyzer with a 32-s averaging time. Immediately after this measurement the ANC was turned on, and without physically disturbing the hearing protectors or manikin, measurements were obtained. Additional tests were conducted turning the ANC on and off and the resultant attenuations were averaged for the two cases (ANC on and off).

Figure 7[9] shows the broadband noise attenuations of the hearing protector without safety glasses on the Kemar manikin with the ANC on and off. Since the hearing protector in this situation has the best fit and thus the best performance, this is the ideal case. The ideal case is the best possible performance that can be expected for this noise environment. Under normal real world application, the acoustical seal of the hearing protector can be breached via poor fit, glasses, hair, head movements, etc. The difference in figure 7 between the "ANC on" and "ANC off" plots shows the added attenuation the ANC provided under ideal conditions. Under ideal conditions the ANC performed well from the 31.5- to 500-Hz third octave bands, providing from 5 to 23 dB additional attenuation. Above 630 Hz to the 2,000-Hz third octave band the ANC actually amplified noise levels. The amplification was 2 to 5 dB in the 800-, 1,000-, and 1,250-Hz third octave bands. Thus under ideal laboratory conditions, the ANC provided substantial sound pressure reductions from 500 Hz and below, but degraded performance between 630 and 2,000 Hz.

The second series of tests were conducted exactly as the first except a pair of MSA Model 791207 safety glasses was placed on the Kemar manikin. Figure 8 shows the results of these tests. Note that the differences in figure 8 are due entirely to the effect of the ANC component in the hearing protector. This condition is the nonideal condition because the safety glasses degrade the hearing protector seals. Note that in the "ANC off" mode the hearing protector actually amplifies noise in the 63- to 630-Hz range. This low-frequency amplification is typically seen in hearing protectors with broken seals and is caused because the hearing protector and ear canal act as a resonator. The difference in figure 8 between the "ANC on" and "ANC off" plots shows the "added" attenuation the ANC provided under the nonideal conditions. In this case very different results were obtained from the ideal condition (fig. 7). The ANC degraded substantially in performance below the 160-Hz third octave band and actually amplified noise levels below 125 Hz. From 160 to 630 Hz the ANC functioned well, providing 8 to 16 dB additional attenuation. From 800 Hz to 4,000 Hz the ANC amplified noise levels.

[9]Figures 7, 8, 9, and 10 are graphs of the test results. Appendixes A, B, C, and D, respectively, are the data.

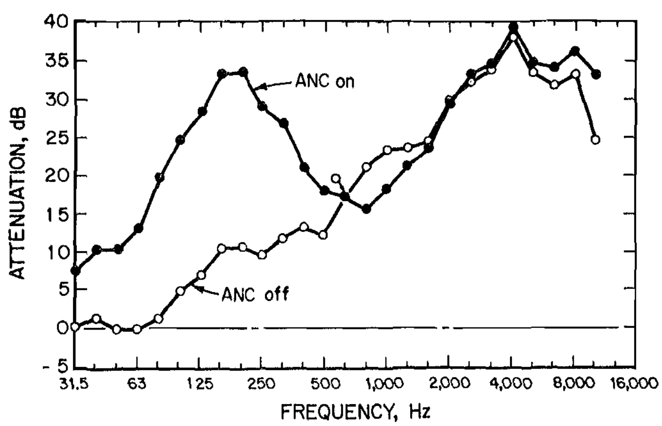

Figure 7.—Kemar manikin ANCHP attenuations for ANC turned on and off without safety glasses in broadband, reverberant, pink noise field.

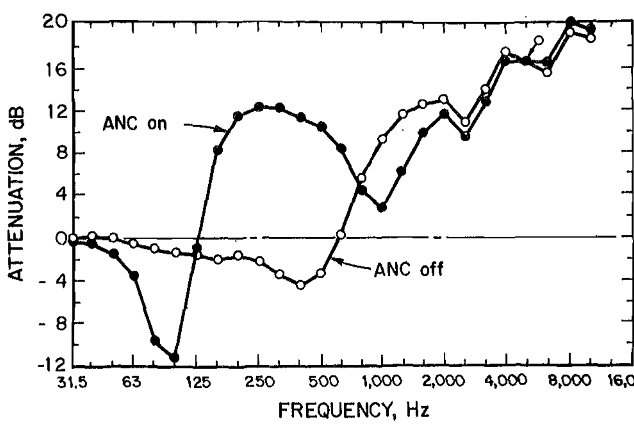

Figure 8.—Kemar manikin ANCHP attenuations for ANC turned on and off with safety glasses in broadband, reverberant, pink noise field.

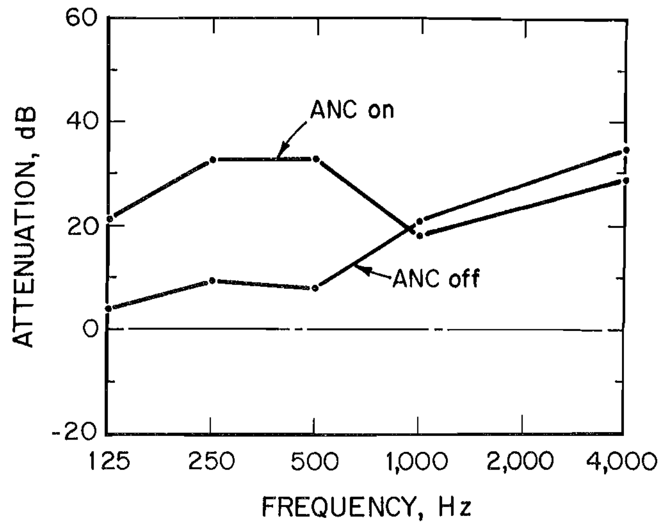

Figure 9.—Kemar manikin ANCHP attenuations for ANC turned on and off without safety glasses in pure tone, reverberant sound fields.

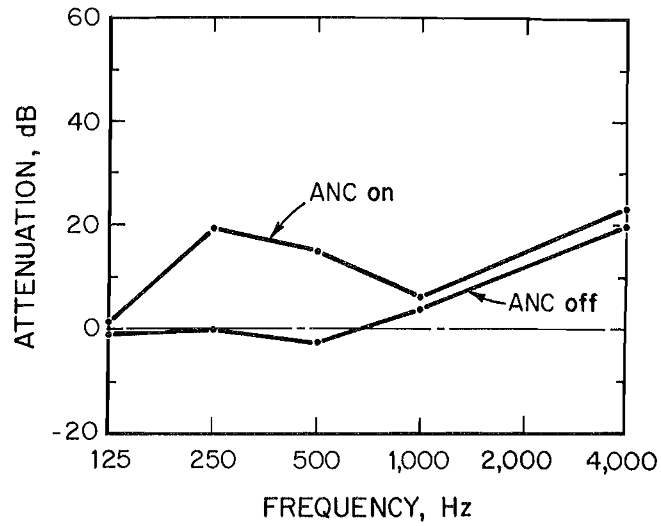

Figure 10.—Kemar manikin ANCHP attenuations for ANC turned on and off with safety glasses in pure tone, reverberant sound fields.

The third series of tests were conducted using pure tones. First a 125-Hz pure tone sound field was established in the MNLRC. The Kemar ear sound pressure level was measured in the 125-Hz third octave band without any hearing protector. Next, the hearing protector was placed on the manikin with the ANC turned off and a second Kemar noise level was measured at the 125-Hz third octave band. As before, the difference between these measurements is the Kemar attenuation for 125-Hz pure tones, with the ANC off, under ideal conditions (i.e., best fit—no safety glasses). The above procedure was then repeated for pure tones at 250, 500, 1,000, and 4,000 Hz. Similarly, pure tone tests were done with the ANC turned on. The results of this series of tests are shown in figure 9. Again, the difference between these two curves is due entirely to the ANC component of the earmuff.

The final series of tests were conducted exactly as the third series except the safety glasses were placed on the Kemar manikin for all tests. These tests yield the pure tone, nonideal attenuations (i.e., with safety glasses) and are shown in figure 10.

CONCLUSIONS

The ANCHP's performance in a reverberant random noise field was mixed. The performance varied when the conditions changed from ideal to nonideal (with safety glasses). The ANC provided substantial additional sound pressure reductions in the 160- to 500-Hz third octave bands for all testing conditions (with and without safety glasses). With broadband noise, the ANC under ideal conditions provided excellent additional attenuation from 125 Hz and below, but under nonideal conditions the ANC amplified noise below the 125-Hz third octave band. There was a middle band of frequencies at which the ANC amplified broadband noise ranging from 630 to 4,000 Hz for both the ideal and nonideal conditions. The results for the pure tones showed that attenuations were higher but that they followed the same general trend as the broadband random noise attenuation.

This study showed that ANC can work in very controlled environments where the most noise energy is in the lower frequencies. If the environment is not well controlled, the ANCHP can actually cause a worse hearing hazard than standard hearing protectors. For example, the ANCHP studied would be appropriate for trained aircraft pilots if the majority of cockpit noise was low frequency. In this situation the pilot has limited movement. This, coupled with training, should ensure that the ANCHP functions consistently.

In contrast, in a mine, the worker is typically in a noisy, uncontrolled, dirty, changing environment. The working environment typically involves movements and other conditions that can break an earmuff hearing protector's seal or otherwise degrade performance.

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APPENDIX A

Table A-1.—Kemar manikin ANCHP attenuations without safety glasses in broadband, reverberant, pink noise field

Third octave band center frequency, Hz	ANC off	ANC on
31.5	0.2	7.5
40	1.1	10.5
50	-.2	10.4
63	-.2	13.2
80	1.2	19.8
100	4.8	24.8
125	7.0	28.6
160	10.6	33.3
200	10.7	33.7
250	9.7	29.2
315	11.9	27.0
400	13.4	21.3
500	12.3	18.0
630	17.5	17.4
800	21.4	15.7
1,000	23.6	18.5
1,250	23.9	21.6
1,600	24.7	23.9
2,000	30.0	29.8
2,500	32.6	33.6
3,150	34.2	35.1
4,000	38.6	39.7
5,000	33.8	35.2
6,000	32.3	34.5
8,000	33.6	36.7
10,000	25.0	33.7

APPENDIX B

Table B-1.—Kemar manikin ANCHP attenuations with safety glasses in broadband, reverberant, pink noise field

Third octave band center frequency, Hz	ANC off	ANC on
31.5	-0.1	-0.1
40	.1	-.7
50	-.1	-1.8
63	-.7	-3.2
80	-1.1	-9.8
100	-1.5	-11.2
125	-1.7	-1.1
160	-2.1	8.5
200	-1.7	11.8
250	-2.3	12.3
315	-3.5	12.1
400	-4.5	11.3
500	-3.5	10.5
630	.2	8.3
800	5.4	4.2
1,000	9.3	3.0
1,250	11.5	6.1
1,600	12.5	9.8
2,000	13.0	11.8
2,500	10.9	9.8
3,150	14.0	13.1
4,000	17.5	16.6
5,000	16.6	16.6
6,000	15.5	16.7
8,000	19.3	20.1
10,000	18.7	19.5

APPENDIX C

Table C-1.—Kemar manikin ANCHP attenuations without safety glasses in pure tone, reverberant sound fields

Frequency, Hz	ANC off	ANC on
125	3.6	20.7
250	9.5	32.2
500	8.1	32.5
1,000	20.6	17.7
4,000	34.2	28.7

APPENDIX D

Table D-1.—Kemar manikin ANCHP attenuations with safety glasses in pure tone, reverberant sound fields

Frequency, Hz	ANC off	ANC on
125	-0.9	1.2
250	.0	19.1
500	-2.3	14.6
1,000	3.9	6.0
4,000	19.9	22.9

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