Passive Hearing Protection Systems and Their Performance

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ABSTRACT

While ideally noise should be reduced at the source, in the military environment the most effective solution in terms of both cost and operational effectiveness has been to provide personnel with personal hearing protection. This protection may be in the form of either an earplug that occludes the ear canal or a circumaural protector that inserts a barrier between the ambient noise and the ear. For both devices the level of passive protection provided changes with frequency. A great deal of research was conducted in the 1940/50s to define the mechanisms and parameters that appeared to limit the performance of these types of protectors and this presentation will provide an overview of the findings of this early research.

By the 1970s the performance of such devices, particularly those used in military applications, had been best optimized for use with the types of cranial protection being worn by soldiers, sailors, and aircrew. Since that time the major thrust in hearing protection enhancement has been the development and integration of Active Noise Reduction (ANR) systems where an electronic circuit is incorporated into the device to provide additional active attenuation in addition to the passive attenuation. ANR has provided significant benefits in low frequency attenuation and provides complementary performance to the passive device. However, for future military noise environments ANR headsets and ANR earplugs will not individually provide sufficient levels of protection, and passive earplugs and earmuffs may have to be used in some combination to provide adequate hearing protection.

Recent research developments have resulted in improved passive earplug and earmuff attenuation performance. Deep inserted custom earplug performance and custom earmuff/earcushion design techniques have provided a substantial increase in hearing protection. Issues associated with the fitting of personal hearing protection and their performance in the field will also be discussed.

INTRODUCTION

Noise of sufficient intensity and duration can cause irrepairable damage to human hearing. High intensity noise has traditionally been associated with many military vehicles, especially airplanes and helicopters, Dancer (8) and James (11). However, the process of incurring a hearing loss is insidious. The person has little or no warning that the hearing loss is occurring other than possibly a little ringing in the ears. Once hearing sensitivity has been lost, it is thought to be impossible to reclaim. The only workable solution has been prevention, i.e. limiting the noise exposure by either reducing the time of exposure and/or reducing the intensity of the noise at the ear. The reduction in duration of exposure is usually so onerous that the person cannot reasonably accomplish the required work in the reduced time. Many times the required reduction is a factor of 10 or more. Noise intensity can be reduced at the source, in the path, and at the person. Source reduction and path reductions of noise are expensive and many times severely limit the performance of the vehicle or other system. Reductions of noise at the person have proven to be the most effective and least costly of the options.

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Currently, two basic types of personal noise reduction approaches are in use. Passive noise reduction and active reduction are most often used in combination, and frequently passive noise reduction is used in isolation. Passive noise reduction systems, earmuffs and earplugs, and their performance in continuous noise environments are the subjects of this report. Active noise reduction devices and their performance along with performance of hearing protectors in impulse noise are the subjects of other reports in this lecture series.

BACKGROUND

The first hearing protectors, the fingers, were passive noise reducers and in reality are one of the better performing passive noise reduction systems. However, it is hard to work with the index fingers of your left and right hands pressing against the ears. Passive hearing protectors have been divided into two general categories, circumaural hearing protectors or earmuffs, and insert protectors or earplugs. Each general group can also be divided into subgroups as those described by Nixon (17).

The first headsets used in aircraft provided a mounting location for earphones but no real hearing protection. It was not until the end of WWII that hearing conservation and hearing protection became an issue. Some of the first hearing protectors were constructed by taking glass jelly jars and dipping them in rubber, and mounting them on the side of the head. In the 1950s, Henning von Gierke (23) and Edgar Shaw (22) independently developed models of passive hearing protection performance. These two models identified the important parameters in passive hearing protector performance, mass, volume under the earcup, headband tension, earcushion compliance, acoustic leaks, and absorption in the earcup. Both of these models were realized as analogous electrical circuits (an example of Shaw's model is shown in Figure 1). The size of the acoustic leak between the hearing protector and the head has a dramatic effect on passive hearing protector performance. Saunders and Homma (20) have used finite element modeling to construct a new model of passive hearing protector performance. One of the more important parameters of passive earmuff performance in their model is the size of the acoustic leak. Others such as Johnson (13) have examined the effects of headband tension on passive attenuation while Nixon and Knoblach (15) investigated the effect of eyeglasses on hearing protection provided by earmuffs. One could conjecture that the effect of headband tension could be just the minimization of acoustic leaks by the increased headband force. Similarly, the eyeglasses cause acoustic leaks which also affect passive attenuation. Nixon and Knoblach (15) described the effect of eyeglasses on earmuff noise attenuation as shown in Figure 2. Earcushions attempt to seal the leak between the earmuff and head but also affect passive attenuation as described by Shaw (21).

Figure 1
Hearing Protector Performance Model
Shaw – 1980

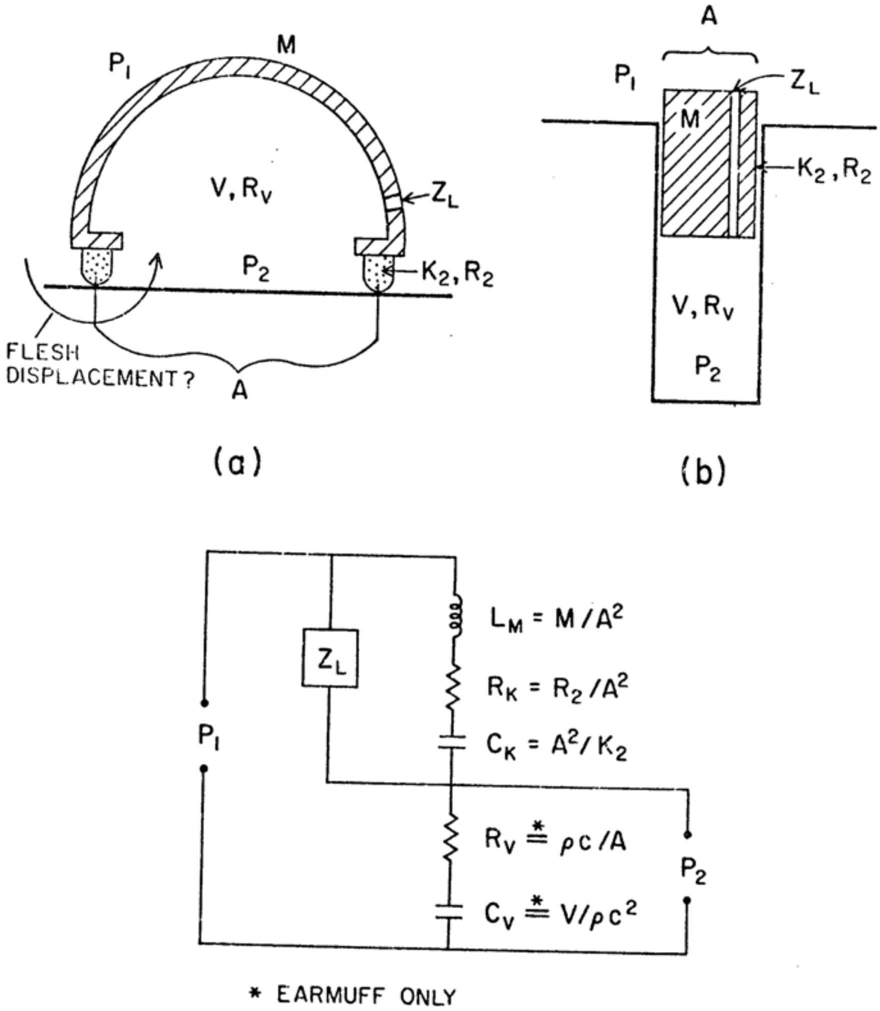
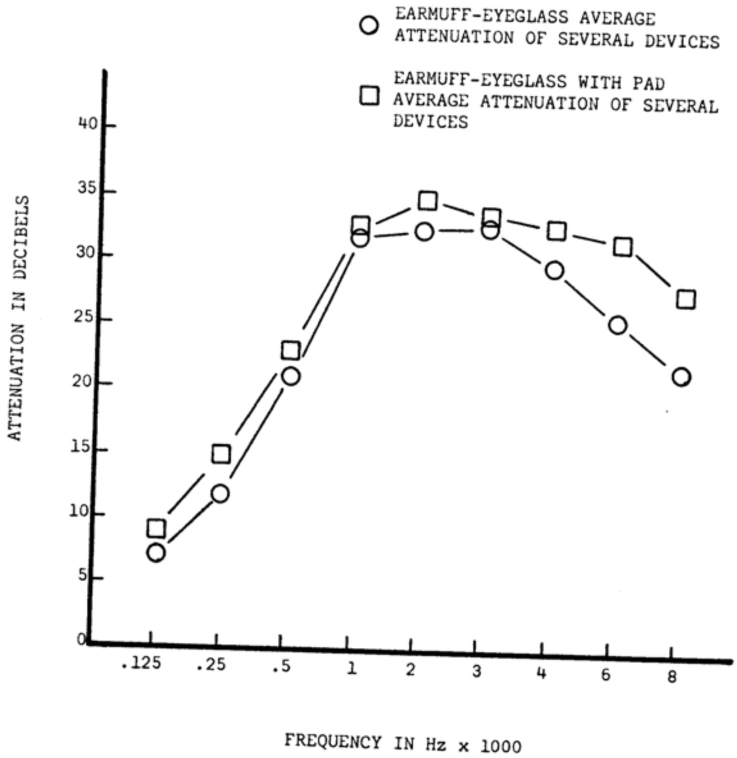


Figure 2
Effect of Eyeglasses on Attenuation
Nixon & Knoblach - 1974



The development of effective insert hearing protectors or earplugs lagged the development of the earmuffs. Many of the WWII pilots and aircrew stuffed cotton in their ears to try to reduce the noise levels (see Figure 3). Cotton by itself was not very effective. The V-51R earplug performance was described in 1944. Other efforts included mixing the cotton with wax, such as “Flents,” and stuffing the mixture into the earcanal. The performance of this mixture was described by Guild, et al. (10). The approach for improving passive attenuation with earplugs was similar to the approach for earmuffs, i.e. reduce the size of the acoustic leak.

Figure 3
Early Earmuff Design and Cotton Earplug

David Clark Company
Earmuffs, Circa 1953

The V-51R earplug was one of the first effective earplugs. It was made of soft vinyl and in 1944 originally came in three sizes, later, in 1956, it was expanded to five sizes (see Figure 4) by adding an extra small and extra large size after a study examining eight sizes by Blackstock and von Gierke (3).

Figure 4
V-51R Vinyl and Sized Earplugs

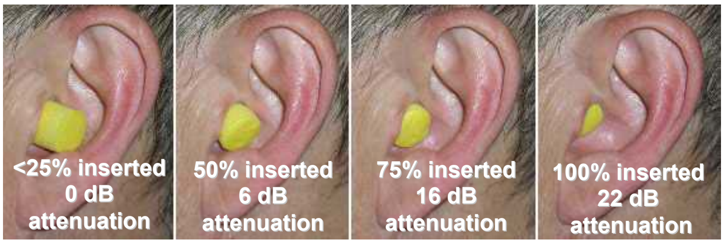
Sized earplugs presented some dispensing and user-related problems. First, the earplugs had to be fit to the user by medical personnel -- a process that required several minutes for each fitting and needed to be repeated approximately once per year especially for the first few years when the earcanal was adapting to the earplug. Some users required different sized earplugs for each ear. Other users preferred earplugs that were too small but felt more comfortable. Many users did not use the earplug insertion tool, the eraser tip of a lead pencil, and therefore did not achieve a good seal or good noise attenuation.

Cleary, if earplugs could be designed as one size fits all, then dispensing earplugs would be much simpler and probably more effective. These designs included the triple flange earplug with three different diameter flanges mounted on a stem (see Figure 5).

Figure 5
Sized Triple Flange Earplugs

Later, foam earplugs were introduced by EAR. The foam earplugs were probably the best performing single sized earplug if properly and deeply inserted. However, the attenuation of foam earplugs depends significantly on insertion depth (see Figure 6).

Figure 6
Foam Earplug Insertion Depth Versus Attenuation

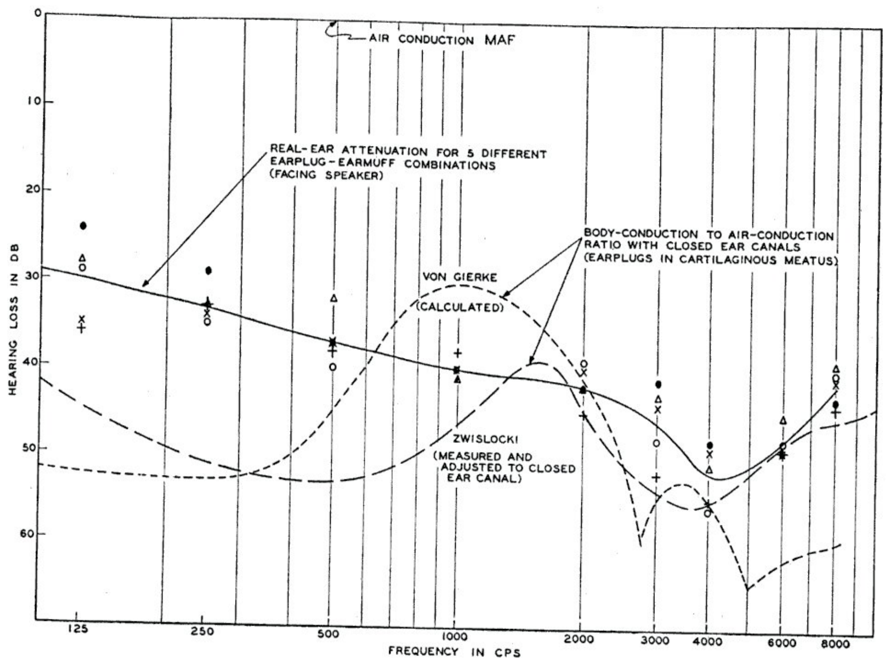


Noise Reduction Ratings from earplug insertion depth study completed by the Air Force Research Laboratory.

In early 1974, with the advent of a new class of high-performance fighter jet engines, custom molded earplugs, like those used in hearing aides, were used for hearing protection and communications enhancement. These communication earplugs had a hole drilled through the hard custom molded earplug and had a snap-ring attached earphone. The concept was designed by Henry Sommer and Charles Nixon of the Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base.

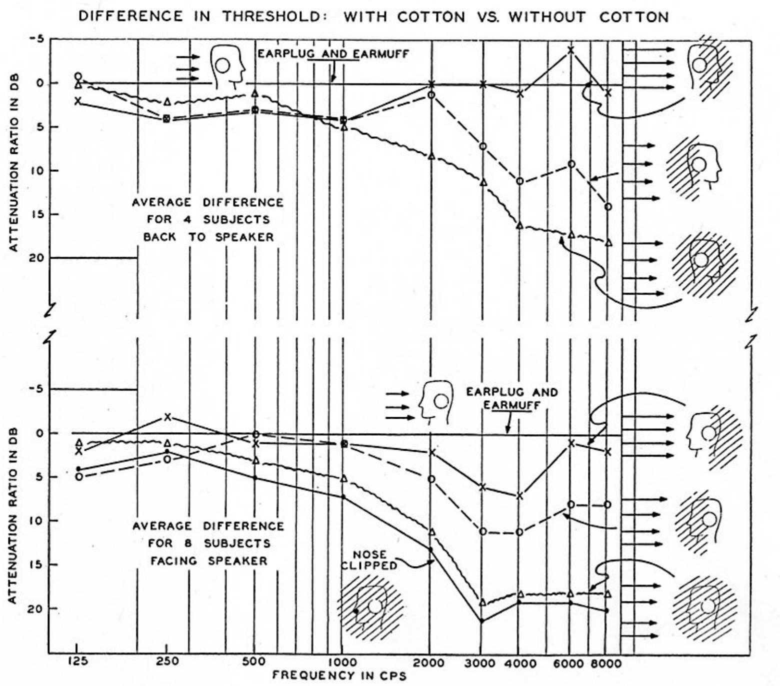
In many military environments, insufficient hearing protection or attenuation was provided by a single earplug or earmuff. In these high noise environments, such as jet engine maintenance or the operations of a flight deck of an aircraft carrier, double protection, earplugs under an earmuff, was employed. However, the overall attenuation of the combination was not the sum of the individual device attenuations. A part of the explanation has to do with conduction of acoustic energy to the cochlea via pathways other than the earcanal/middle ear. These alternate pathways include bone and tissue conduction of noise to the cochlea. The effects of these paths were described by Zwislocki and separately by Nixon and Von Gierke (14), see Figure 7. Berger (1) used an average of the Zwislocki and Nixon data as an estimate of the bone conduction effects. Once the attenuation of the earplugs and earmuffs is sufficient, the bone/tissue conduction path becomes an alternate and sometimes predominant pathway for acoustic energy to reach the cochlea.

Figure 7
Acoustic Pathways – Air and Bone Conduction
Nixon and von Gierke - 1959



Nixon and von Gierke also investigated other factors, such as plugging the nose (Figure 8) while Franke, von Gierke, and von Witten (9) described the effects of jaw vibrations in bone/tissue conducted noise. Whether the jaw is closed or open can have a 3-5 dB effect on the bone conduction thresholds.

Figure 8
Effect of Nose Clipping
Nixon and von Gierke – 1959



OBJECTIVE

The objective for effective hearing protection devices is to develop a device which is easy to use, comfortable to wear, and provides good noise attenuation performance. Frequently these desired parameters are opposing. For example, headband force improves attenuation performance but decreases comfort and wearability. The best performing hearing protection system has little functional use if it is so uncomfortable that few people will wear it. Additionally, repeatability of fit and performance is also important. Many hearing protectors can be difficult and time consuming to fit and wear properly, leading sometimes to poor use and decreased noise attenuation. Some commonly used materials such as acoustic foams inside earmuffs and earcushions degrade measurably over the period of one year and therefore should be replaced annually. Operations of high-performance aircraft generate high levels of noise up to 150 dB SPL in some personnel locations. In order to protect these personnel, the maximum performance in both passive and active attenuation needs to be achieved. The overall goal needs to be a hearing protector that achieves approximately 50 dB of noise attenuation.

APPROACH

The approach taken in this recent effort to improve hearing protector performance has been to minimize acoustic leaks in both earmuff and earplug passive protection and to integrate active noise reduction technologies to collectively improve attenuation and speech communications. Reducing acoustic energy conducted via bone and tissue conduction pathways was also examined.

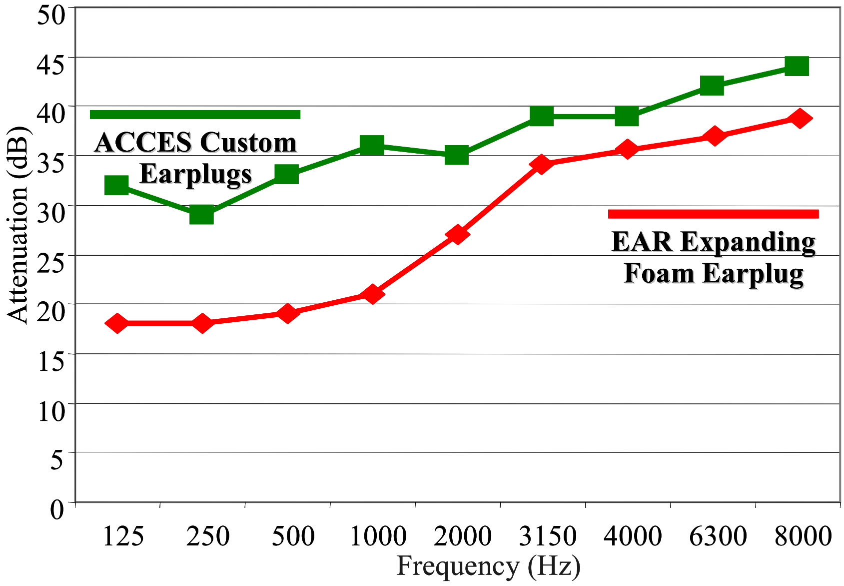
Custom Earplugs

The first area of focus was improving the performance of earplugs. The field performance of earplugs has been reported to be approximately 1/3 of the performance, in dB, measured in the laboratory. Many times this dramatic loss of performance can be attributed to poor insertion of the earplug by the user. However, with deep insert (to the second bend of the earcanal) custom earplugs, comfort was achieved only when the plugs were inserted completely and therefore correctly (see Figure 9). Investigations showed that deep insertion significantly improved attenuation performance by approximately 10 dB as shown in Figure 10. The performance gains were also repeatable and reliable. Users also reported deep insert custom molded plugs integrated with miniature earphones were so comfortable they used them to listen to music while off duty.

Figure 9
Custom Earplugs

The substantial increase in attenuation (see Figure 10) was achieved by taking deep impressions of individual earcanals and molding the plug to the second bend in the earcanal. This approach required special methods and training for taking the impressions. The ear dam had an integrated silicone pressure relief tube. This tube helped the pressure equalize behind the impression and the ear dam, and substantially reduced the number of hematomas which occasionally occur with deep impressions.

Figure 10
Attenuation Comparison
Custom Earplugs and Expanding Foam Earplugs

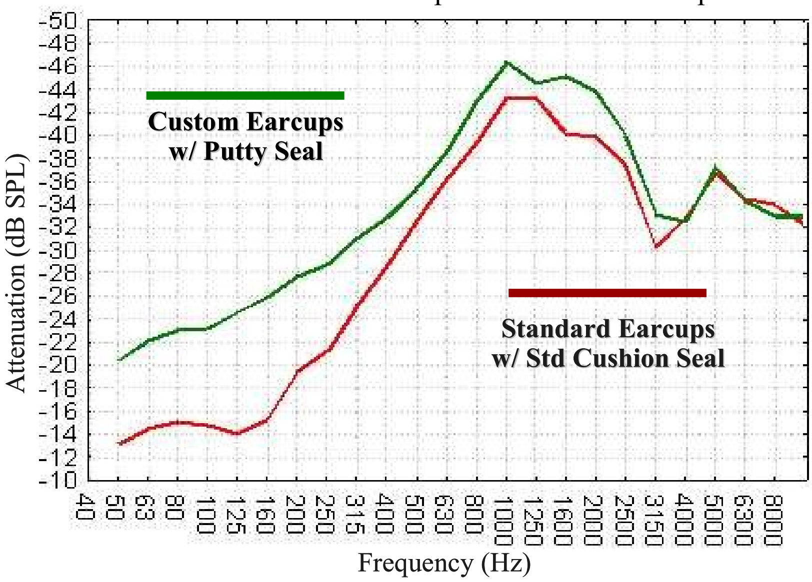


Custom Earmuffs

Earcups are traditionally constructed of high density material such as plastic and are interfaced to the head with foam-filled earcushions attached to a flat flange on the earcup. Earcushions are commonly constructed of low density materials such as foams and covered with a polyurethane skin. However, these low density foams provide a leak path for acoustic energy. Additionally, earcups and earcushions offer a flat interface to the human head which most often is not flat in the region in which the earcup contacts the head. The research concept was to match the contour of the head, i.e., customize the interface with high density material similar to that used for the earcup (see Figure 11). The technique involved the laser scanning of the user's head. The resulting head contours were then used to fabricate a custom earcup flange which was attached to a standard high volume (150cc) earcup and headband. Custom earmuff attenuation compared to earmuffs with flat earcup flanges and normal earcushions showed that custom earmuffs provided attenuation gains of approximately 5 dB at the lower frequencies (below 400 Hz) and less at high frequencies (see Figure 12). Both the custom fit and normal fit earcups had identical internal volume and mass. Clearly, reducing the size of the acoustic leak by custom fitting the earcup and seal had a positive effect on the overall attenuation of the earmuff.

Figure 11
Head Shape Extraction and Resulting Custom Earmuff

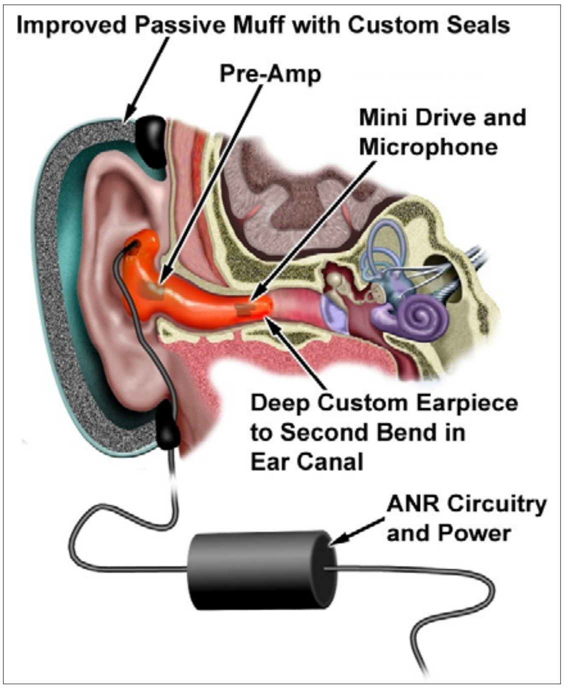
Figure 12
Attenuation of Custom Earcups and Standard Earcups



ANR Earplugs

The addition of active noise reduction to passive earmuffs and earplugs was needed to achieve the overall noise attenuation performance goal of 50 dB. Figure 13 shows the concept of ANR added to the deep insert custom earplug. The combination of a high performance earmuff, deep insert custom earplug, and active noise reduction in the earplug has demonstrated approximately 47 dB in overall noise attenuation in a broad band jet noise spectrum.

Figure 13
ANR Deep Insert Custom Earplug



Active noise reduction earplugs should not to be confused with level dependent earplugs designed for use with impulse noise such as those described by Dancer, et al. (7). These types of earplugs exhibit attenuations which vary in noise levels above 130 dB. They normally were not designed for use in continuous noise, but are effective for use especially with infantry and artillery units.

Bone Conduction Passive and Active Control

These new high-performance hearing protection systems meet or exceed bone conduction limits and thereby provide a motivation for a better understanding of bone/tissue conducted noise and methods of possibly controlling it. Current research is being conducted to isolate, quantify, and model noise pathways through the body and head. Techniques to overcome the bone conduction limits in hearing protector performance are also being developed. Possibly, active control, either with bone conduction drivers and/or an air conducted source could exceed the bone conduction limitations.

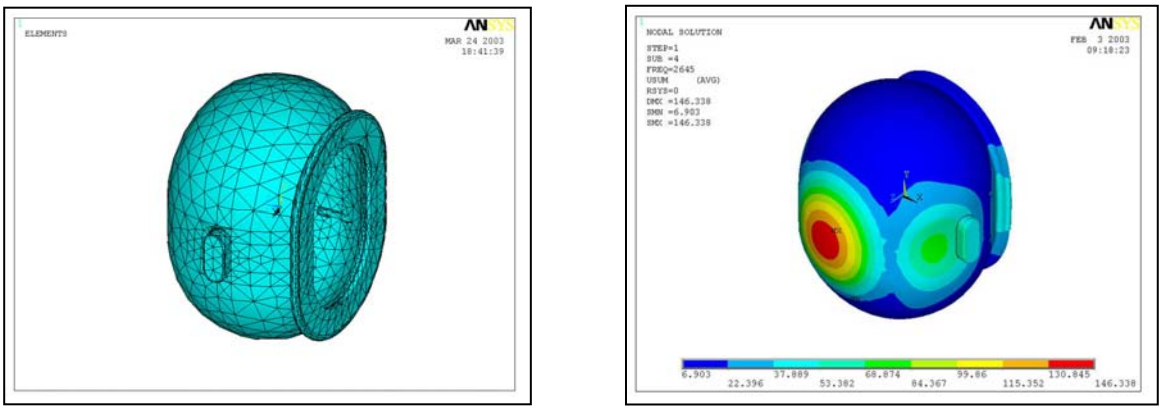
Performance Standards

The advancement in hearing protector performance has been and will continue to be dependent on the accurate measurement of noise attenuation performance. The national and international standards organizations with expert scientists, Berger (2), Johnson and Nixon (12), Nixon (16), Rood (19) have also developed several measurement techniques for both earmuffs and earplugs using both human subjects and head test fixtures. Certainly, in dangerous environments and/or when the acoustic levels are very high, for example over 150 dB, acoustic manikins should be used. Special acoustic manikins, such as one developed by Parmentier, et al (18) were constructed such that the attenuation met or exceeded the human bone conduction attenuations. Dancer, et al. (5, 6) and Crabtree (4) have described the use of manikins in measuring the performance of hearing protectors in both continuous and impulse noise fields.

SUMMARY

The main defenses used by people working in noise are passive noise reduction earmuffs and earplugs. The performance of these devices depends on many parameters, the most important being the size of the acoustic leak. Recent developments in minimizing the size of the acoustic leak in both earplugs and earmuffs have led to improved attenuation performance. The gains have been approximately 10 dB in earplugs and up to 5 dB in earmuffs. Active noise reduction technology also can improve attenuation performance when integrated with passive devices. However, to meet the 50 dB attenuation need, bone conducted noise needs to be reduced. Bone/tissue conducted noise can be reduced by passive means, helmets and whole-body enclosures, or possibly by active means. The future of hearing protection depends on the continued pursuit of new scientific knowledge of both psychoacoustics and the physical acoustics of hearing protectors, such as the FEA model by Saunders and Homma (20) shown below in Figure 14, and in investigating the numerous transmission paths of acoustic energy to the cochlea.

Figure 14
Finite Element Analysis Model of Earcups
Saunders and Homma - 2004



Bibliography

1. Berger, E. H., Review and Tutorial - *Methods of Measuring the Attenuation of Hearing Protection Devices*, J. Acoust. Soc. Am. 79(6), pages 1655-1687, 1986
2. Berger, E. H., *International Activities in the Use, Standardization, and Regulation of Hearing Protection*, J. Acoust. Soc. Am. 99(4), Pt.2, page 2463, 1996
3. Blackstock, D.T. and von Gierke, H.E., *Development of an Extra Small and Extra Large Size for the V-51 R Earplug*, Wright Air Development Center Technical Report, WADC 56-142, Wright-Patterson Air Force Base, Ohio, April 1956
4. Crabtree, R. B., *Application of an Acoustic Manikin to the Study of Continuous and Impulsive Noise Exposure*, in Proceedings of Inter-Noise 92, edited by G. A. Daigle and M. R. Stinson, Noise Control Foundation, Poughkeepsie, NY, pages 279-282, 1992
5. Dancer, A., Grateau, P., Cabanis, A., Barnabe, G., Cagnin, G., Vaillant, T., and Lafont, D., *Effectiveness of Earplugs in High-Intensity Impulse Noise*, J. Acoust. Soc. Am. 91(3), pages 1677-1689, 1992
6. Dancer, A. L., Franke, R., Parmentier, G., and Buck, K., *Hearing Protector Performance and NIHL in Extreme Environments: Actual Performance of Hearing Protectors in Impulse Noise/Nonlinear Behavior*, in Scientific Basis of Noise-Induced Hearing Loss, edited by A. Axlesson, H. Borchgrevink, R. P. Hamernik, P. Hellstrom, D. Henderson, and R. J. Salvi, Thieme Medical Pub., Inc., New York, NY, pages 321-338, 1996
7. Dancer, A. and Hamery, P., *Nonlinear Hearing Protection Devices*, Spectrum, 15(Supplement 1), 21, 1998
8. Dancer, A., Buck, K., Hamery, P., and Parmentier, G., *Hearing Protection in the Military Environment*, Noise & Health 5, 1-15, 1999
9. Franke, E.K., von Gierke, H.E., and von Wittern, W.W., *The Jaw Motions Relative to the Skull and Their Influence on Hearing by Bone Conduction*, Aero Medical Laboratory Technical Report number 6466, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, May 1951
10. Guild, E., Nixon, C.W., and Baker, D.J., *User Test of Flents Anti-Noise Ear Stopples*, Internal Memo, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, May 1959
11. James, S., Hancock, M., Hazel, A., and Rood, G. M., *Primary Contributors to Hearing Damage Risk in the Military Aircraft Cockpit*, Intl. Military Noise Conf., Baltimore, MD, 2001
12. Johnson, D.L., and Nixon, C.W., *Simplified Methods for Estimating Hearing Protector Performance*, Journal of Sound and Vibration, June 1974
13. Johnson, D. L., Nixon, C. W., and Skelton, M., *The Effect of Reduced Headband Force on the Attenuation of Muff-Type Protectors*, J. Acoust. Soc. Am. Suppl. 1, 74, S94, 1983
14. Nixon, C. W. and von Gierke, H. E., *Experiments on the Bone-Conduction Threshold in a Free Sound Field*, J. Acoust. Soc. Am. 31(8), pages 1121-1125, 1959
15. Nixon, C. W. and Knoblach, W. C., *Hearing Protection of Earmuffs Worn Over Eyeglasses*, Aerospace Medical Research Laboratory, Report No. AMRL-TR-74-61, Wright-Patterson AFB, OH, 1974
16. Nixon, C.W., Chapter 5 *Hearing Protector Standards, in Personal Hearing Protection In Industry*, edited by Alberti, P.W., Raven Press, New York, 1982
17. Nixon, C.W., Chapter 12 *Hearing Protective Devices: Ear Protectors*, in Handbook of Noise Control, edited by Harris, C., McGraw-Hill, 1979
18. Parmentier, G.; Buck, K.; Kronenberger, G., and Beck, C., *Artificial Head (ATF) for Evaluation of Hearing Protectors*, Institut Franco-Allemand De Recherches De St. Louis, St Louis, France, 1999
19. Rood, G. M., *The In-Situ Measurement of the Attenuation of Hearing Protectors by the Use of Miniature Microphones*, in Personal Hearing Protection in Industry, edited by P. W. Alberti, Raven Press, New York, NY, pages 175-197, 1982

20. Saunders, W. and Homma, K. *A Finite Element-Based Acoustic Engineering Design Program for Advancements in Passive Noise Reduction Performance of Helmet Mounted Noise Defenders*, ATI, Blacksburg, VA, personal communication, July 2004
21. Shaw, E.A.G. and Thiessen, G.J., *Improved Cushion for Ear Defenders*, J. Acoust. Soc. Am., Vol 30, Num 1, pages 24-36, Jan 1958
22. Shaw, E.A.G., *Hearing Protector Design Concepts and Performance Limitations*, International Symposium on Personal Hearing Protection, University of Toronto, Canada, May 1980
23. von Gierke, H. E., *Protection of the Ear from Noise: Limiting Factors*, J. Acoust. Soc. Am. 95(5), Pt. 2, page 2914, 1994