HEARING PROTECTION AND COMMUNICATION IN VERY NOISY ENVIRONMENTS

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1. INTRODUCTION

Conventional passive hearing protectors - ear-plugs, ear-muffs and noise-excluding helmets - are very widely used to protect hearing against damage from excessive noise exposure. They may be combined with microphone and telephone transducers to form communications headsets. This approach may fail in very intense noise because:

- The attenuation of ambient noise by the headset may not be sufficient to give a low enough noise level at the ear;
- Even if the attenuation measured under ideal conditions is sufficient, the attenuation in practical use is likely to be less (see, for instance, Hempstock and Hill [1]);
- In the case of communications headsets, noise at the ear is increased by speech and noise picked up by "live" microphones;
- At very high levels, the intelligibility of spoken communications is reduced by distortion within the communications system and within the ear.

Where noise cannot be reduced at source, it is necessary to find improved forms of hearing protectors and communications headsets which overcome, or at least alleviate, these problems.

The main problem within the Army is the noise within tracked armoured fighting vehicles (AFVs). The tendency of such vehicles to become faster and more heavily armoured has, unfortunately, given rise to a tendency to become ever more noisy; we now have vehicles in service which, in the most noisy condition (generally fast movement on roads), approach or even reach a sound pressure level (SPL) of 130 dB at crew positions. The noise is generated principally by track link contact with sprockets or with the road surface. Crew members need to hear spoken communication, and in most cases also require to speak to their comrades. Head-sets need to be very robustly constructed, and also need to be compatible with other headgear such as helmets.

Although the work described in this paper is concerned chiefly with military requirements, similar problems will occur in some civil applications, and the same approaches may be helpful.

2. POSSIBLE IMPROVEMENTS TO CONVENTIONAL HEADSETS

It may be helpful to consider improvements under three separate headings;

2.1 Reduction in airborne noise

Ear-muffs and noise-excluding helmets typically give a good attenuation of high frequencies above 1 kHz, but a much less good attenuation of low frequencies. For instance, the assumed protection (ie mean - standard deviation) at 125 Hz may be only 10 dB, yet the noise may be most intense in this band. This attenuation can be improved, for instance by increasing head-band force or ear-cup volume, but this will result in severe discomfort during prolonged use or in incompatibility with other headgear.

Ear-plugs can give a better mean attenuation at low frequencies, but their attenuation shows a large standard deviation in laboratory tests (and an even larger standard deviation in practical everyday use), so that some users are not effectively protected. Fortunately, a solution - Active Noise Reduction (ANR) - has been developed over the last few years.

ANR, adapted for this purpose, uses a small microphone inside the ear shell, near the ear, which senses the noise penetrating the headset; the microphone signal is amplified and inverted, then fed to a telephone transducer within the ear shell, thus cancelling some of the noise. The system is now well known and well proven; see, for example, Twiney, Holden and Salloway [2], and Nixon, McKinley and Steuver [3].

There is little point in achieving a good ANR performance at the expense of conventional (passive) protection, since the total protection achieved is a combination of the two. The requirements need to be carefully balanced, because (for instance) good passive protection demands a large ear shell volume while ANR works best with a restricted volume; it follows that ANR is most useful where ear shell volume is restricted by other headgear.

2.2 Reduction in noise transmitted through the intercommunications system

This communications load consists of speech, noise picked up by "live" microphones, and radio interference; it is difficult to quantify, since it depends on how the system is used. For instance, if there is little or no use of radio communications, and the crew's microphones are switched off except during brief periods of use, then the noise dose arising from the communications load will be small. The level of the communications signal is usually adjustable, and in theory should be at the minimum level consistent with reasonable intelligibility. However, it is much more usual to find the microphones permanently "live" (which the user finds convenient since it permits hands-free operation), and the level set permanently at "maximum" in the belief that loudness gives clarity. Typically, this can give an increase in "A" weighted SPL at the ear around 8, possibly 12, dB above that measured without the communications load; the existence of several live microphones, where only one is being used to transmit speech, will also degrade intelligibility.

Usually, the microphones are pressure-gradient (noise cancelling) boom microphones, with the boom fixed to the headset such that the microphone is just in front of the user's mouth. (Throat microphones are rarely used, since their speech quality is poor and they become very uncomfortable during prolonged use.) Unfortunately, the discrimination between the near source (voice) and far source (vehicle noise), which may be 20 dB at 250 Hz, falls off badly at higher frequencies.

Microphones of improved performance are available, and can reduce noise dose as well as improve speech intelligibility; however, the microphone housing, which is needed to protect against rain, mud, impacts and other environmental stresses, can degrade the microphone performance.

A voice-operated switch (VOS) will give the user "hands-free" operation, but will switch the microphone "off" when it is not being used. The VOS has been seen as a possible solution for some years, but has generally either given an unreliable performance or has been very expensive. Recently, VOSs have been developed which are more acceptable to the user.

The use of adaptive noise cancelling to remove tonal components from the microphone signal is a possible development for future headsets.

2.3 Ergonomic factors
Such factors as: ease of use, comfort, robustness, compatibility with other headgear, ease of donning and doffing, stowage, and reliability, are just as vital as good acoustical performance.

3. LESSONS FROM PRACTICAL EXPERIENCE

APRE has now evaluated a number of different types of headset, produced by several different manufacturers including contractors working for APRE. We have the advantage of being able to work closely with several Army units, including a small trials section at APRE who provide test subjects. Although much of our work is directed towards noise in AFVs, most of our experience will be of interest in a wider context.

3.1 Methods of measurement
Real-ear attenuation at threshold (REAT) measurements of attenuation, such as defined in ISO 4869 Part 1 [4], cannot be used with ANR, since the electronic noise masks the hearing threshold and will give exaggerated values for attenuation Further, REAT methods are useful only where the attenuation can be expected to be independent of SPL; this is so for conventional passive protectors, but not for ANR at high SPLs where the performance may be limited by transducer output. We therefore use miniature (Knowles, type BL 1785) microphones at the ear canal entrance, both to measure the noise at the ear and, with a microphone on the outside of the protector, to calculate the transmission loss (Rood [5]).

In common with ISO 4869, we use human subjects since we do not yet have enough confidence that artificial heads will reveal all the possible weaknesses in headset design. "A" weighted SPL at the ear is monitored continuously, and care is exercised to ensure that the 8-hour L Eq at the ear does not exceed 90 dB(A) on any one day; usually it is much less. As additional safeguards, monitoring audiometry is used routinely before and after each series of measurements, and subjects are drawn from a pool of men with good hearing (due to the possibility that poor hearing could be associated with vulnerability to noise-induced hearing loss).

The majority of measurements are conducted in a "noise facility" consisting of an old personnel carrier hull equipped with a battery of loudspeakers. Loudspeaker input is derived from a "white noise" source, shaped by two 1/3 octave spectrum shapers in series. This allows SPLs up to 130 dB. Subjects are visible through closed-circuit TV, and are usually audible to the experimenters via a standard Army (Clansman) intercommunications system. A number of safety cut-outs are fitted, including one accessible to the subjects. Measurements in this facility are always supported by measurements in moving vehicles.

3.2.2 Intelligibility of speech is measured using the Diagnostic Rhyme Test (DRT) (Voiers [6]). We also use the STIDAS test devised by Steeneken and Houtgast ([7]), which is much quicker to use than DRT, and gives far more information, but needs to be validated against DRT or similar methods. STIDAS yields a score between 0 and 1 for Speech Transmission Index (STI), a score of 1 representing the ideal.

3.2.3 Microphone response is measured, in terms of frequency response and sensitivity at 1 kHz, using an artificial voice (such as that in the Bruel and Kjaer Artificial Head and Torso Simulator) placed in an anechoic room. Comparison with corresponding measurements in a reverberant field gives the noise discrimination. Alternatively, STIDAS can be used to check microphone response.

3.3 Results of measurements.
Figure 1 shows a typical passive attenuation (measured as a transmission loss) of a communications headset intended for use beneath a ballistic helmet. By comparison with a heavyweight industrial ear-muff, the attenuation is only moderately good, since the internal volume of the ear cup and the headband configuration are governed by the shape of the helmet.

Figure 2 shows the additional attenuation provided by ANR. It can be seen that ANR works over a limited frequency range, outside which noise is enhanced to some extent; this is most marked, for this particular headset, around 630 Hz. Evidently, ANR will be effective if the noise components are strongest around 80 - 250 Hz (as is generally the case with noise in vehicles), but will be ineffective with high-frequency noise and will be counter-productive in this case if the noise has its strongest component around 630 Hz.

This headset, tested in our noise facility using a simulated AFV noise of 120 dB, 113 dB(A), gave a mean "A"-weighted SPL of 91 dB(A) at the ear with the ANR "off", and 85 dB(A) with ANR "on"; this was measured without any contribution from communications.

Joyner [8] investigated the effect of adding ANR to the in-service "Crewguard" tank crewman's helmet. This reduced the passive attenuation, since the volume within the ear cup was effectively reduced, but the attenuation with the ANR operating was better than that of the standard item below 500 Hz. Noise measurements included the communications load, in this case speech and noise picked up by a live microphone; the level of the communications load was controlled by the subject. In the noise facility with a sound field similar to that described previously, and both talker and listener in noise, the "A" weighted sound pressure level at the ear was about 103 dB(A) with the standard in-service headset and 98 dB(A) with the ANR headset.

Several vehicles in current service can give SPLs above 120 dB, in some cases approacing 130 dB. Some prototype headsets have been able to limit noise at the ear to a mean "A"-weighted SPL of about 90 dB(A) (without communications load). This is helped by the headsets in such vehicles being designed as an integral part of a noise-excluding helmet, rather than as an addition to a helmet designed primarily as ballistic protection. Even so, at such levels, the ANR may be barely able to cope, which is seen experimentally as a marked increase in standard deviation as well as an increase in the mean of the "A"-weighted SPL at the ears.

3.4 Effects of protective headgear
In addition to the helmet, other forms of protective headgear, such as fabric hoods or respirators, may be needed. These introduce air leakage paths beneath the ear cup seal, with a corresponding effect on passive attenuation. Typical "A"-weighted SPLs at the ear, again with the 120 dB (113 dB(A)) noise field described previously, may be 105 dB(A) with the ANR "off". Use of ANR provides only marginal improvement, since the transducers cannot produce enough sound pressure to cancel the noise (in this case, the mean level was 104 dB(A) with a standard deviation of 5 dB). Such measurements require either very brief exposures, or the use of ear-plugs! A related problem is the effect of respirators on the signal from the microphone; if a dedicated respirator microphone is used, its positioning relative to the airguide is critical.

3.5 Ergonomic factors

Practical experience at APRE, and even more so at Army trials units, have revealed a host of ergonomic problems with headsets, including:

- Lack of robustness - too often, the item will not stand up to laboratory, let alone military or industrial, usage.
- Incompatibility with other headgear.
- Excessive headband force.
- Insufficient space inside ear cup for ears.
- Failure of ear cup seals to make contact over entire circumference with side of head.
- Insufficient movement on microphone boom.
- Lack of waterproofing, with consequent failure to function in the British climate.

3.6 An ear-plug with ANR

It is now possible to miniaturise the transducers used for ANR so that it becomes practical for use in ear-plugs, although the power source and electronics are still at present housed in a separate box. The advantages of this approach are that:

- Ear-plugs, provided they fit well in the ear canal, offer more passive attenuation at low frequencies than do ear-muffs.
- Since the volume in which the noise is to be cancelled is much less, the ANR should function over a wider frequency range.
- The problem of compatibility with other headgear is much reduced.

Against this, the difficulty of providing an effective, reliable and comfortable fit is even greater than with ear-muffs.

Such an ear-plug has been described by Cole [9] and by Goodfellow [10]. It has been shown to give the passive and active attenuation shown in Figures 3 and 4 (measured as a transmission loss using the sense microphone). Mean "A"-weighted sound pressure level in the ear canal was 85 dB(A), measured in the noise facility with the sound field described above: in the corresponding noise of the real vehicle at maximum speed on roads, it was 86 dB(A).

This ear-plug also incorporates an external microphone on the body of the plug; this transmits low-level sounds so that the ear can easily hear speech under quiet conditions without needing to remove the plug. The gain in the microphone amplifier is reduced as external noise increases, so that protection against noise is retained.

4. DISCUSSION

Under ideal conditions, with a carefully defined fitting procedure, ANR can give very substantial attenuation. In practice, the quality of fit will vary between different users, with their different head shapes, different degrees of care in fitting, etc. ANR which has been optimised to an ideal fit may very well oscillate and increase the noise at the ear when fitting is less good. Making the ANR unconditionally stable will result in some loss of performance compared to the laboratory optimum, but will give more dependable results in practical use.

There is no single design change which will solve the problem of hearing protection and communication in very noisy environments. Rather, progress can be achieved through a number of small improvements. Passive protection, microphone performance and ergonomic factors, together with the user's training and appreciation of the necessity for protection, remain dominant; recent advances such as ANR can supplement but do not replace these. The most important improvement, however, can be made by the reduction of ambient noise levels.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] T I HEMPSTOCK & E HILL, The Attenuation of Some Hearing Protectors as used in the Workplace, Ann Occup Hyg 34 (5) p 453-470 (1990).

[2] TWINEY R C, HOLDEN A J & SALLOWAY A J, Some Transducer Design Considerations for Earphone Active Noise Reduction Systems. Proc. IOA 7 (2) p 95 - 102(1985).

[3] C W NIXON, R L MCKINLEY & J W STEUVER, Performance of Active Noise Reduction Headsets. In: A L Dancer, D Henderson, R J Salvi & R P Hamernik (eds), Noise-Induced Hearing Loss, Mosby Year Book (1990).

[4] International Standard ISO 4869-1:1990(E), Acoustics - Hearing Protectors - Part 1: Subjective Method for the Measurement of Sound Attenuation.

[5] G M ROOD, The In-Situ Measurement of the Attenuation of Hearing Protectors by the Use of Miniature Microphones. In: P W Alberti (ed), Personal Hearing Protection in Industry, Raven Press, New York, 1980.

[6] W D VOIERS, Diagnostic Evaluation of Speech Intelligibility. In: M E Hawley (ed), Benchmark Papers in Acoustics/11, Speech Intelligibility and Speaker Recognition. Dowden, Hutchinson and Ross (1977).

[7] H J M STEENEKEN & T HOUTGAST, A Physical Method for Measuring Speech Transmission Quality. J Acoust Soc Am 67 (1) p 318 - 326 (1980).

[8] S M JOYNER, Unpublished Ministry of Defence Memorandum (1990).

[9] S H COLE, Unpublished Ministry of Defence Memorandum (1991).

[10] E A GOODFELLOW, A Trial of a Prototype In-Ear Hearing Protector [to be presented at the 5th International Conference on Environmental Ergonomics] (1992).

Figure 1 Headset - Passive Attenuation

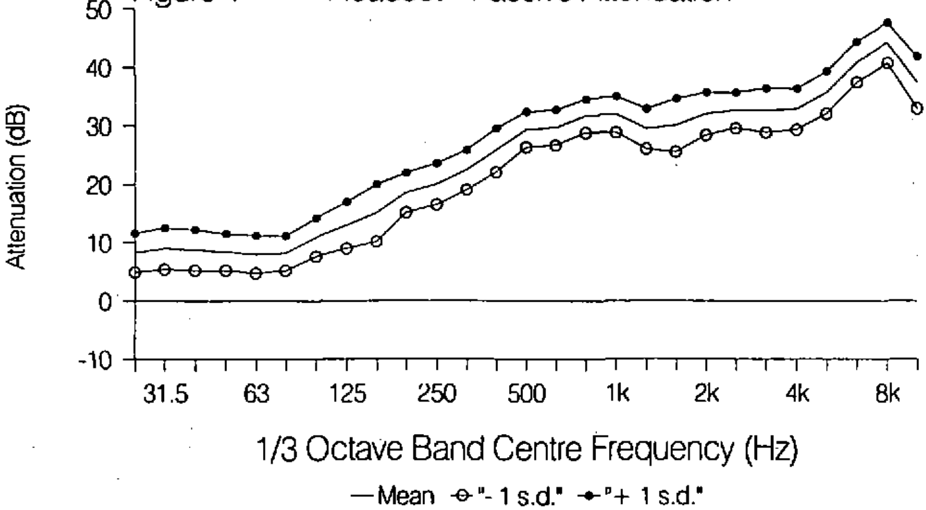
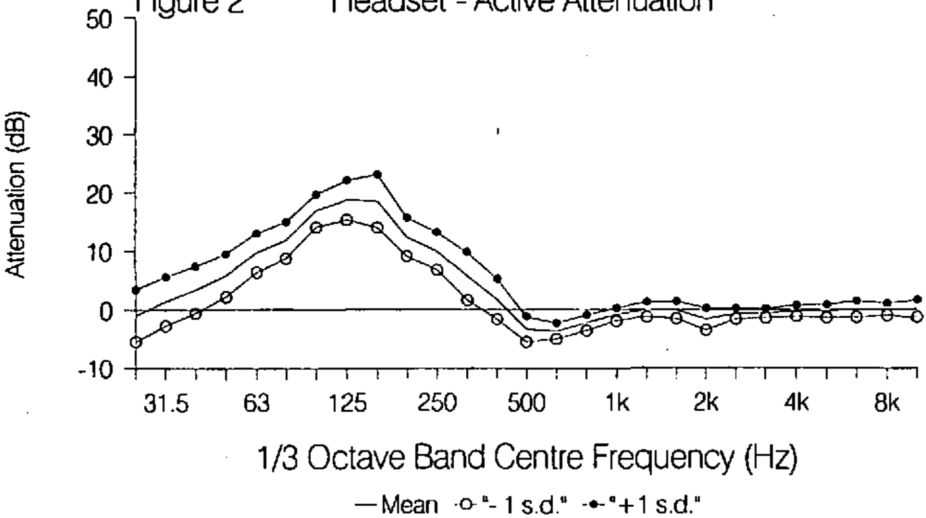


Figure 2 Headset - Active Attenuation



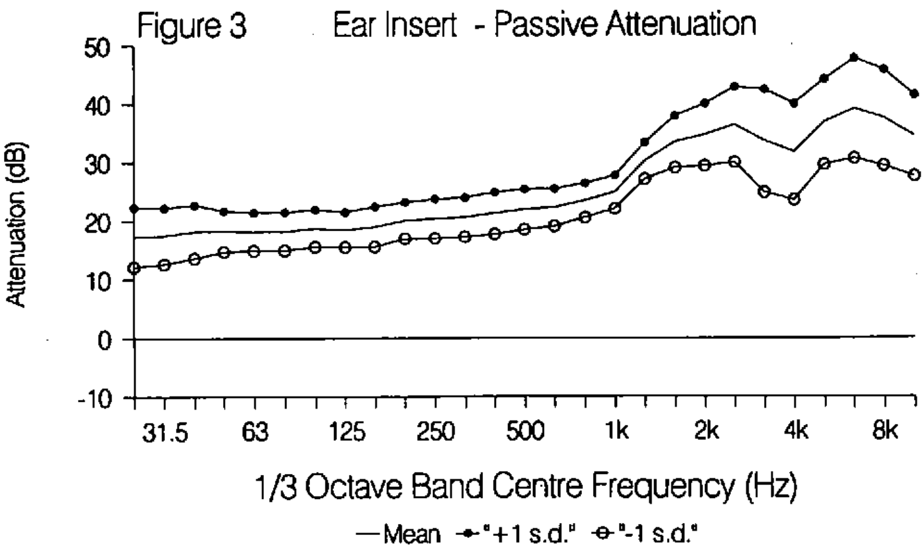


Figure 3 Ear Insert - Passive Attenuation
Attenuation (dB)
50
40
30
20
10
0
-10
31.5
63
125
250
500
1k
2k
4k
8k
1/3 Octave Band Centre Frequency (Hz)
—Mean "+1 s.d." "-1 s.d."

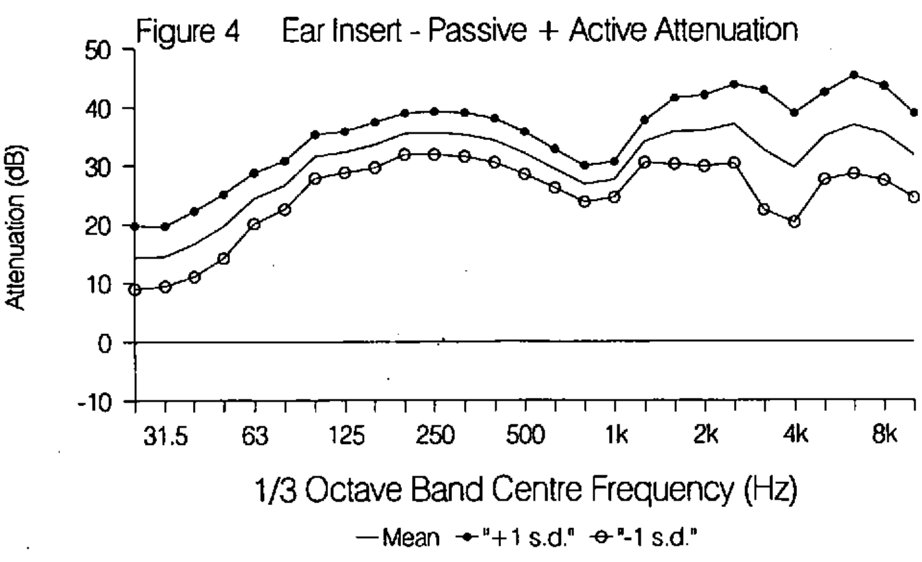


Figure 4 Ear Insert - Passive + Active Attenuation
Attenuation (dB)
50
40
30
20
10
0
-10
31.5
63
125
250
500
1k
2k
4k
8k
1/3 Octave Band Centre Frequency (Hz)
—Mean "+1 s.d." "-1 s.d."