PROTECTION & COMMUNICATION IN EXTREME ENVIRONMENTS

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Introduction In the military environment, personnel can be exposed to very high-level noises: impulse noises produced by weapons can reach 190 dB peak, continuous noises in the vicinity of jet engines can exceed 150 dBA! Although these extreme exposures conditions are relatively infrequent and concern only a few people, they present serious problems as they can produce immediate cochlear lesions and large PTS [1]. Moreover, even "moderate" intensity noises: impulse noises of 150 to 165 dB peak (produced by rifles in military training or recreational shooting), continuous noises of 100 to 120 dBA (existing in armored vehicles, planes and ships), are well over admissible exposure conditions (ISO 1999). Altogether these noises correspond to a major cause of acoustic trauma among the military personnel: in 1999, the American government spent 291.6 million dollarr to compensate for the NIHL of 56,792 veterans!
Hearing Protectors (HP) offering an adequate performance in such extreme noise environments are especially difficult to design and to use properly. Moreover, the use of HP induces difficulties to detect, localize and identify acoustic sources in the environment, and impedes the efficiency and the security of the user. The HPs also generally decrease the speech intelligibility and drastically reduce the global performance of complex and expensive weapon systems [2]. To cope with these problems new hearing protection techniques and devices are actively sought.

Methods
Noise Reduction (NR) and Insertion Loss (IL) measurements [3] To determine the attenuation afforded by earplugs and earmuffs at very high levels, the classical measurements performed either by the subjective method: "Real-Ear-At-Threshold" (REAT), or by the objective method "Microphone-In-Real-Ear" (MIRE), are not suitable. Undergoing the action of high-level noises, the HPs may exhibit nonlinearities (deliberately created or not) which cannot be assessed by REAT measurements. MIRE measurements are impossible to use as a routine technique with high-intensity noises because of the safety of the subjects. Moreover, the evaluation of Active Noise Reduction (ANR) HPs must address the electronic background noise, the stability, the saturation level... . Therefore, it is necessary to use an Artificial-Test-Fixture (ATF) and preferably an artificial head with an ear simulator [4].We designed a new ATF which fits: (i) the HEAD Acoustics GmbH device corresponding to the external ear and the circumaural region, (ii) the Brüel & Kjaer ear simulator (type 4157). To allow the measurement of peak levels up to 190 dB, the 1/2" Brüel & Kjaer microphone of the original ear simulator is replaced by an underpolarized (28 V) 1/4" microphone (type 4136) [5]. The maximum Insertion Loss (IL) afforded by this ATF is better than 80 dB from 0.4 to 5 kHz and well over the ANSI and ISO criteria.
The attenuation afforded by linear and/or nonlinear, passive and/or active, earplugs and earmuffs was measured during exposure: (i) to impulse noise (Friedlander waves of 150, 170 and 190 dB peak; A-durations: 0.2 and 2 ms) and, (ii) to high-level continuous noise.

Results

Nonlinear earplugs Some HPs behave linearly: there is no significant modification of the IL when the level of the impulse changes. Some HPs behave nonlinearly: the nonlinearity may be either unfavourable (the higher the level, the lower the IL), or favourable (the higher the level, the higher the IL). The I.S.L. perforated earplugs present an attenuation which increases with the peak pressure (the acoustic resistance through the orifice(s) increases with the level) [6] (fig. 1). The NR peak attenuation of these earplugs increases by 20-25 dB from 110 to 190 dB.

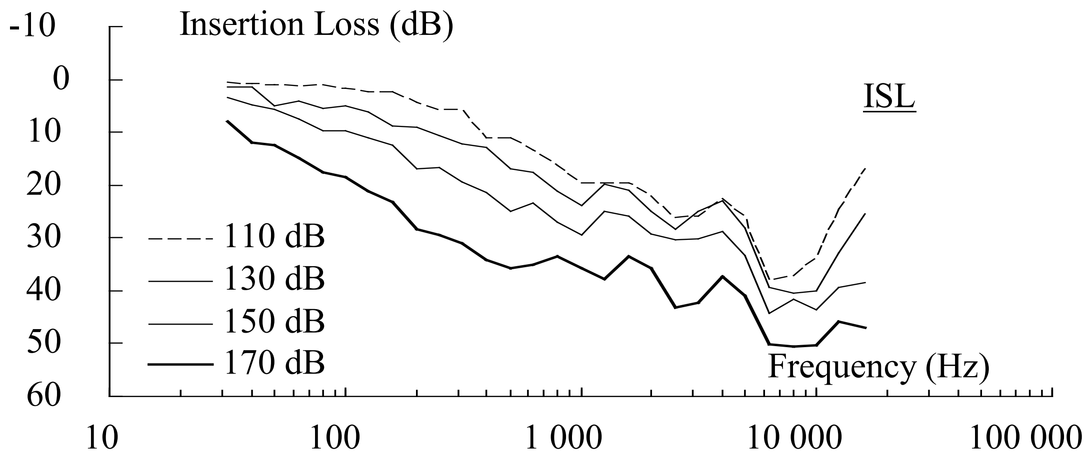

Figure 1 Insertion Loss afforded by the I.S.L. nonlinear earplugs for different peak pressure levels of the impulses: 110 dB, 130 dB, 150 dB and 170 dB (A-duration: 2 ms, normal incidence)

To protect the ear against high-level impulse noises, nonlinear earplugs are a very attractive solution. They are light, cheap, easy to clean and to maintain, they work without any energy supply and without intervention of the subject, and they are compatible with other head equipments. Unlike classical plugs and because they present a limited IL at the low and moderate levels, these plugs allow speech communication, detection and localization of acoustic sources in about the same conditions as an unprotected subject. All the same, they afford a protection adapted to occasional exposures to impulse noises such as those produced during training or combat. Human studies have demonstrated that these earplugs are efficient for repeated exposures up to 187 dB peak (Friedlander waves, 1.5 ms A-duration, free field, normal incidence, 100 rounds), when they are well fitted [7,8]. These plugs are presently in use in the American and French armies.

ANR hearing protectors Nixon et al. [9] summarized the main characteristics and possible applications of ANR. It is necessary to emphasize that the ANR-HPs work as well for continuous as for impulse noise. However, with impulse noise their efficiency is limited by the operational bandwidth and by the output level of the electro-acoustic system. Therefore, they are actually of little use for large impulses (weapon noises).

The present ANR HPs (ANR earmuffs) improve the attenuation by a maximum of 20 dB at the low frequencies (between 50 and 300 Hz) and no ANR attenuation exists beyond 700-800 Hz (on the contrary, uwanted noise is amplified around 1000 Hz).

ANR earplugs which are under development will operate up to 3 kHz (fig. 2). They will represent a significant improvement especially for the intelligibility of speech (which is only marginally improved by the present ANR earmuffs) and for the protection of hearing in intense continuous noise (jet noise). The ANR (molded) earplugs will incorporate a mini-microphone

and a mini-receiver located close to the tympanum. The use of digital filtering (feedback loop, IIR filter) will allow to optimize the ANR performance as a function of the electroacoustic system, of the user and/or of the noise exposure condition. It will also improve the stability of the system. New ANR-HPs will be compatible with high quality speech intercom system (adaptative critical band filtering) and even include a three-dimensional virtual reality. This new equipment will be incorporated in the headgear of the soldier. It will present interesting perspectives for a lot of other users: fire fighters, underground workers, steel workers... .

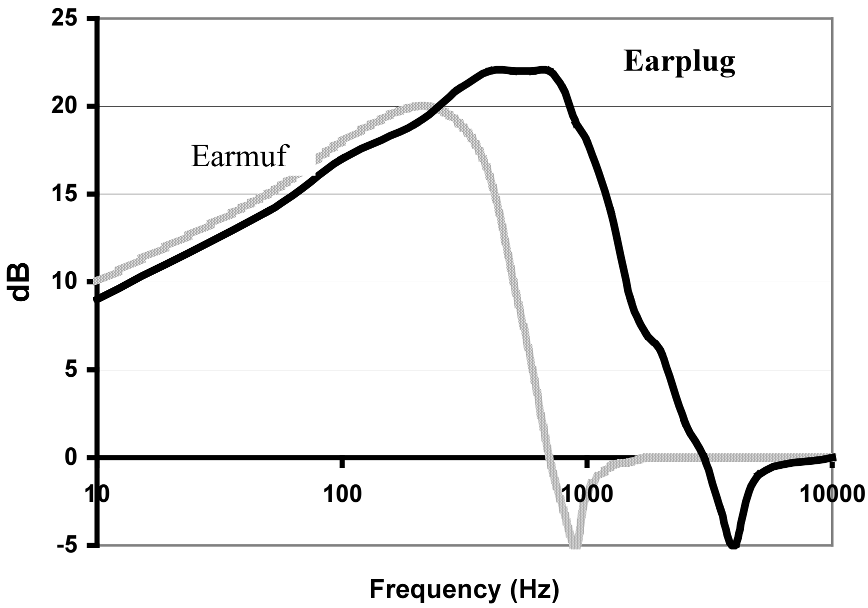

Figure 2 Contribution of the ANR to the IL
dashed line: typical ANR earmuff, full line: typical ANR earplug

Double hearing protection The measurements which are feasible thanks to the large dynamics (80 dB) of our ATF allow to determine the physical performance of any HP or combination of HPs. Generally, very large IL values which are measured in that way (with a double hearing protection) are not taken into account because they exceed the bone conduction (BC) limits [10]. However, it is always possible to apply correction curves corresponding to the BC limits (and/or to the physiological masking noise and the occlusion effect) [11], and obtain a good evaluation of the efficiency of a double hearing protection.
Interest in double hearing protection and bone-conduction limits from air-borne sound has been revived by the development of new military jet aircrafts which produce extreme noise levels (> 150 dBA). In these exposure conditions, even when equipped with a well-fitted double hearing protection, one can fear hearing damage due to the bone-conducted noise [12].
However, all investigations concerning the BC limits rely on threshold detection methods (REAT) at sound levels which do not exceed 70-80 dB SPL: i.e., within the linear range of the bone-conduction pathways. There is no proof whatsoever which indicate that BC pathways are linear up to 150 dB and that TTS and/or PTS could be induced by BC sounds (when exposed to very high-levels of air-borne sound waves). If the bone conduction pathways were nonlinear at the highest levels, the effect would probably be compressive (as observed for impulse noise [13]) and the input to the cochlea would be less than feared.
In order to clarify this point and to decide whether a more sophisticated and more performant hearing protection than afforded by a combination of classical earplugs and earmuffs is

necessary, human studies are to be performed (Air Force Research Laboratory, Hearing and Communication Branch, WP-AFP, USA).

Discussion

Hearing Protection and Communication Measurements performed in armoured vehicles have shown that, when the voice communication system is keyed, the A-weighted level measured under a classical earmuff may be higher than the level recorded in the crew compartment! In practice, the low frequencies go through the muff with very little attenuation and mask the speech, forcing the subject to increase the level of the speech signal. This masking effect is nonlinear (the larger the level, the larger the spread and the amplitude of the masking: fig. 3). In these conditions, the direct use of IL data (whether measured by REAT, MIRE or with an ATF) are misleading and may underestimate the hazard in actual exposure (operational) conditions with voice communication capabilities.

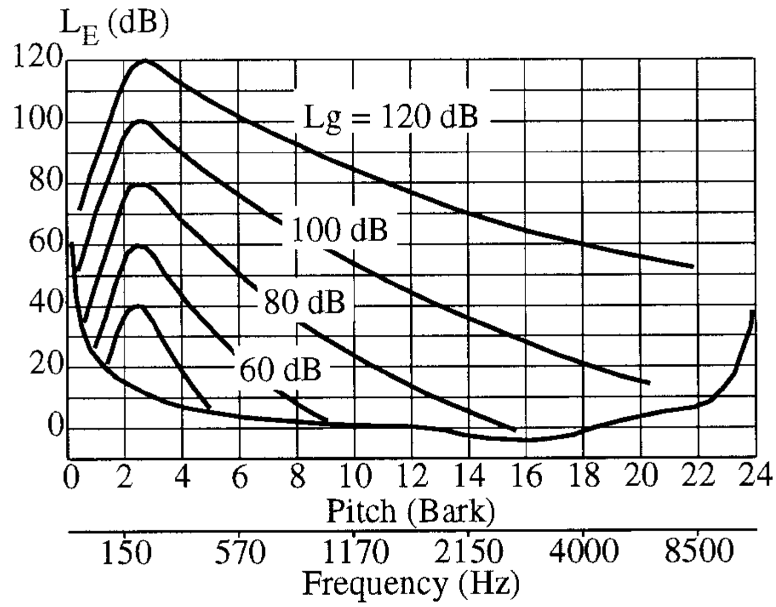

Figure 3 Masking curves corresponding to a "critical band" noise at 250 Hz (LE: excitation level, Lg: global level) (after Zwicker and Feldkeller, 1967)

Figure 4 allows to better understand this phenomenon. We can observe that it is not the attenuation performance of the HP at medium frequencies which determines the speech level as adjusted by the listener (and the global level to which the ear is exposed), but the masking effect due to the (very) low frequencies. A better HP, as far as the medium and high frequencies are concerned, would not perform better with respect to the communication and the overall exposure level.

The only solution is to improve the low frequency attenuation characteristics of the HP.

In these circumstances, the use of a double hearing protection was recommended by Kryter a long time ago [14,15]. The level difference between the speech signal and the noise was not modified over the whole frequency range but the earplugs worn under the earmuff brought both signals (noise and speech) down to a level at which the ear was not saturated and at which the masking by the low frequencies was less effective.

Today, the use of ANR earmuffs and/or ANR earplugs with digital filtering allows to customize the hearing protection and to protect the ear while improving the intelligibility of the communications in different noise environments.

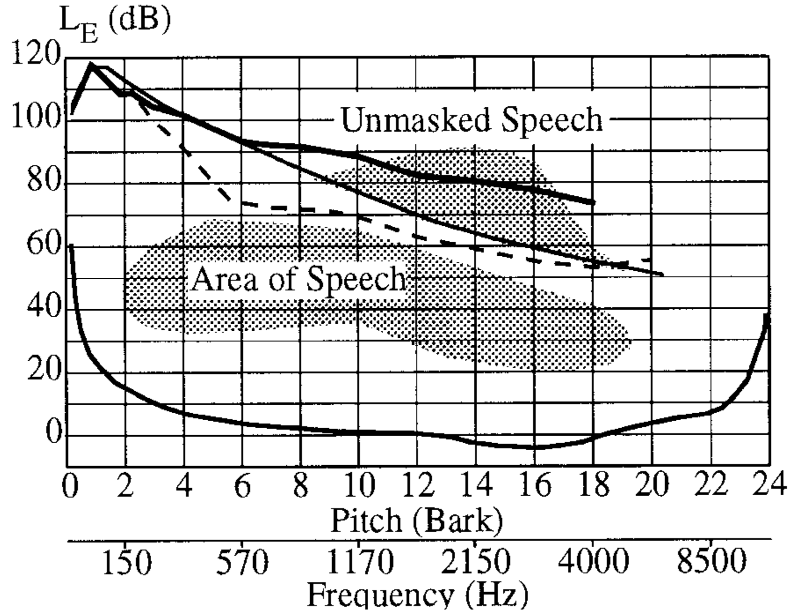

Figure 4 Noise level (1/3 oct. bands) into a turbopropeller plane (solid thick line); noise level under the pilot's headset (dashed line), masking curve (solid thin line)

The new HPs will be designed by taking into account the acoustic environment in which they will be used and the communication requirements necessary to preserve the operational efficiency.

Keywords: hearing protection, earmuff, earplug, nonlinearity, active noise reduction, communication

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