Active Hearing Protection Systems and Their Performance

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Summary

The present paper gives a brief history of active noise cancellation. It shows that the possibility of using ANR in hearing protection devices was proposed long before the first commercial devices became known. The basic theory of active noise cancellation is quite simple and was first described in the 1930's. The basic principles and the different approaches to obtain active noise cancellation are described in this paper. Different ANR techniques are presented (feed-forward, feedback) as well as different possibilities for their implementation (analog and/or digital). The possibility for optimum insertion of a communication signal into an ANR hearing protector is described. The impact of ANR protectors on the noise exposure and on the speech intelligibility is discussed. Critical parameters like stability and overload are discussed and some basic design rules will be shown. The problems arising during an implementation of ANR in earplugs will finally be discussed.

Introduction

The noise to which the servants of modern weapon systems are exposed (figures 1 and 2) becomes, in some configurations, a major limiting factor for their use. Pilots of armoured vehicles may be exposed to maximal A-weighted noise levels in the order of 112 dB. Due to the poor efficiency of passive hearing protectors in the low frequency range, the exposure level when "protected" with a standard circumaural protector is still 105 dBA. This means that, when respecting the legal limits, the pilot may not be exposed to this noise for a period longer than 5 minutes (L_{eq8h} = 85 dBA) respectively 15 minutes (L_{eq8h} = 90 dBA). These exposure limits represent a serious impact on possible training periods. Even if we consider that the exposure limits will be disregarded during combat, the lack of realistic training will impede on the effectiveness.

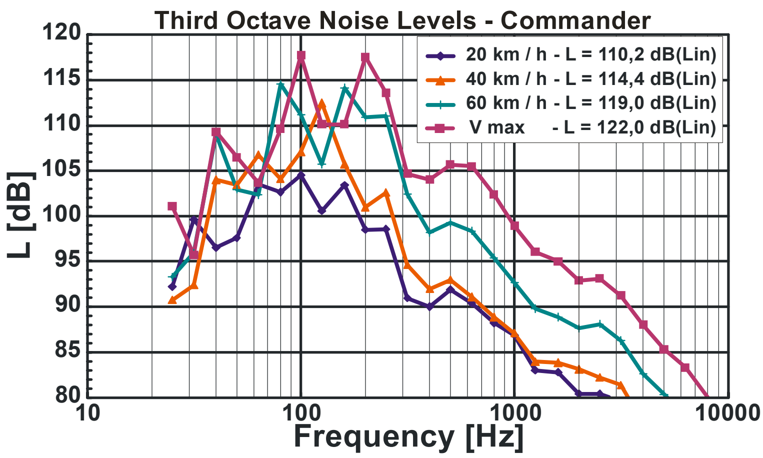

Figure 1: Typical noise inside an armoured vehicle

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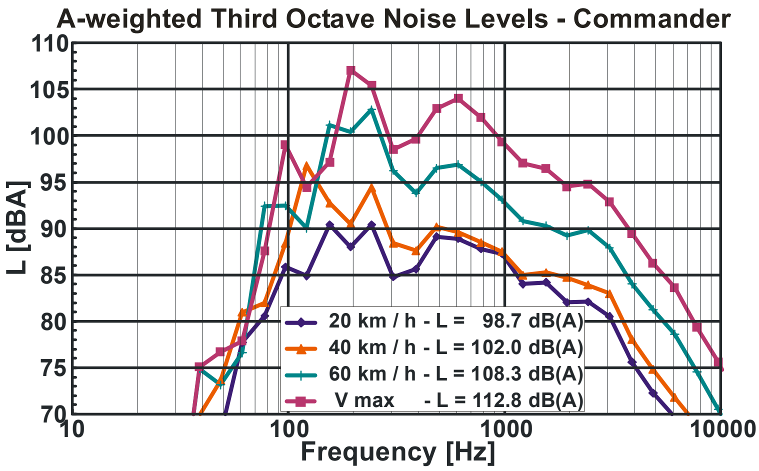


Figure 2: Typical A-weighted noise inside an armoured vehicle

But there are not only the health issues that demand hearing protectors with better attenuation in the low frequency range. The communication may be as well disturbed and even may contribute to hearing damage due to the high levels of the speech signal, needed to obtain an acceptable intelligibility. It has been shown [1], that the success of a mission is directly related to the intelligibility of the communication. It is therefore important to improve the intelligibility by lowering the noise levels at low frequencies in order to avoid masking of important higher frequency speech components.

Another factor limiting the efficiency of crews is the increasing fatigue when continuously exposed to high level noise and high level communication. Especially in combat, a lower noise exposure may help to avoid unnecessary fatigue, and so increase efficiency.

These three factors, exposure time limitation, reduced speech intelligibility and increased fatigue impede strongly the efficiency of the soldiers. One possibility to avoid these problems inside of land and air vehicles, where the major acoustic energy is centred at low frequencies (tanks, helicopters, propeller aircraft …) is the use of ANR hearing protectors. These systems offer an increased attenuation in the low frequency range.

History

In 1933 an U.S. Patent has been issued to Lueg [2] for a device attenuating noise by means of superimposing a second noise with opposite phase. At this time, the technology did not yet allow the implementation. The first experimental devices only showed up in the 1960s [3], but were still too bulky to be used. When the integrated circuits (OpAmps) and reliable miniature microphones became available, the first usable ANR headsets were presented to the Armed Forces [4]. Still, at the beginning, the ANR hearing protectors were considered as luxury equipment and of no real use for the crews of armored vehicles or helicopters. Only when different studies showed an increase of efficiency, ANR headsets were considered in the Armed Forces. Now, the usefulness of this type of equipment is accepted but it is still not introduced in all Armies.

Principle

The principle, on which the ANR is based, is the possibility to superimpose acoustic waves. Figure 3 shows, that if two acoustic signals are generated, one being in opposite phase to the other the measured pressure on the line of symmetry will be 0. This principle is applied for the so-called ANR (Active Noise Reduction) hearing protectors. In this case (figure 4), the residual noise in the cavity underneath the ear cup is cancelled by an "anti"-noise generated by a loudspeaker, whereas the higher frequency components of the noise are attenuated by the passive acoustic isolation of the shell.

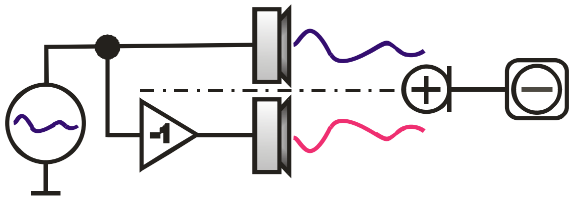


Figure 3: Scheme of the basic principle of ANR

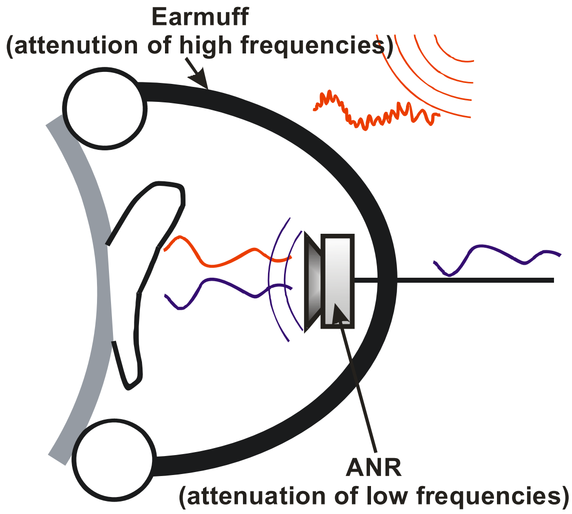


Figure 4: Principle of ANR underneath an earmuff

There are two basic possibilities to implement active control underneath a hearing protector:

Feed-forward

This principle is based on the prediction of the pressure signal in the cavity from a measurement of the noise outside the hearing protection. To do this, the measured acoustic signal is filtered with the same filtering function (figure 5) as the acoustical signal by the earmuff. In addition, the electrical signal is inverted before being reproduced with the loudspeaker inside the cavity. As the acoustical transfer function of the ear cup is not constant; it depends on different factors (wearer of the device, fit on the head, location of the sound source with respect to the reference microphone …), the control cannot be done by using fixed analog filters. More complicated digital control schemes have to be used. These adaptive algorithms (e.g. Fx-LMS) continuously optimize the coefficients of the digital filter in order to obtain a minimum signal power at the place of the error microphone inside the cavity (figure 5). If the external noise is stationary (no change in level and/or spectrum) the error signal will converge to a minimum and the protector will have its best performance. However if the noise is not stationary (level and/or spectrum are fluctuating), as it will be observed inside most vehicles, the algorithms will continuously restart the adaptation and maybe never be able to converge to the optimum effectiveness. This is the main reason why this type of control is only used in experimental devices for helicopters [5] where the noise, once the aircraft is in the air, may be considered to be stationary.

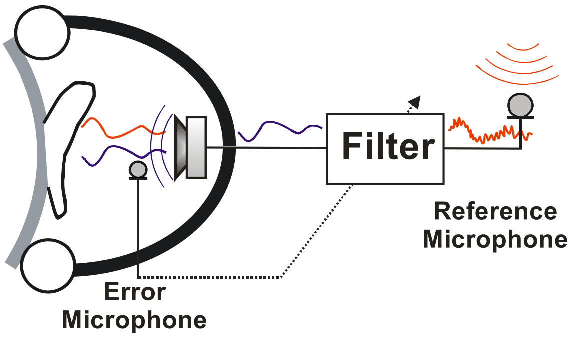


Figure 5: Principle of a feed forward control

Feedback

This control principle works independently of the noise outside of the hearing protector. It is based on the measurement of the residual noise in the cavity of the earmuff. The basic principle of a feedback control system is represented in figure 6. The residual noise in the cavity is recorded; its polarity is inverted and this signal is fed back underneath the muff. A system as it is shown in figure 6 would be instable in normal situations and therefore some precautions have to be taken.

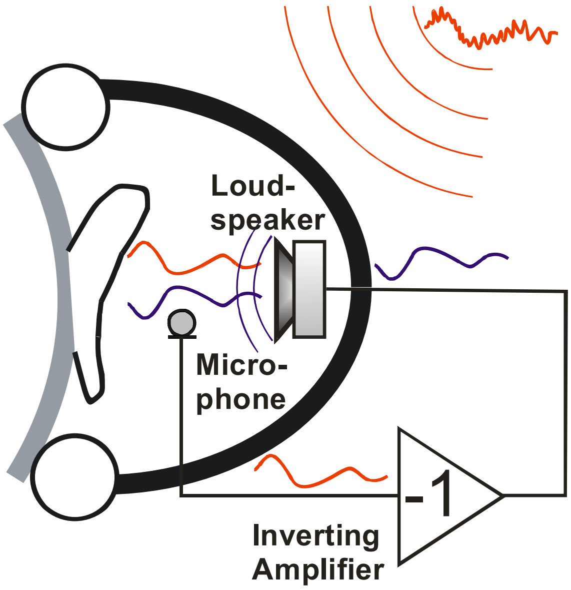


Figure 6: Basic principle of ANR using feedback control

Figure 7 a shows a schematic representation of all elements participating in the feedback loop of an ANR system. The electrical equivalent of this representation is shown in figure 7 b. It takes into account the transfer functions of all electric and the electro-acoustic elements. The active attenuation of such a feedback system can be represented as the modula of its closed loop transfer function *Bc* which is expressed as

$$B_c = \frac{1}{1+B_o}, \qquad (1)$$

Bo being the open loop transfer function,

$$B_o = \frac{V_{out}}{V_{in}} = F \cdot A_1 \cdot A_2 \cdot K_m \cdot K_t \,. \qquad (2)$$

The active attenuation expressed in dB is

$$A_{ANR} = 20 \cdot \log(|1 + B_o|) \ \ [dB] \quad . \tag{3}$$

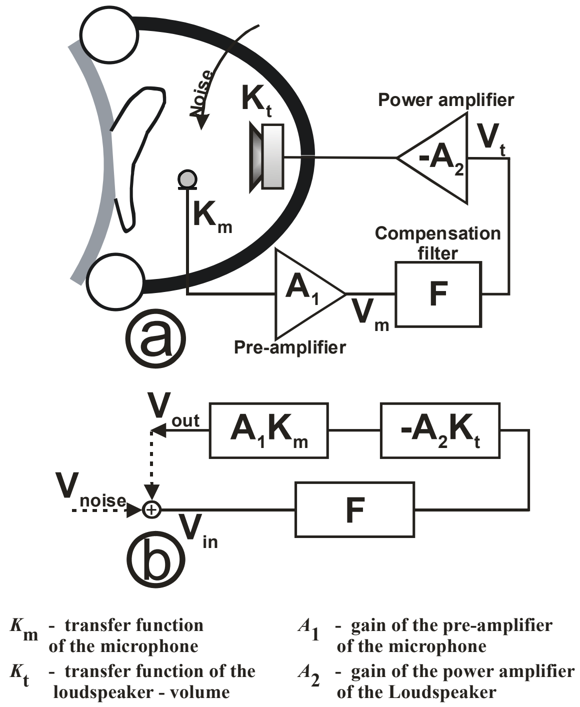


Figure 7: (a) Different electrical and electro-acoustical elements of the ANR system.
(b) Equivalent block diagram of the opened (solid line) and closed (solid + dotted line) feedback loop

(1) and (3) show, that the stability and the active attenuation of the feedback system are determined by the open loop transfer function Bo. Three distinct cases have to be considered:

1. $|1+Bo| > 1$ → $Bc < 1$ and $A_{ANR} > 0$ dB — The noise is attenuated

2. $0 < |1+Bo| < 1$ → $Bc > 1$ and $A_{ANR} < 0$ — The noise is amplified

3. $|1 + Bo| = 0$ → Bc and A_{ANR} are not defined — The system is instable

As A_1 and A_2 are linear amplifications and the transfer function of the microphone can as well be considered to be flat, the ANR capability is only dependant on the frequency response of loudspeaker + volume underneath the cup (*Kt*) and of the transfer function of the compensation filter (*F*).
Once the choice of the loudspeaker is done and the acoustics of the volume of the passive protector is defined, the ANR performance is fixed with the choice of the compensation filter. The shape of this filter controls the stability and the contribution of the ANR [6].

Insertion of communication (speech) signal
As ANR hearing protectors are always used where the user has an important need for communication the insertion of the communication signal is very important. Two methods for the insertion of such a signal are used:

- acoustic addition via a second loudspeaker
- electric addition into the feedback loop

In figure 8 a schematic for the insertion of the communication signal (Se) is drawn. Underneath the shell of the hearing protector, the acoustic signal is treated as if it were noise and can be formulated:

$$S_A = S_e \cdot A_s \cdot K_s \cdot \frac{1}{1+B_o} \qquad (4)$$

$$\text{with } B_o = F \cdot A_2 \cdot K_t \cdot A_1 \cdot k_m$$

two frequency ranges may now be considered:
- |1+Bo| >1 and |Bo|>1 → range of ANR;
  the transfer function of the communication is:

$$\frac{S_A}{S_e} \approx \frac{A_s \cdot K_s}{F \cdot A_2 \cdot K_t \cdot A_1 \cdot k_m} \qquad (5)$$

- |1+Bo| < 1 → outside of the range of ANR;
  the transfer function of the communication is:

$$\frac{S_A}{S_e} \approx A_s \cdot K_s \qquad (6)$$

If for the two paths identical loudspeakers and power amplifiers are chosen,

$$\text{(5) becomes } \frac{S_A}{S_e} \approx \frac{1}{F \cdot A_1 \cdot k_m} \quad (7)$$

and

$$\text{(6) becomes } \frac{S_A}{S_e} \approx A_2 \cdot K_t \qquad (8)$$

As A_1 and K_m may be considered to be independent of the frequency, the transfer function of the speech signal depends only on the compensation filter at low frequencies (ANR range) and on the loudspeaker for frequencies outside the ANR range. If a one-loudspeaker system is used, the formulae (7) and (8) are valid if the signal is inserted after the compensation filter F (red insertion point in figure 8).

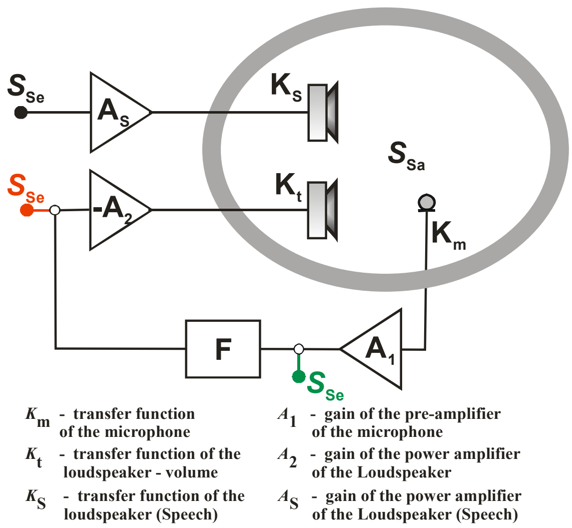


Figure 8: Insertion of a communication signal into an ANR system

Another insertion point for the communication signal is marked in green. If the signal is inserted at this point the transfer function of the speech signal is:

$$\frac{S_A}{S_e} = \frac{F \cdot A_2 \cdot K_t}{1 + F \cdot A_2 \cdot K_t \cdot A_1 \cdot K_m} \tag{9}$$

In this case the communication signal in the frequency range of the ANR will be :

$$\frac{S_A}{S_e} \approx \frac{1}{A_1 \cdot k_m}$$

and outside the range of ANR

$$\frac{S_A}{S_e} \approx F \cdot A_2 \cdot K_t$$

This means that the transfer function of the communication channel is "flat" in the low frequency range. However, the gain of the compensation filter is, for stability reasons, much lower than 1 in the frequency range outside the ANR bandwidth. Therefore this insertion path is not suitable for a good intelligibility of the speech.

The best speech transmission is performed when the speech signal is inserted at two points [7], one before and one after the compensation filter of the feedback loop as it is shown in figure 9. The speech transfer function is represented as:

$$\frac{S_A}{S_e} = \frac{A_2 \cdot K_t \cdot (1 + A \cdot F)}{1 + F \cdot A_2 \cdot K_t \cdot A_1 \cdot k_m} \tag{10}$$

if |Bo| > 1 and A.F > 1 ; $\frac{S_A}{S_e} \approx \frac{A}{A_1 \cdot k_m}$

and if |Bo|<1; $\frac{S_A}{S_e} \approx A_2 \cdot K_t \cdot (1 + A \cdot F)$

Using this scheme, the low and high frequency range become independent of the transfer function of the loop compensation filter. If necessary, the speech transfer can be optimized by a pre-filtering of the speech F_2. A transfer function of the communication channel with the ANR switched on and off is drawn in figure 10. It can be seen that, if the ANR is switched on (blue curve), the transfer function is "flat", whereas it follows the curve representing "ANR off" for higher frequencies. The use of two insertion points for the speech transmission is without any doubt the most elegant way to obtain an optimum speech quality with ANR hearing protectors, especially if the speech spectrum is pre-filtered (F_2 in Figure 9).

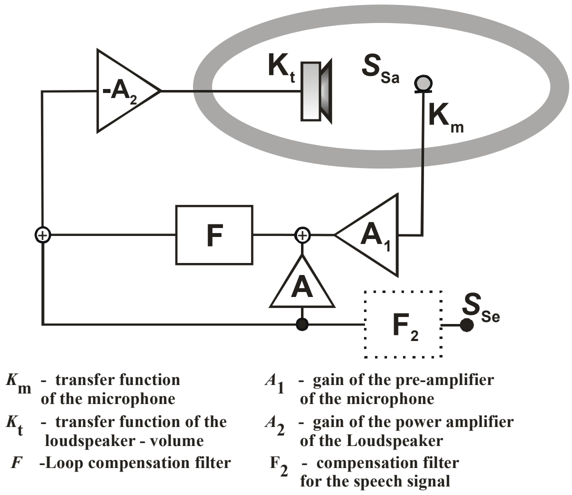


Figure 9: Schematic for the insertion of a communication signal at two points.

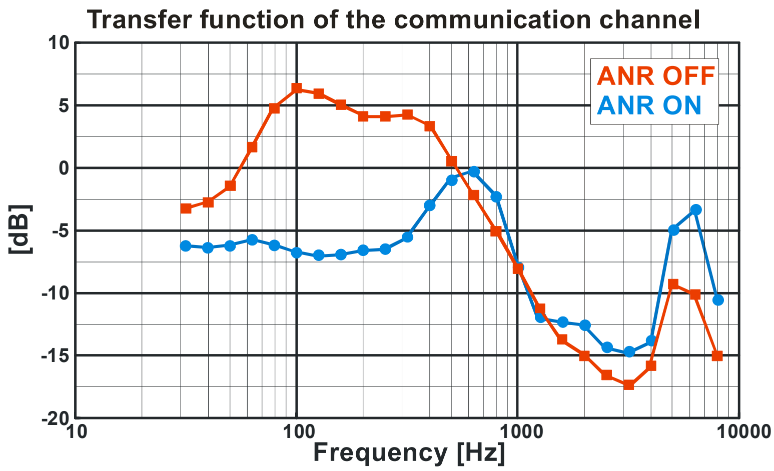


Figure 10: Transfer function of the speech transmission when inserted at two points (fig.9)

The use of a two-loudspeaker system is attractive for military use, as the communication system stays fully operational even if the ANR system has to be shut down for some reason.

Implementation

The physical implementation of an ANR system is usually devised into two parts:

- the electro-acoustical part contains, the loudspeaker, the error-microphone and their peripheral electronics (pre- and power-amplifiers etc.) as well as the hardware of the hearing protector (volume, damping material …).
- the feedback compensation filter.

These two parts contribute to the open loop transfer function (Bo) of the ANR system which is determining the ANR capabilities of the protector. The transfer function of the electro-acoustic contribution to Bo is determined

- by the choice of the microphone. This choice is usually not critical. The response of microphones is normally quite flat in the required frequency range.
- by the choice of a loudspeaker. The loudspeaker has to be compatible with the noise level it has to cancel. It should have a good efficiency over a large frequency band. Resonances within this band should be avoided as they lead to undesirable phase shifts.

- by the mechanical implementation of the microphone and the loudspeaker into the volume of the earmuff. This implementation has a big influence on the passive protection of the device as well as on the ANR efficiency and bandwidth. It also represents often a compromise between the requirements of ANR and the need for passive attenuation. E.g. the effective volume in front of the loudspeaker should not be too small in order to maintain passive attenuation at low frequencies. But in order to avoid resonances in the lower frequency range it should not be too large either. A good placement of the microphone is in front of the center of the membrane of the loudspeaker. There is no need to put it too close to the membrane. The acoustic wavelength that are involved (1 kHz corresponds to 30 cm) are always very long compared to this distance.

The choice of the transducers and of their mechanical implantation fixes the electro-acoustic transfer function (denominated K_t and K_m in earlier figures). In figure 11 the electro-acoustic transfer function of an actual device is shown. Once this function is determined, it is the design of the feedback compensation filter that controls the final efficiency of the ANR system: it is possible to tune the ANR device, within limits given by the need of stability, to get optimal performance for a given noise environment.

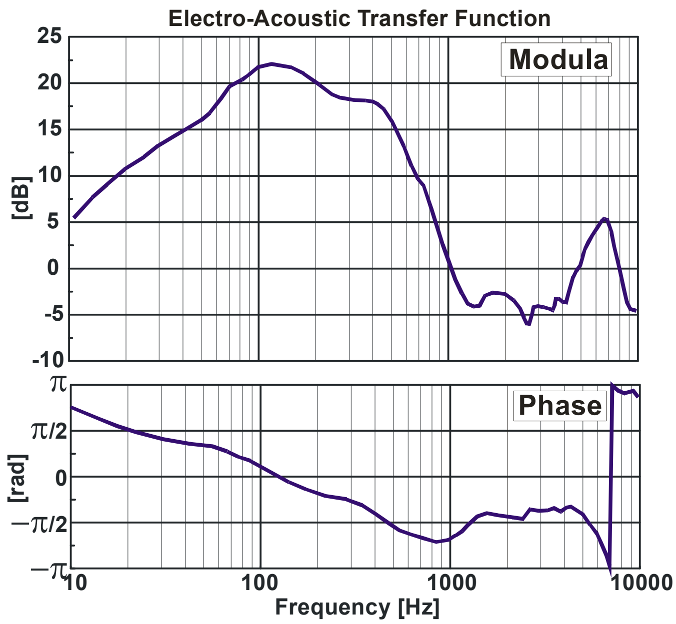


Figure 11: Electro-acoustic transfer function (amplitude, phase) of an ANR system.

Analog or digital filtering
In all ANR systems that are presently available on the market, the compensation filter is implemented in analog technologies. These systems are easy and cost effective to implement as far as large series are produced. However, if the active attenuation must be optimized for actual noise at the listener's place, analog systems need hardware modification in order to change the ANR characteristics (figure 12). Digital ANR systems, however, only need the download of a new parameter set. Figure 13 shows the ANR that has been obtained when the same electro-acoustic hardware has been used with 3 different coefficient sets in the digital filter. Although the analog systems are mostly used, digital systems have the potentiality to allow specific adaptations for the noise environment, a feature that will be most important for severe noise exposures where the ANR has to be optimized in order to set acceptable noise levels for different users.

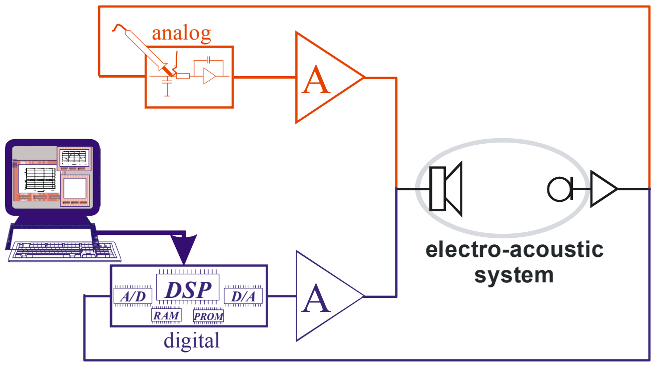


Figure 12: Analog (blue) and digital (red) controlled ANR system

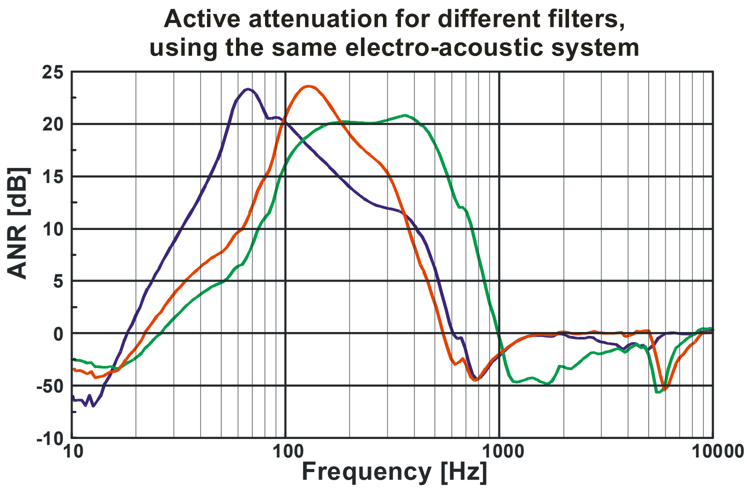


Figure 13: ANR obtained using three different digital filters with the same electro-acoustic hardware.

Performance of ANR hearing protectors

Protection against noise

For ANR hearing protectors, as for any other personal protection device, performance does not only mean to show a certain amount of attenuation or to fulfill some standard's requirements. It also means, especially in the military context, that it will allow better performance if worn. So it is important to verify if the problems that have been denominated earlier in this paper are resolved with this type of device. Figure 14 shows the capabilities as far as the protection is concerned. The blue curve represents the Insertion Loss of the passive hearing protector (the ANR system is switches off). It displays the typical curve for a passive earmuff. The protection effect is close to 0 dB for frequencies below 100 Hz, for higher frequencies it increases. If the ANR system is switched on, we can see that the IL in the frequency range up to 500 Hz is increased. The contribution of the ANR to the insertion loss is drawn in figure 15. It can be clearly seen, that the bad efficiency at low frequencies, inherent to passive circumaural hearing protectors, may be corrected by ANR systems. In figure 16 the A-weighted exposure levels when using the passive protection (figure 14) is represented for the commander and the pilot of a tank. The levels to which the crews are exposed are still too high if realistic exposure times are required. The allowance of 19 minutes for the commander and of 6 minutes for the pilot of the tank cannot be considered to be sufficient. Figure 17 shows the same situations but with an ANR earmuff. Adding active attenuation for this type of noise, changes the acceptable exposure time dramatically (3 h for the commander and 1h30 for the pilot). It shows also, that if the exposure time for the pilot has to be increased, this can only be done by a still better attenuation in the 100 Hz third octave band. As long as this is not decreased to at least 85 dBA, a better attenuation for higher frequencies will not have any influence. However, in the case of the commander of the tank it would be necessary to attenuate the noise between 500 and 1000 Hz if a longer exposure time is required. In figure 18 the acceptable exposure times are shown for different configurations and for crew members equipped with passive or with active hearing protectors. This example shows, that ANR equipped earmuffs are able to give the protection that is necessary to obtain sufficient exposure time for the crew of an armored vehicle at the efficiency of these devices in terms of A-weighted exposure level, for the noise inside a tank.

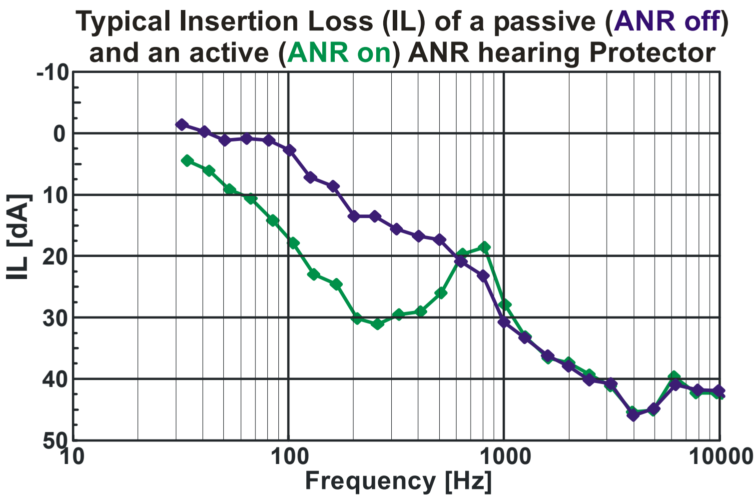


Figure 14: Insertion Loss (IL) for an ANR Hearing Protector wit ANR switches ON and OFF

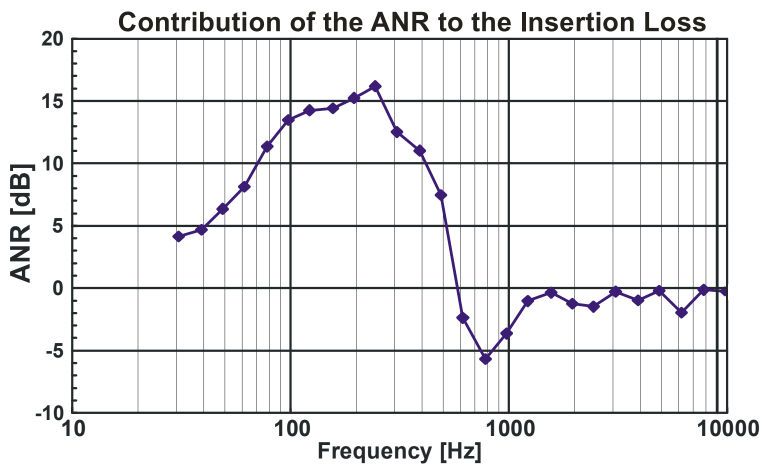


Figure 15: Contribution of the ANR to the insertion loss of an active hearing protector

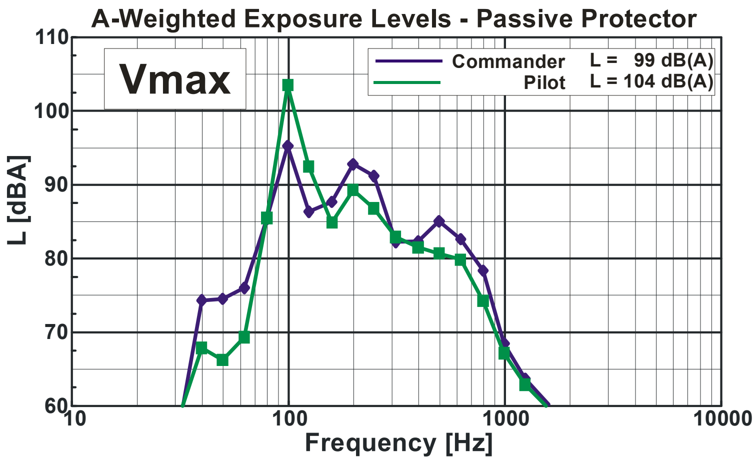


Figure 16: A-weighted third octave band exposure levels for the commander and the pilot of a tank when protected with a passive hearing protector.

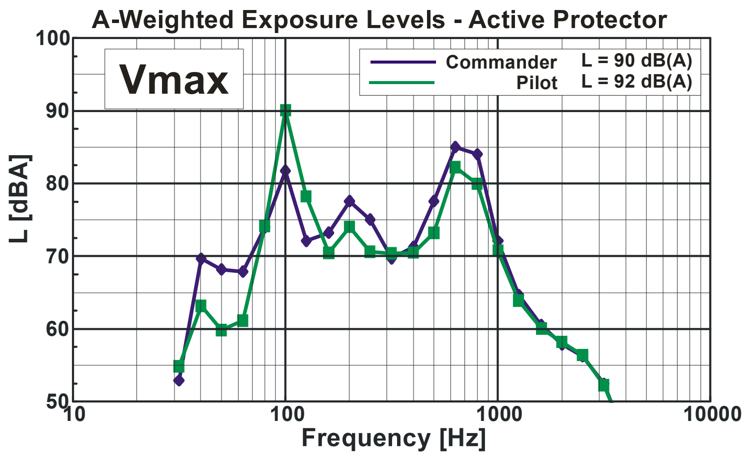


Figure 17: A-weighted third octave band exposure levels for the commander and the pilot of a tank when protected with an ANR hearing protector.

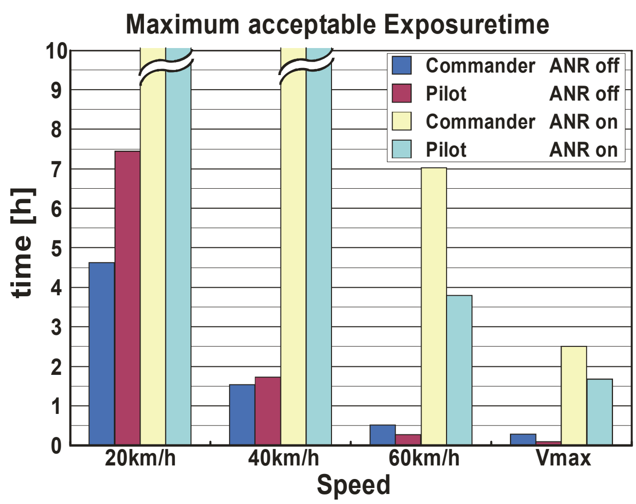


Figure 18: Maximum exposure times at different places (commander or pilot) and for different running conditions of the tank when using active or passive hearing protectors.

Influence of ANR on Speech Intelligibility

Measurements underneath the hearing protectors of tank crews [8] have shown that the noise exposure of the crew of armored vehicles during speech communication is very high and may be comparable to the exposure level without hearing protector. In figure 19 exposure levels for the pilot of a tank are drawn for three conditions:

- The pilot wears no hearing protection (blue line). The linear noise level for this condition is 128 dB(lin) or 112 dB(A). This means an acceptable exposure time is ~1 minute per day.
- The pilot wears a passive hearing protector (green line). It can be observed that the level of the mid and high frequencies is attenuated but as there is no attenuation at low frequencies, the exposure level remains high (121 dB(lin), 104 dB(A)). The maximum exposure time is still short (6 minutes).
- The pilot receives a message through the communication system underneath the passive hearing protector (red line). Although the soldier wears his hearing protection, the A-weighted exposure level is 110 dB (1.5 minutes) maximum exposure time.

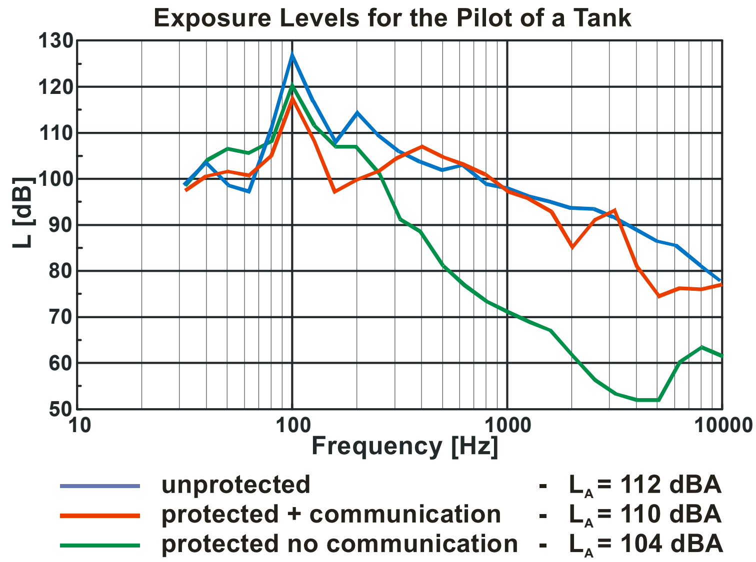
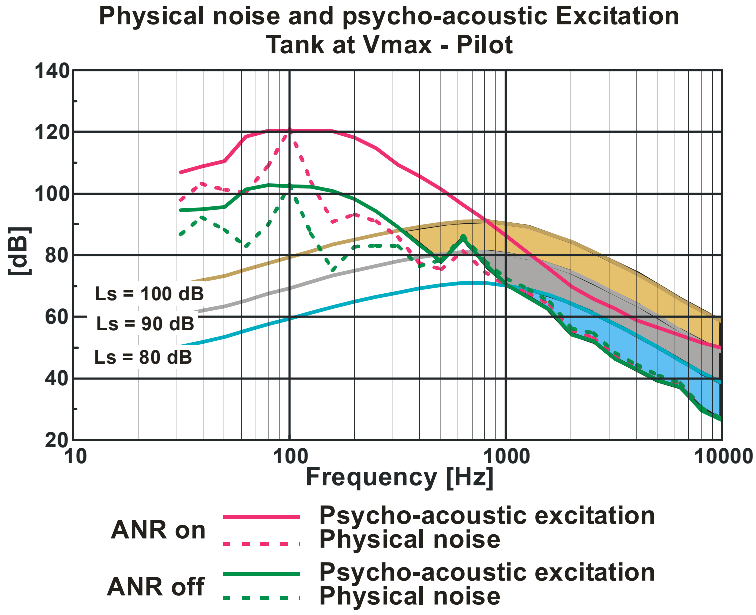


Figure 19: Exposure Levels of the Pilot of a Tank at Vmax for different conditions.

In a first approach it seems unusual that such a high speech level has to be used by the soldier in order to obtain an acceptable intelligibility, especially, as the noise in the frequency range that is important for intelligibility is already well attenuated. This high speech level can be explained by two effects:

- The psycho-acoustical masking of the high frequency components of the communication by the low frequency components of the noise.
- The bad quality of the transmission channel.

In fact, both of these effects have a part of responsibility for this effect. The transmission quality is degraded as, due to masking, a high communication level is needed. Due to the degraded signal, a higher level is needed for good intelligibility. In order to confirm this assumption, the calculation method of the STI (Speech Transmission Index) has been modified by Wessling [8]. The modification consisted in the use of real, level depending, masking curves for the calculation of the signal to noise ratios. In figure 20 the masking curves (solid lines) and the third octave spectra of the physical noise (dashed lines) are drawn for the noise to which the pilot of a tank is submitted when wearing an ANR earmuff (red curve – ANR off; green curve – ANR on). The spectrum of speech is represented for 3 different levels (80, 90 and 100 dB). For the exposure with the ANR switched off, the speech is not masked by the noise (dashed red line) but by the psycho-acoustical excitation (solid red line). In this condition, the area of speech at 80 dB (blue area) is fully masked. As for a good intelligibility the Speech Transmission Index (STI) should be about 0.6 a speech level of about 100 dB has to be used (see table in figure 20). When switching the ANR on, only the noise exposure at frequencies lower than 500 Hz is decreased. But, as at the upper spread of making is, (a) induced by the high noise levels at low frequencies, (b) nonlinear (the masking at higher frequencies decreases faster that the level of the masker), the speech spectrum is now only masked by the physical noise. As a consequence the unmasked area of speech increases considerably and the level of speech, required for good intelligibility (STI > 0.6) is already reached at 80 dB.



	ANR off	ANR on
Ls = 80 dB	STI = 0.157	STI = 0.575
Ls = 90 dB	STI = 0.397	STI = 0.784
Ls = 100 dB	STI = 0.656	STI = 0.879

Figure 20: Noise exposure of the pilot and its impact on the quality of speech

This example shows that if the noise exposure has strong low frequency components, ANR will be very beneficial to the intelligibility and help to avoid unnecessary noise exposure due to communication.

Response to impulse noise

When ANR hearing protectors are used by soldiers, it is important to know, how these devices will behave when exposed to weapon noise. In theory, these devices should reduce the noise level of impulse noise in the same way they reduce continuous noise. In reality, the transducers and the electronics are usually not able to handle the levels that occur in such situations. Figure 21 shows the contribution of the ANR when the protectors are exposed to impulse noise with different peak pressure levels. It can be observed that per Noise impulses with a peak level up to 150 dB (red and green curve) the contribution of the ANR is the same as for continuous noise (black line). For the higher peak pressure levels (blue and mauve curves) the contribution of the ANR breaks down. The reason for this diminution can be seen in figure 22.

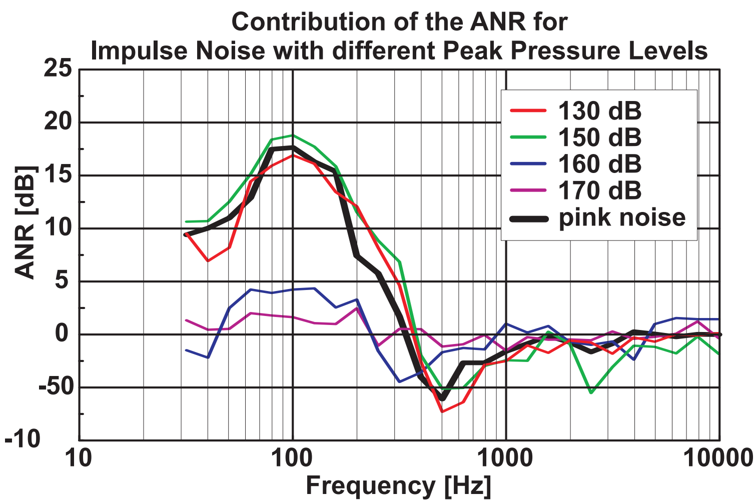


Figure 21: Contribution of the ANR for impulse noise (explosion) with different peak pressure levels and for continuous noise.

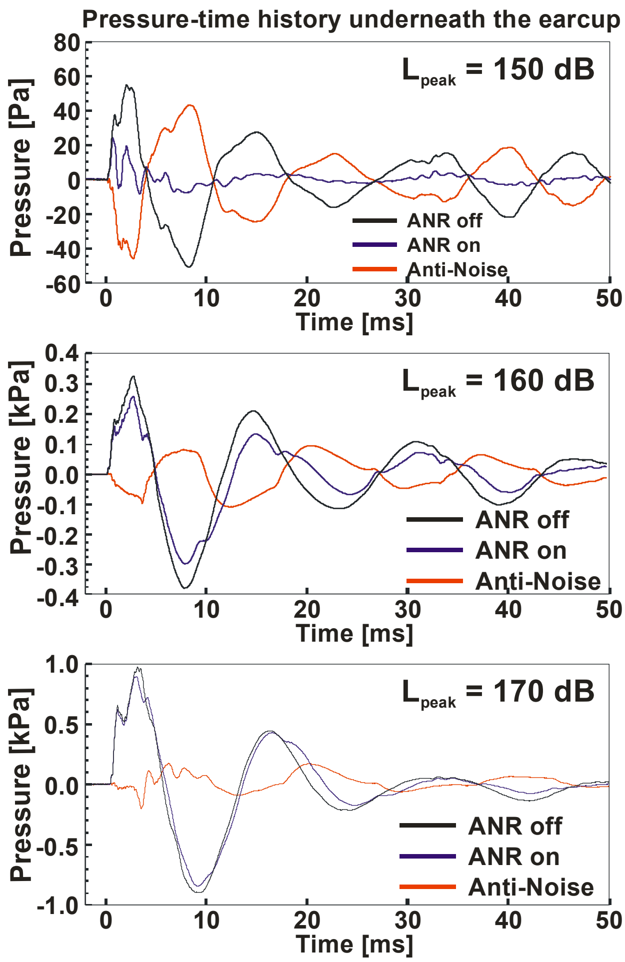


Figure 22: Pressure time histories underneath the hearing protector, when exposed to impulse noise.

In this figure the pressure-time histories underneath the earmuff are displayed for three impulse noises with different peak levels. For each level, the peak pressure history with the ANR switched on (blue) and off (black) is drawn. The red curve represents the difference between these curves; it can be assimilated to the "cancellation" pressure or "anti-noise". It can be observed, that the peak pressure of the 150 dB impulse noise is reduced by about 10 dB when the ANR is switched on, whereas no significant (~1 dB) can be measured for higher peak pressure levels. When looking at the curves of the "anti-noise" (red curves) it can be seen, that for the 150 dB peak level no saturation of the signal is present. For the two higher levels, the "anti-noise" is limited to a pressure of about 100 Pa (134 dB). Apparently the electro-acoustic system cannot produce higher pressures in the bandwidth where the ANR is attenuating.

ANR Earplugs

Need

The use of active headsets is appropriate when supplementary protection against low frequency noise and good communication are needed. This is typically the case for crewmembers of armored vehicles, propeller aircraft or helicopters. For other noise sources like jet engines the use of ANR earmuffs will not bring any supplementary protection. In figure 23 a typical third octave band noise close to a fighter aircraft (position of ground support during takeoff) is compared to noise inside an armored vehicle. It can be seen that the maximum level for the jet engine noise is situated at frequencies (>600 Hz) where the ANR in earmuffs is no more effective (figure 15). Worse, the ANR system amplifies the residual noise just at these frequencies (figure 16). For the jet engine noise A-weighted exposure levels when using different hearing protectors are shown in figure 24. We can see that the exposure level when using ANR in an earmuff (dashed black line) is increased by 1 dB, compared to the same earmuff with the ANR switched off (solid black line). The use of standard earplugs (blue line) reduces the exposure level to 101 dBA. However this level is still too high to guarantee a sufficient exposure time allowance and a good quality of the communication. The problem can be solved if an ANR earplug is used. The contribution of the ANR should be:

ANR = 5 dB for f < 200 Hz
ANR = 10 dB for 200 Hz < f <1500 Hz
ANR = 5 dB for f < 1.5 kHz < 3 kHz
ANR = 0 dB for f > 3 kHz).

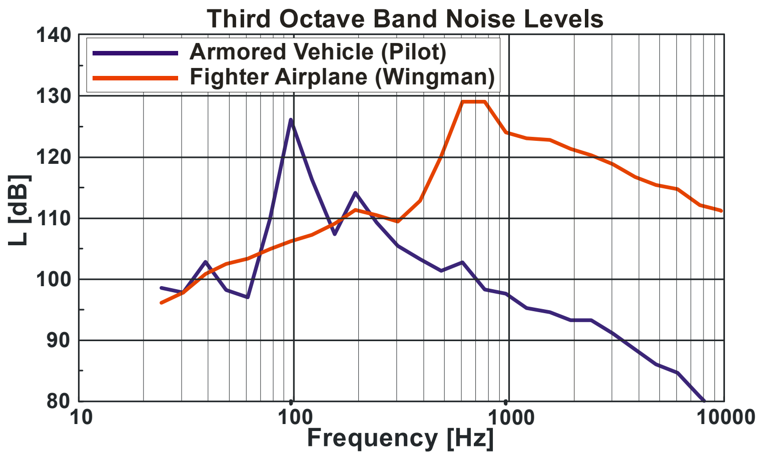


Figure 23: Third octave band noise levels near a fighter airplane and inside an armoured vehicle

The use of such an ANR earplug (green curve in figure 24) will bring the exposure level to 93 dBA.

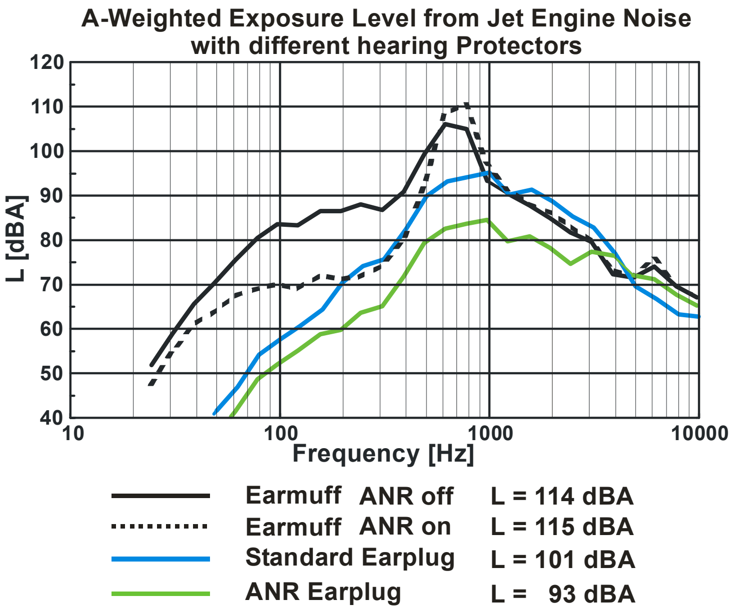


Figure 24: A weighted exposure levels near a fighter airplane when using different hearing protectors

Possible transducers

As the bandwidth of ANR earmuffs is limited by the size of the transducer and the volume underneath the shell, the use of smaller transducers close to, or in, the ear canal should allow a larger range for the ANR. In figure 25 two possibilities for the implantation of an ANR earplug are shown:

- the "close to the ear canal" ANR earplug.
- the "in the ear canal" ANR earplug.

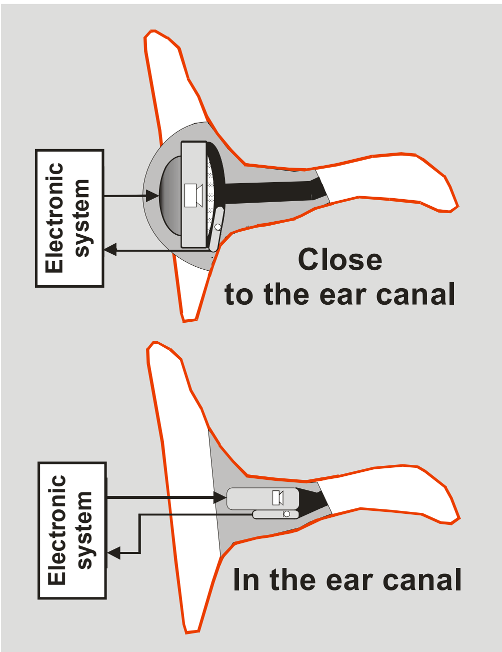


Figure 25: "Close to the ear canal" and "in the ear canal" position of the transducers in an active earplug

For the "close to the ear canal" system walkman-type transducers can be used. However, the characteristics of these transducers, resonances at medium frequencies, do not allow to extend the bandwidth far enough [9]. In order to overcome the problems that are characteristic to the walkman-type transducer, a miniature piezo-ceramic transducer has been developed [10]. Figure 26 shows the design and the electro-acoustic transfer function of this device. The electro-acoustic transfer function is almost flat over the whole frequency range. The first resonance is situated at about 20 kHz (not on the plot) and has not a strong influence on the ANR. Two simulated ANR curves (red and blue solid line) are drawn in figure 27. One has been optimized for maximum ANR amplitude, the other for a maximum bandwidth. The maximum ANR amplitude is about 22 dB at 200 Hz and the higher ANR limit (0 dB crossing) is at 1.5 kHz. The experimental values (dots) are in good agreement with the simulated values. The simulated maximum bandwidth curve (blue solid line) shows that the objective of an effective ANR up to 4 kHz can almost be reached with this type of transducer. There is only one major problem with this technology; due to its low sensitivity the voltage that is needed to produce significant pressure levels (in the order of 100 dB) is substantially higher than 100 Volts. This voltage is too high to be applied to a personnel protection device. However emerging technologies may allow to increase the sensibility by a tenfold or more, and in this case the use of piezo-ceramic transducers will be reconsidered.

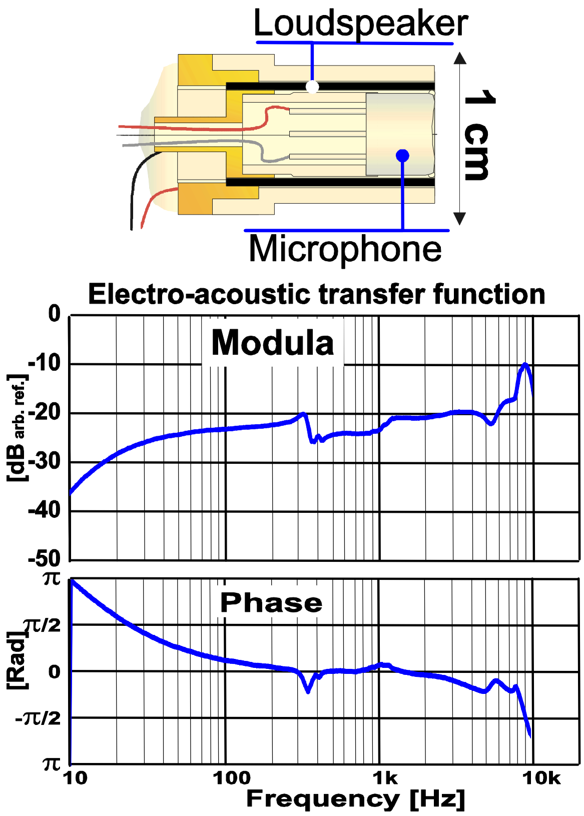


Figure 26: Piezo-ceramic ANR earplug and its electro-acoustic transfer function

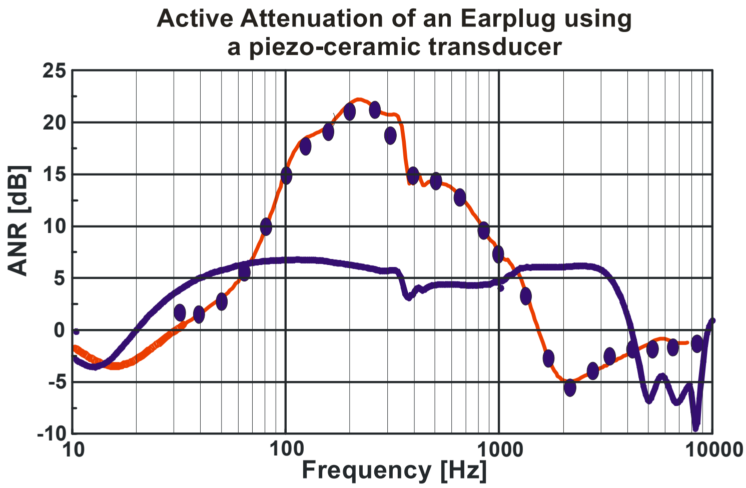


Figure 27: ANR earplug using a "hearing aid"-type receiver and the electro-acoustic transfer function of the system

Another type of transducers to be used for "in the ear canal" ANR systems are "hearing aid"-type receivers. These miniature loudspeakers are small enough to fit into the ear canal and they are sensitive enough to produce the needed pressure levels. Figure 28 shows such an experimental earplug and the transfer function of the electro-acoustic system when adapted to an ear simulator. The photograph shows that the loudspeaker (receiver) and the microphone are hosted inside the casing in a way that there is only a minimum distance between those two elements. This is necessary to keep the delays due to the distance between receiver and microphone as small as possible. The plug has been designed in a way to obtain a minimum of total volume underneath the earplug (volume in front of the transducer + residual volume of the ear canal).As a consequence, the efficiency of the receiver is increased at low frequencies, and the resonance of the volume of the ear canal is at a high frequency.

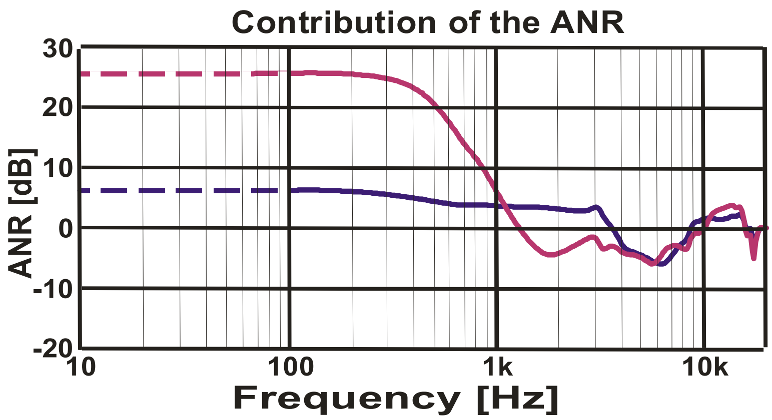


Figure 28: ANR of an active earplug using "hearing aid"-type receivers

The electro-acoustic transfer function of this configuration is shown in figure 28. Although the transfer function of this system is not as flat as that of the piezo-ceramic transducer (there are two distinct resonances at frequencies below 10 kHz) it allows good ANR performance. Simulations of the ANR contribution have been made as shown in Figure 29. One curve (blue) shows the ANR when compensated for maximum bandwidth, the other curve (red) represents the ANR when calculated for maximum level. The low frequency part of this simulation has been kept artificially. If compared to the results with a piezo-ceramic transducer, the bandwidth when yielding maximum ANR is comparable. However, the maximum bandwidth of the ANR is smaller and the ANR level is lower in this case. The reason of this lower performance seems to be a delay that is present in earplugs using electromagnetic receivers and not in those using piezo-ceramic transceivers. Up to now, the reason of this time lag is not clear. It does not seem to be of acoustic origin but to originate from the mechanic and/or magnetic properties of the receiver. If the cause of this delay is found and if it can be corrected, the ANR performance of an ANR earplug with an electro-magnetic receiver could become the same than the simulated ANR performance of the mechano-electrical model in figure 30.

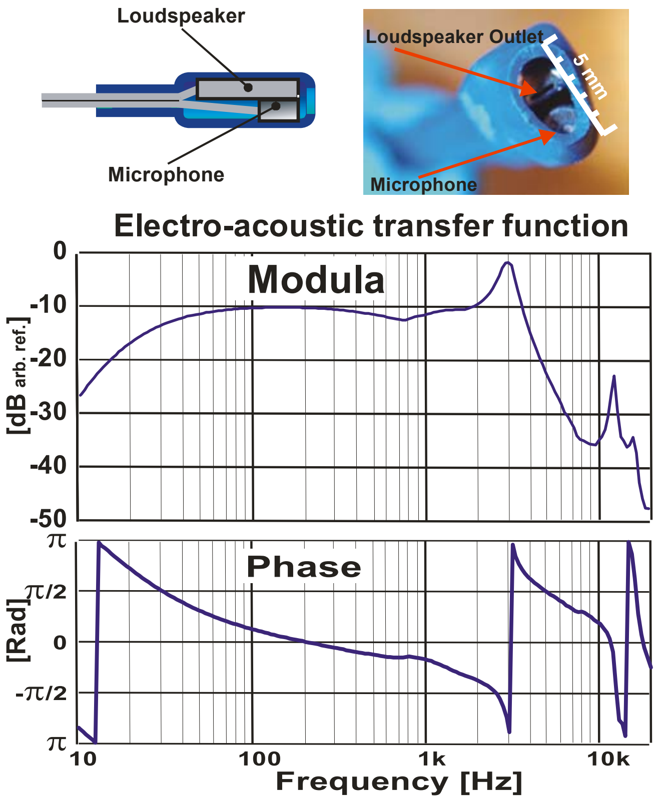


Figure 29: ANR earplug using a "hearing aid"-type receiver and the electro-acoustic transfer function of the system

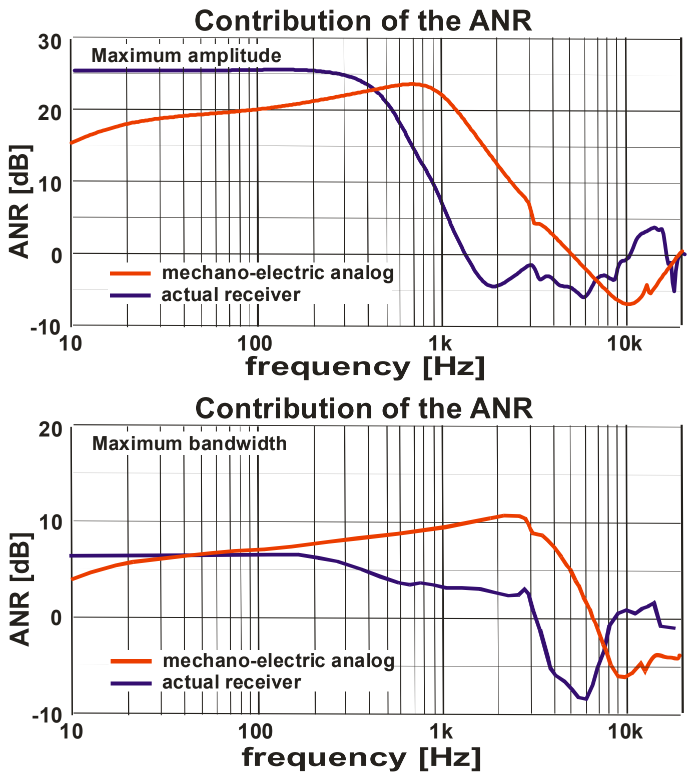


Figure 30: Contribution of ANR in an active earplug with an actual receiver (blue) or the electro-mechanic analog (red)

Conclusions

When military personnel is exposed to noise with high levels having a very strong low frequency component (armored vehicles, helicopters, propeller driven airplanes …) ANR headsets are a good choice as personnel hearing protector. With the help of the ANR system (complementary to the passive protection of the headset by itself) the efficiency of the soldier is increased. In the frequency range below 500 Hz an ANR headset has an insertion loss that is about 15-20 dB better than a standard hearing protection. This improvement leads to

- longer acceptable exposure times. This means longer and more representative training scenarios.
- better intelligibility at the same speech level. This leads to a better success rate for missions.
- lower noise exposure levels that will induce less fatigue and therefore lead to a better performance of the soldier.

The presently available analog ANR hearing protectors are without any doubt helpful in many situations. However, for some situations, it could be helpful to use more flexible digital ANR devices.

In some situations, e.g. ground personnel around jet airplanes, present ANR hearing protectors do not add any protection, in contrary the noise exposure could even increase. These personnel may be exposed to such high levels, that the performance of standard single or double passive hearing protection (ear cups and/or earmuffs) is not enough. Considering the requirements for such protection devices, only ANR earplugs (personal fit if possible) may be suitable. These future devices have to be designed in a way, that the contribution of the ANR at 3 KHz (and higher if possible) should not be less than 7 dB and not less than 10 dB for frequencies lower than 1.5 kHz. There is still some technical challenge to reach this performance.

Once arrived at this protection level, the next step for better hearing protection will be the limitation of bone conduction.

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