Development of a wireless "Communications EarPlug" for application in military aviation.

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A laboratory model of a wireless "Communications EarPlug" (w-CEP) was developed. Standard Communications EarPlugs (using wires) are known to offer relatively good intelligibility of intercom speech at high ambient noise levels. The intercom sound is produced by means of a commercially available miniature transducer, integrated in the earplug. With the w-CEP, the signal is transferred from the helmet to the earplug inductively. The w-CEP prototype performs well, in near-compliance with the many constraints imposed by military aviation.

0. Introduction

Speech communication between crewmembers is crucial in military aviation. Sufficient intelligibility of intercom speech must be obtained under all conditions, to ensure safe and effective operation of the aircraft.

Unfortunately, adequate intelligibility of intercom speech is often difficult to achieve, mainly because of the high ambient noise levels that are often found in military aircraft. Usually, all crewmembers use helmets fitted with earmuffs. These earmuffs attenuate the ambient noise; telephones placed inside the earmuffs are used to present the intercom audio. Hence, the earmuffs not only serve to protect crew members' hearing against the harmful effects of high noise levels; the function of the earmuffs is also to improve the signal-to-noise ratio of intercom speech. The signal-to-noise ratio is an important determining factor for the intelligibility of speech in noise [1, 2, 3].

Unfortunately, the attenuation of earmuffs alone is insufficient in some (rotary wing) aircraft [4].

To enhance the sound attenuation of earmuffs some alternative approaches are possible. Active Noise Reduction (ANR, attenuating the noise by adding the same noise in anti-phase) is successfully applied in earmuffs for some applications [5]. Unfortunately, ANR systems often tend to be unstable in high level ambient sound with strong extremely low-frequency noise components (such as the 10-20 Hz rotor frequency in some helicopters) [4]. Also, ANR systems are relatively costly. Another option is to use earplugs in addition to the earmuffs, the obvious disadvantage of which is that the intercom speech is also attenuated.

An approach that was first proposed by Mozo [6] is to integrate miniature transducers *in* the earplugs. Hence, the earplugs will attenuate ambient noise, but *not* the intercom sound, which is produced by the miniature transducers in the ear canal, behind the earplugs. This type of earplug with integrated miniature telephone was called "Communications EarPlugs (CEP)". An example of a laboratory model of a simple CEP-system is shown in figure 1.

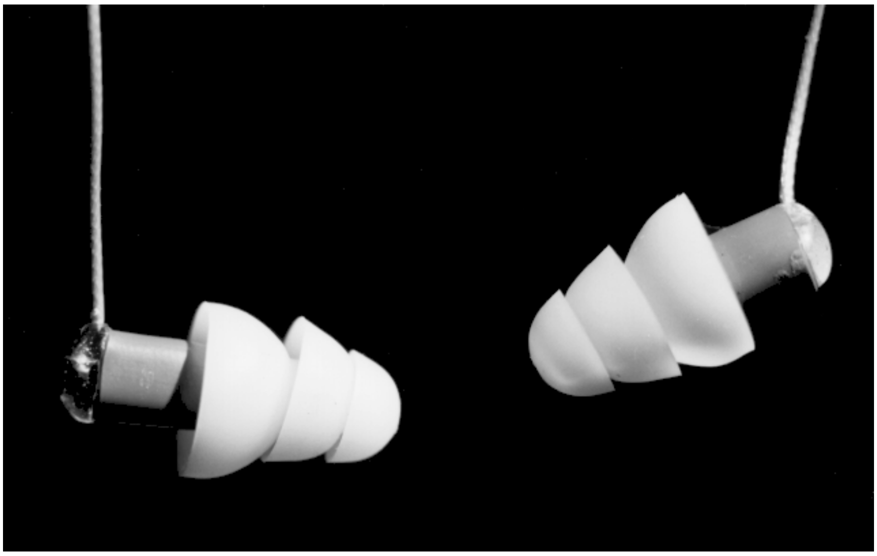

Figure 1. Laboratory model of a CEP system

Although military aviators have responded positively to the CEP-concept, the necessary use of wires (for the intercom signal) between the helmet and the earplugs is considered to be a drawback. These wires are not only a nuisance to connect each time the helmet is donned; the main problem is the fact that in the unpolished interiors of military aircraft, these vulnerable wires may get caught behind objects. This may (painfully) pull an earplug out of the crewmember's ear canal, or may even cause the system to malfunction, cutting of the crew member from the intercom system. An obvious solution to this appears to be to use some kind of wireless transmission [7]. Although this may be considered a worthwhile improvement on the CEP-concept, the implementation of a wireless connection is not without difficulty.

1. Wireless CEP design

1.1. Design constraints

Although the basic idea of a wireless connection between helmet and CEP is simple, there are many constraints complicating the design of a wireless CEP (w-CEP). For the w-CEP to be a serious competitor to conventional CEP and ANR systems, the design will have to be simple and inexpensive to manufacture. The use of batteries (which may run empty) in the earplugs is considered unacceptable, since battery-operated systems can not always be fully depended upon. This rules out many types of wireless connections (infrared, ultrasound, regular FM-radio, etc.). The receiver must be able to operate without a supply voltage; also, its dimensions must be small, since it will have to be fitted in an earplug.

The use of electromagnetic waves for transmitting the intercom signal from helmet to earplug now seems to be a logical choice; simple electromagnetic receivers may be constructed, that allow passive demodulation of transmitted signals with relatively few components (hence allowing for small dimensions of the receiver). However, the specific application to (military) aviation imposes additional constraints.

Strict ElectroMagnetic Compatibility (EMC) requirements are imposed on all systems used in aircraft, both in terms of radiation and susceptibility. Any electromagnetic field produced by the w-CEP system outside the helmet is considered to be unwanted "pollution" of the electromagnetic environment in the aircraft, which may potentially interfere with the operation of other equipment. Military standards [8] specify maximum field strengths that the w-CEP transmitter may produce. On the other hand, the w-CEP receiver must be insensitive to EM-fields generated by other equipment.

Also, health aspects connected with using EM-waves need to be considered. The human body may not be exposed to electromagnetic sources of exceedingly high field strengths, or the human tissue may suffer from potentially harmful effects (such as heating up, or the induction of electric currents).

Of course, apart from all of the secondary requirements imposed on the design the achieved speech intelligibility has to be equal or better than a standard CEP-system. The earplugs should also be able to generate A-weighted sound pressure levels at the tympanic membrane of at least 80 dB.

1.2 w-CEP principles

The principle of transmission for the w-CEP was chosen to be *magnetic* radiation. This may be achieved by using coils for transmission and reception, at close range. Electric currents in the transmitter coil induce -much smaller- currents in the receiver coil. The magnetic component of the EM-field is used to transmit the signal, as opposed to the use of the electric component of the field that is common in radio frequency transmissions.

By shielding of the transmission coil (covering the surface of the coil with a metal coating), the electric radiation is reduced. Since the magnetic field strength reduces greatly with distance, the overall electromagnetic radiation will be relatively small, except at close range. This means that the transmitter coil must be placed near the receiver (earplug). To be able to use w-CEP receivers (earplugs) at both ears, transmitter coils are placed inside each earmuff.

To minimize the influence of audio-frequency electromagnetic interference, the audio signal will need to be transmitted by making use of some type of modulation technique, on a carrier signal with a suitable frequency. For the w-CEP laboratory prototype, simple amplitude modulation was selected, the main reason being the possibility to construct very simple AM-detectors.

For reasons of convenience, a relatively low carrier frequency was chosen (90 kHz).

1.3. w-CEP laboratory model specifications

The design w-CEP laboratory model was intended to investigate the feasibility of a wireless CEP system. No effort was made to optimize the design in terms of power consumption, dimensions of the transmitter, and several other factors that *are* important in real-life avionics design. These matters are expected to be solved in a prototype design process relatively easily, and are not expected to threaten the feasibility of a w-CEP system.

The laboratory model of the w-CEP transmitter was mounted on a standard helmet used by helicopter crews (figure 2). Two separate transmitters were used for the left and right transmitter coils (figure 3). These transmitters share a single generator for the carrier wave, to avoid audible interference in the audio signal.

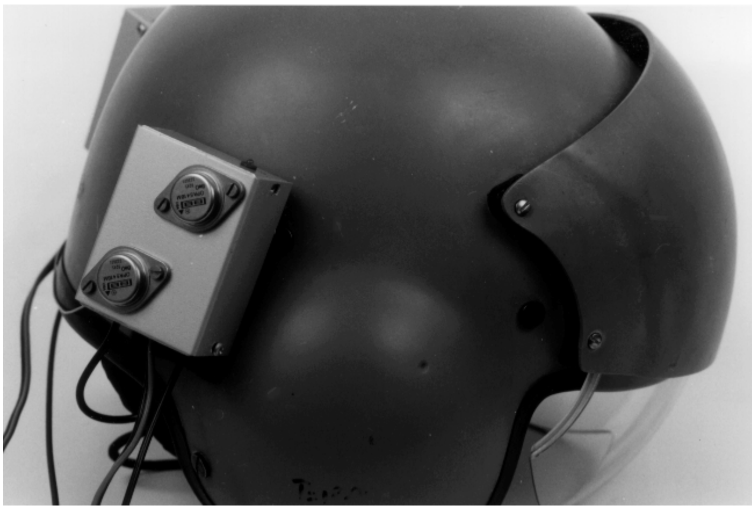

Figure 2. Helmet with w-CEP transmitters

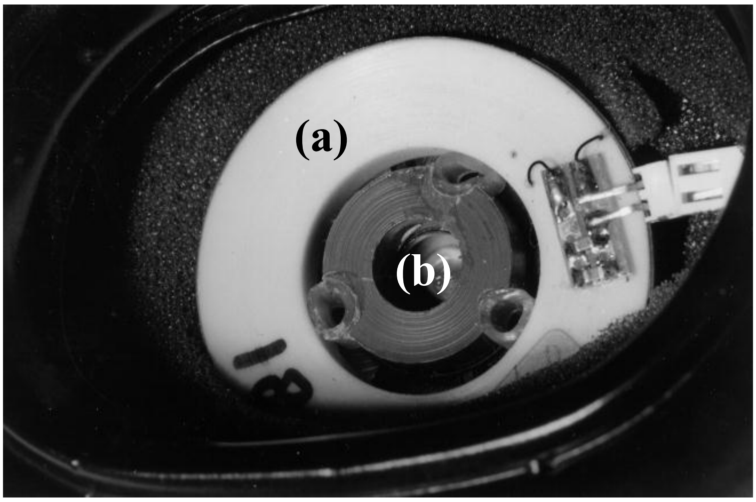

Figure 3. Inside of an earmuff, with a transmitter coil (a) and behind the transmitter coil a regular earphone (b) as a backup.

The transmitter coils were placed inside the earmuffs. Conventional earphones were also integrated in the earmuffs, to be used as a backup system in case of failure of the w-CEP system.

The earplugs (with integrated AM-receiver and miniature earphone) are shown in figure 4, together with an artificial ear to indicate the scale. The earplug is both shown as placed in the ear, and separately.

Figure 4. Wireless Communications Earplug receivers (in an artificial ear and separately).

The design of the receiver is very simple; a single diode, the receiver coil and two capacitors are used (together with a Knowles ED-7288 miniature transducer) to construct a classic single tuned LC-circuit AM-receiver using half-wave rectification. The ‘receiver coil’ is a simple SMD-inductance.

A block diagram of the *transmitter* is given in figure 5.

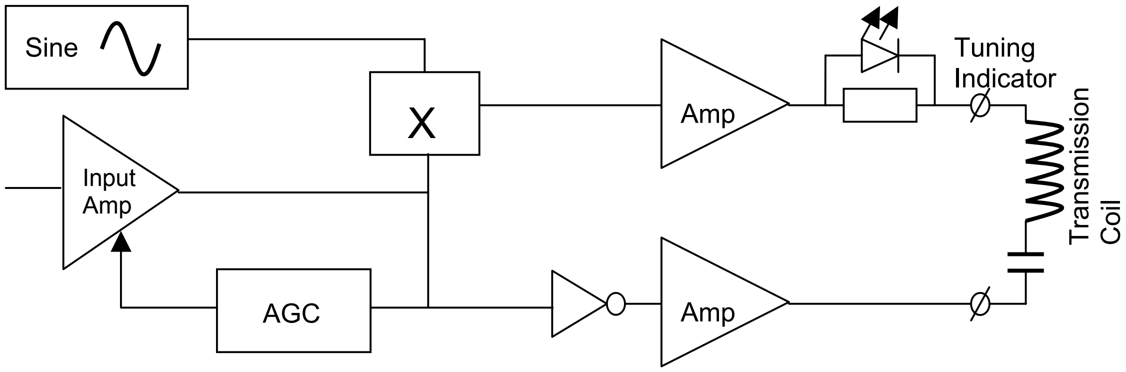

Figure 5. Simplified block diagram of the transmitter.

The input signal (intercom audio) is pre-amplified, giving it a DC-offset, and multiplied with a sine-carrier. The modulated signal is amplified using a push-pull configuration and presented to the transmission coil. A capacitor is used to tune the transmission coil to resonance, for better efficiency. Automatic Gain Control (AGC) is applied to the input signal to obtain a stable modulation depth that is less dependent on the intercom audio level.

2. Sound attenuation and speech intelligibility

2.1. Sound attenuation

Sound attenuation of the w-CEP was measured according to a standardized procedure for measuring sound attenuation of hearing protectors [9]. This method measures attenuation by using the hearing threshold of test subjects; 16 subjects are used for each measurement point. To verify the improvement in overall sound attenuation, the sound attenuation as a function of frequency was measured for three alternative configurations: a frequently used type of helmet for helicopter crew members, the w-CEP earplugs, and the combination of both. The latter corresponds with w-CEP use as intended in future practice, the first is current practice in (for instance) Royal Netherlands Air Force Chinook helicopters. The sound attenuation curves are given in figure 6.

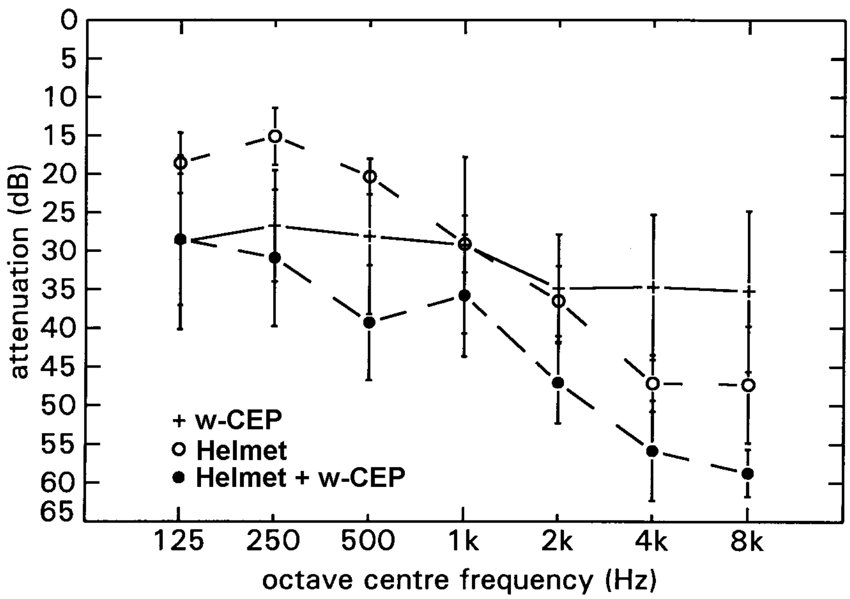

Figure 6. Sound attenuation according to ISO 4869-1 (average and standard deviation, 16 subjects) for the wireless CEP earplugs, a common type of helmet and the combination of helmet and earplugs.

The use of the w-CEP earplugs in combination with the helmet clearly increases the overall sound attenuation. The level of ambient noise that the tympanic membrane is exposed to (which, by the signal-to-noise ratio at the tympanic membrane, is closely correlated with speech intelligibility) will be lower for all relevant frequencies by using the w-CEP earplugs.

2.2. Speech intelligibility

Besides the attenuation of the ambient noise by the w-CEP earplugs, the speech transmission quality (bandwidth, distortion) of the w-CEP system will be very important to the achieved speech intelligibility. A measure of speech transmission quality that is known to be a good predictor of speech intelligibility is the Speech Transmission Index (STI) [1, 2, 3]. This method uses an artificial test signal, that resembles speech in both time and frequency domain. By analysis of the test signal at the output of a speech transmission channel, the contribution of 7 octave bands (125 Hz - 8 kHz) are used to calculate a single index in the 0 –1 range. This index predicts many subjective speech intelligibility measures [1]. In general, a minimum STI-value of 0.60 is required for good speech intelligibility during nominal operation of a system. In worst-case situations, the minimum that can be allowed is STI=0.35.

Using a Head Acoustics artificial head with an ear simulator, STI-measurements were performed of the complete w-CEP system. The test signal was presented to the intercom input of the w-CEP transmitter, and analyzed at the microphone output of the ear simulator. STI-values were measured for a range of intercom input signal levels. The resulting STI-values as a function of A-weighted sound level at the artificial ear are given in figure 7, for two prototype versions of the w-CEP earplugs. The difference between the two earplug versions is in the tuning; the tuning curve of earplug 1 has its optimum at the exact frequency of the carrier wave, earplug 2 is tuned to a frequency approximately of 20 kHz lower. The effect on speech intelligibility is clearly illustrated by the STI-curve. The sound levels in figure 7 are the sound levels due to the intercom speech; the contribution of the ambient noise to the overall sound level is not included.

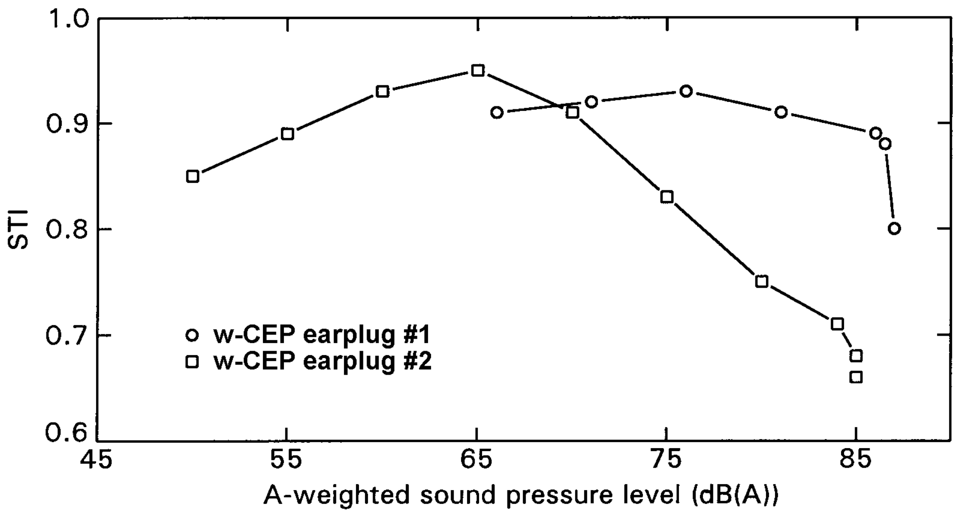

Figure 7. STI as a function of A-weighted sound pressure level *of the intercom speech* at the ear, for two prototype versions of the w-CEP earplugs.

Figure 7 also shows that high STI-values (>0.90) can be reached at A-weighted sound pressure levels up to 85 dB; increasing the input signal level further does not lead to higher sound pressure levels, due to the effect of the automatic gain control circuit of the transmitter. The actual speech intelligibility will be lower than would be expected from figure 7, since figure 7 does not include the influence of ambient noise. In figure 8, the STI-performance in ambient noise of the helmet and the helmet/w-CEP combination is given as a function of the

A-weighted *intercom speech* level at the ear. The ambient noise spectrum used is the noise of the Royal Netherlands Air Force Chinook helicopter (cargo compartment, 111 dB(A)).

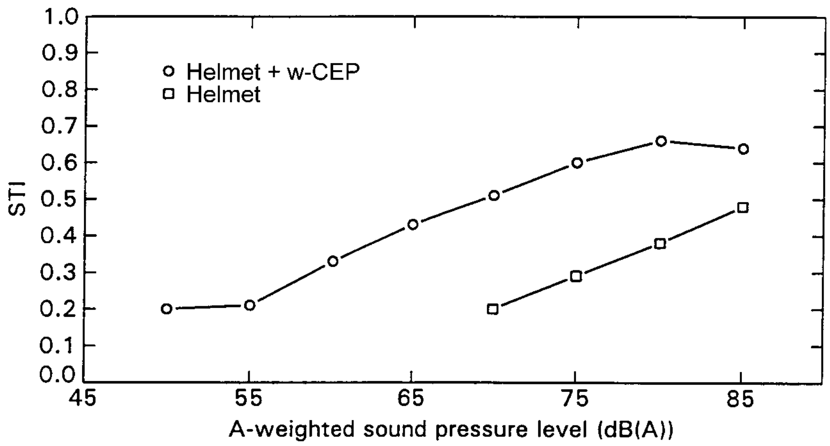

Figure 8. STI as a function of A-weighted intercom speech level at the tympanic membrane, in representative ambient noise (Chinook cargo compartment, 111 dB(A))

Clearly, the application of the w-CEP system leads to a considerable improvement in STI-results, hence in speech intelligibility. At an A-weighted intercom speech level of around 80 dB, the nominal STI requirement of 0.60 is met by the w-CEP system. This would not be possible without Communications Earplugs.

3. Electromagnetic compatibility of the laboratory model

3.1. Military EMC requirements (equipment)

The wireless CEP system was tested informally for compliance with standard MIL-STD-461D. Although the requirements in practice vary with nation and the type of aircraft, these limits were used as an indication of compliance with limits in practice. The EMC tests were performed with the exact same settings of the w-CEP system as during the speech intelligibility measurements described above.

Immunity tests were performed for the earplugs, and radiation test for the transmitters. The immunity of the transmitter electronics was not evaluated, since this is a matter of electronics design rather than feasibility; the immunity of the transmitter electronics was not included as a design criterion in the construction of the laboratory test model.

Immunity of the earplugs could be tested at frequencies up to 30 MHz. At higher frequencies, the proper functioning of the earplugs could not be verified because of interference at the audio measurement equipment. At frequencies below 30 MHz, the earplugs did not suffer from interference at fieldstrengths up to 200 V/m. This is the maximum fieldstrength that could be generated given the facilities, and well within the limits.

The magnetic and electric radiation of the transmitter coils are given in table I, together with the limits given by MIL-STD-461D.

Table I. Measured electric and magnetic radiation under the conditions specified by MIL-STD 461D, together with limits (given a carrier frequency of 100 kHz).

	Limit	Measured	Difference
Magnetic fieldstrength (7 cm from surface of helmet)	111 dBpT	115 dBpT	4 dBpT
Electric fieldstrength (1 m distance)	46 dBμV/m	48 dBμV/m	2 dBμV/m

The radiation limits (magnetic and electric component) are exceeded by 4 and 2 dB. Note that a reduction of the signal level by only 5 dB would bring the system within radiation limits, while the receiver was well within immunity limits. A more sensitive receiver (achievable by applying better receiver coils, as used in the hearing aid industry) would allow far lower transmitter radiation values.

3.2. Health aspects

The influence of electromagnetic radiation on human health is a topic that is much under discussion. A review of relevant research has resulted to national and international guidelines (eg. [10]). Following the guidelines of [10], the magnetic fieldstrength at the approximate position of the outer ear (in the earmuff) is estimated to be around 10 dB higher than the limit set for the exposure of the *whole body*. Partial exposure will allow higher exposure, but how much higher in the case of the w-CEP is uncertain. A reduction of the transmitter power will also be a solution here; by reducing the transmitter power by 10 dB, the *whole body* limit will be upheld for *any part* of the body. For the same reasons stated above, such a reduction in transmitter power is considered feasible.

4. Conclusions

None of the principles used to design the w-CEP are new, nor is the concept of wireless transmission of intercom speech from a helmet to an earplug. What is new about the w-CEP, is the integration of the Communications Earplug concept with simple radio transmission techniques in a way that meets the specific requirements of military aviation.

The wireless CEP laboratory model shows that the application of wireless Communications earplugs is indeed feasible. Design requirements have been met, or it has been shown that these may realistically be expected to be met in further developed versions of the design. Most importantly, measurements have shown that sound attenuation and speech intelligibility targets are reached.

'Good' speech intelligibility (STI=0.60) may be reached in one of the harshest of acoustical conditions in military aviation (Chinook cargo compartment). This is due to the increased overall sound attenuation when using earplugs, and the improved speech-to-noise ratio at the tympanic membrane.

Acknowledgements

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