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SOME TRANSDUCER DESIGN CONSIDERATIONS FOR EARPHONE ACTIVE NOISE REDUCTION SYSTEMS

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INTRODUCTION

The high demands made on the performance of modern military combat vehicles results in little mass or volume being available for the use of passive noise attenuators. The degree of low frequency noise in such vehicles not only produces an unpleasant working environment for the crew but also degrades the quality of their communications links.

The quality of a communications link, expressed in terms of its signal to noise ratio, can be impaired both at the talker's end and the listener's end. Acoustic noise picked up by the talker's microphone is conveyed by the communications link together with the speech signal, and then, when this noisy signal is reproduced in the listener's earphone, it is further corrupted by noise which enters the ear directly from the local environment. A strategy for improving the quality of communication must take account of both these factors. Noise cancelling microphones help reduce noise in the first case, and the partial exclusion of noise at the ear can be effected using acoustically opaque helmets and close fitting earphones.

Earphones are, in general, poor at attenuating low frequency noise, producing increasing noise attenuation with increasing frequency. An active noise reduction (ANR) system can be used at low frequencies to complement the passive earphone noise attenuation.

The first practical work upon the application of the principles of active noise reduction to earphones was carried out by W.F. Meeker in 1958 [1]. In a detailed study he considered the major problems in producing ANR in an earphone. He concluded in general that the effectiveness of his ANR system was limited by the then state of the transducer art and that "for optimum results, transducers should be designed specifically for use in a noise reducing system". More recently work has been done upon a similar system by P.D. Wheeler [2].

The earphone ANR system described here is based upon the Mk. 4 earshell which is in current service with the RAF. This is a circum-aural earphone which totally encloses the ear. Although the earshell is standard the internal design has been developed specifically to meet the requirements of earphone ANR.

THEORY OF EARPHONE ANR

Consider the schematic ANR system shown in Figure 1.

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α, β and γ are the complex transfer functions through the sensing microphone, electronic filter and earphone drive unit respectively. A continuous noise signal pressure N_o is supplied from outside the earshell. This noise will in general have a wide spectrum of components which will be time dependent. It is convenient to consider only one Fourier component of noise, since it is possible to perform a Fourier transform on the result to generate the whole signal.

Initially the presence of the speech signal is ignored i.e. V = 0. Then the total sound pressure N (noise plus diaphragm response) is given by the self consistent equation:

$$N\exp(i\omega t+i\phi_N) = N_o\exp(i\omega t) - \alpha\beta\gamma N\exp(i\omega t+i\phi_N+i\phi_L) \quad (1)$$

where the complex parts have been written explicitly and N, N_o and α, β, γ are now real. The phase change of the whole loop is ϕ_L and the phase of the resulting noise is ϕ_N (measured with respect to the "source" field, N_o). Equating real and imaginary parts and solving for ϕ_N we obtain

$$N = \frac{N_o}{\left(1 + 2\alpha\beta\gamma\cos\phi_L + (\alpha\beta\gamma)^2\right)^{\frac{1}{2}}} \quad (2)$$

$$\text{with} \quad \tan\phi_N = \frac{N_o}{(1 + 2\alpha\beta\gamma\cos\phi_L)} \quad (3)$$

Figure 2 shows the surface generated by plotting noise reduction (i.e. N/N_o) in dB as a function of total loop gain ($\alpha\beta\gamma$) and total loop phase change. In the graph the phase inversion stage has been included in the loop phase change.

It can be seen that the amount of noise reduction produced by the system increases with increasing loop gain. The total phase change in the loop has relatively little effect upon the amount of noise reduction when the gain is high.

If S_o is the total signal pressure field then the total sound field is noise + signal ($N + S_o$). The self consistent equation is now

$$N\exp(i\phi_N)+S_o\exp(i\phi_s) = N_o-\alpha\beta\gamma(N\exp(i\phi_N+i\phi_L)+S_o\exp(i\phi_s+i\phi_L))+\delta\beta\gamma\exp(i\phi_\varepsilon) \quad (4)$$

where ϕ_s is the phase of the resultant signal in the earphone compared to the input voltage V. ϕ_ε is the net phase of the complex product $\delta\beta\gamma$.

Equating signal terms as they share the same phase:

$$\frac{S_o\exp(i\phi_s)}{V} = \delta\,\frac{\beta\gamma\exp(i\phi_\varepsilon)}{1+\alpha\beta\gamma\exp(i\phi_L)} \quad (5)$$

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It can be seen that the pre-emphasis filter δ can be used to optimise the ratio S_o/V across the speech band and so compensate for the speech colouration produced by the ANR system.

Equations 2 and 5 represent the explicit single frequency form of the equations derived by Dorey et al [3].

In all practical systems the loop transfer function is dominated by the combined transfer function of the transducers, sensing microphone and drive unit, mounted with the earphone.

TRANSDUCER DESIGN CONSIDERATIONS

The requirements made upon the acoustic transducers used in earphone ANR are in many ways the same as those made (such as low noise, low distortion, etc.) in other applications. However it is the transducers which ultimately limit the effectiveness of a closed loop earphone ANR system and so there exist some requirements specific to earphone ANR which require special attention.

Electrical Considerations

Operation of the ANR system requires all its elements to function linearly. In the present system this range is limited by the maximum linear output from the earphone drive unit which is a high quality moving coil device.

To maximise this sound output the earphone is divided into two cavities. The back cavity contains the diaphragm back pressure and prevents an acoustic "short-circuit". The relatively high compliance of the back cavity also increases the drive unit sensitivity as measured in the front cavity. The size and weight constraints on the drive unit conflict with the requirement for large volume diaphragm displacement. A large diaphragm unit will have a relatively low resonant frequency - restricting the bandwidth of operation. Increasing the linear throw requires a greater depth of uniform magnetic field and this necessitates the use of a more massive magnet. A compromise has been made between these conflicting requirements by utilising a moving coil drive unit which uses a high energy density rare earth magnet. This offers reasonable frequency response and sensitivity for small size and mass. Using this approach an earphone has been developed which can generate a sound level of ~130dB spl. Above this level of output the earphone exhibits greatly increased distortion and non-linearity, alteration of the transfer function and ultimately permanent damage by overheating of the drive coil. This high output capability allows the system to cancel high levels of ambient noise and improves system resistance to sound generated by earphone vibration relative to the head (so called buffetting).

This vibration can arise from the wearer's environment and by natural movement of the wearer's head. Figure 3 shows the characteristics of such a buffet caused by rotation of the head. Measurements upon the sound level generated by a variety of movements have shown that in general most of the pulse energy is contained in the frequency band 5 to 10 Hz with peak sound pressure levels of typically 110 to 140dB spl being generated. Although the buffet is at a very low frequency the high gain in the ANR loop is sufficient to allow the high peak pressure to overload the drive unit. The low frequency phase advance due to the combined transducer roll-offs produces signal enhancement of 2-3dB at the buffet frequencies, thus increasing the peak pressure level.

The drive transducer is protected from being overdriven by the electronic circuitry but while this clipping is taking place the achieved ANR is greatly reduced. In practice the low frequency limit to the ANR bandwidth is determined by the vibration and noise levels in the intended working environment and the system dynamic range.

The sensing microphone used is a commercial sub-miniature electret and is relatively unaffected by the earphone construction. It introduces a π phase change across its high frequency resonance. The introduction of extra phase lag due to time of flight is minimised by mounting the microphone adjacent to the drive unit. At low frequencies the microphone response is "rolled off" by its pressure equalisation bypass leak. A further roll-off is introduced at very low frequencies by the impedance of the capacitative element becoming comparable with the input impedance of its pre-amplifier.

The high frequency response of the drive unit is smoothed by the inclusion of acoustic damping within the earphone construction. The insertion of the ear into the earphone front cavity also provides damping but leads to some variation in high frequency transfer function between different wearers. As has already been noted in section 2 the loop transfer function can be improved by electronic filtering. The causal relation between amplitude and phase responses limits the amount that can be achieved with electronic filters. Filters with extended second (or greater) order response are of little use because of the large phase change extending either side of the filter frequency. The ANR bandwidth is open to modification by filtering but is fundamentally limited by the transducers' high frequency transfer function.

At low frequencies the drive unit output is controlled by acoustic leak paths through the structure. The bypass hole from the front cavity to the back cavity produces a first order roll-off in output of the drive unit. Sealing onto a real head is generally poor due to the presence of hair lying under the earcushion and this produces a further roll-off in drive unit output. The effect of varying leak size from front cavity to ambient upon the earphone transfer function is demonstrated in Figure 4. The upper curve in the amplitude response and the lower curve in the phase correspond to the earphone being totally sealed. The curves represent leak sizes ranging from well sealed to a leak area of 50mm^2 (length 1mm). The intermediate curves are caused by progressively increasing leak size. The occurrence of this extra leak changes the low frequency transfer function to a third order system with its associated $3\pi/2$ phase advance at very low frequency. This increased phase change allows the possibility of positive feedback at low frequencies with varying gain margin dependent upon the seal quality. Compensation is made within the system for this problem and all wearers will achieve similar low frequency noise reduction as long as a fairly reasonable seal is maintained to the head.

Physical Considerations

The earphones must be supported by the wearer and any increase in mass (particularly for pilots undergoing high 'g' manoeuvres) is undesirable. Indeed it might be hoped that earphones using ANR could offer improved noise protection for reduced total mass. Decreasing the earphone mass does however increase the resonant frequency of the earshell vibrating on the earcushion and thus decreases the earphone low frequency passive attenuation. This can be offset by using a low compliance cushion (such as liquid filled) but under extreme relative movement of head and earphone this cushion increases the risk of total loss of seal with consequent loss in low frequency ANR.

SPEECH ADDITION

To be of any practical use in a communications earphone the wanted speech signal must be heard unaffected by the ANR system. This is achieved by prefiltering the speech signal with the pre-emphasis filter δ. The necessary filter shape can be simplified by adding the speech signal into the loop before the loop stabilising filter. At large values of loop gain the signal term can be approximated by:

$$S_o = \frac{\delta}{\alpha} V \text{ with } \phi_s = \phi_\varepsilon - \phi_L$$

So at frequencies where the gain is high i.e. good ANR, the signal filter must only compensate for the microphone transfer function α. Practically the microphone is flat in response across the speech band, so using this point of signal addition the ANR system will produce no colouration of speech across those frequencies where the loop gain is high. This is demonstrated in Figure 5 which shows the colouration in an unprefiltered speech signal produced by the ANR system. Comparison of the frequency colouration with the measured noise reduction in Figure 6 shows that where the gain is high no colouration is produced. It is only in the low gain region that appreciable signal colouration is produced. This point of signal addition considerably simplifies the prefiltering problem. It is interesting to note that at frequencies below ~4kHz the speech will be heard with a flatter response with the ANR system on than that heard with it switched off.

CONCLUSIONS

1. The ANR system dynamic range is limited by the maximum sound level output available from the earphone drive unit. This dynamic range and the vibration and noise levels of the working environment determine the low frequency limit to the bandwidth of active noise reduction.

2. The upper frequency limit to the ANR bandwidth is determined by the combined transfer function of the earphone transducers.

3. Poor and variable sealing under the earcushion can produce large changes in the earphone low frequency response.

4. The speech signal is relatively unaffected by the action of the ANR system at those frequencies at which the loop gain is high.

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REFERENCES

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[2] P.D. Wheeler, R.D. Rawlinson, S.F. Pelc and A.P. Dorey "The Development and Testing of An Active Noise Reduction System for use in Ear Defenders". Proc. Inter-Noise '78, San Francisco, USA, 8-10 May 1978, 977-981.

[3] A.P. Dorey, S.F. Pelc and P.R. Watson, "An Active Noise Reduction System for Use With Ear Defenders", 8th International Aerospace Symposium, Cranfield, March 1975.

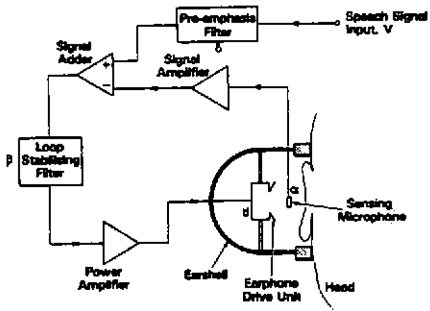

FIGURE 1. A Schematic Diagram of the Essential Elements of a Practical Earphone A.N.R. System

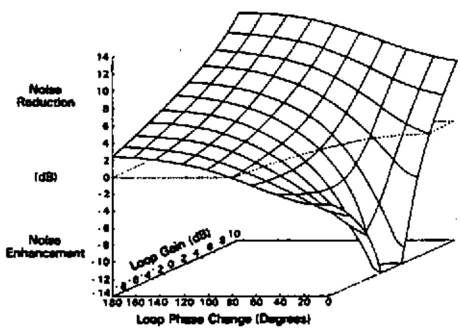

FIGURE 2. Noise Reduction in dB as a Function of Loop Gain and Total Loop Phase Change

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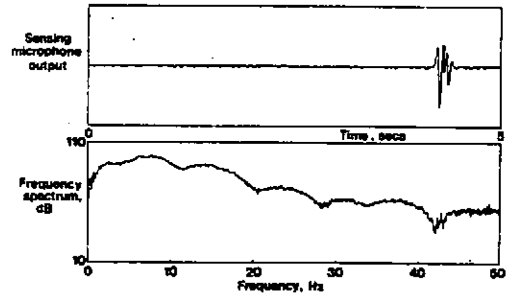

FIGURE 3. Time History and Frequency Spectrum of a "Typical Buffet"

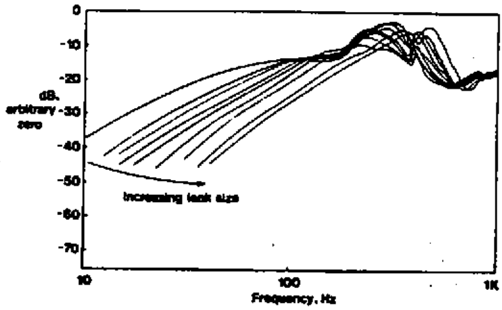

FIGURE 4(a). Variation in Earphone Low Frequency Transfer Function Amplitude caused by Varying Leak under Earcushion

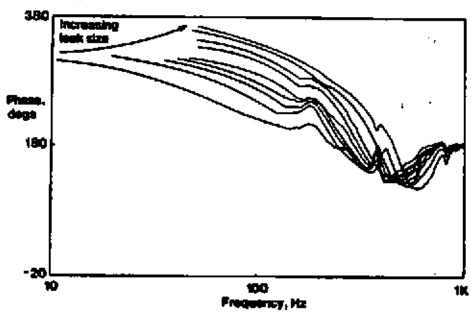

FIGURE 4(b). Variation in Earphone Low Frequency Transfer Junction Phase caused by Varying Leak under Earcushion

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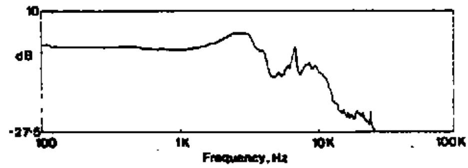

FIGURE 5. Frequency Shaping of Unpre-filtered Speech Signal

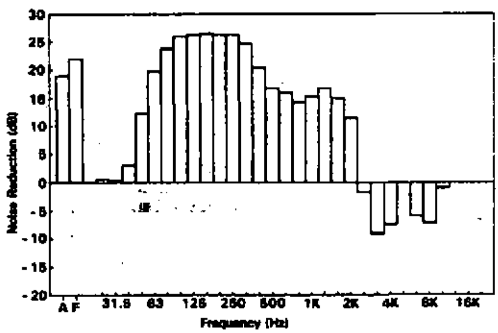

FIGURE 6. A.N.R. System Performance