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CONSTRAINTS IN THE APPLICATION OF PERSONAL ACTIVE NOISE REDUCTION SYSTEMS

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1. SUMMARY

Active Noise Reduction (ANR) systems built into personally-worn headsets and helmets, when properly designed and carefully fitted, have shown considerable potential for reducing noise exposure and improving the listening conditions under which auditory tasks are carried out in military operations. Performance limitations have been identified in certain devices, however. Some have a tendency to overload easily or to cease operating under adverse conditions, and others become unstable when the seal around the ear is broken.

Recent findings indicate strongly that proper fitting around the ear is a functional necessity for satisfactory ANR operation. This is particularly true of units having a low tolerance to overloading and those which continue to operate in the infrasound frequency range. As a consequence, the function of any ANR system must be understood within the context of its intended operating environment in order to estimate whether the system will perform satisfactorily.

2. BACKGROUND

Personal Active Noise Reduction is an electro-acoustic technique for promoting the partial cancellation of sound within the ear cup of a hearing protector. Operating at frequencies below 1000 Hz, ANR is capable of providing greater attenuation at low frequencies than can be obtained by conventional (passive) means. The benefit is greatest in environments containing substantial amounts of low-frequency energy, such as helicopters and tracked vehicles.

DCIEM is studying ANR system characteristics to aid in selecting commercial devices best suited to applications in Canadian Forces environments. Early work consisted of evaluating attenuation properties by objective (physical-ear) and subjective (loudness balance and masked threshold methods) and studying signal detection capabilities among other attributes (Refs. 1 and 2). A recent outgrowth of this work has been the development and implementation of a number of additional tests with which to assess specific ANR characteristics. These include the saturation threshold (the limiting sound level in which systems continue to function properly), issues of fitting integrity, speech discrimination in active and passive modes, and general suitability (freedom from instability, heat build-up and fitting discomfort). The saturation threshold and the role of fitting form the principal subject matter of this paper.

Our laboratory work has confirmed that personal ANR can facilitate the successful execution of listening tasks at lower levels of presentation than would otherwise be necessary. One such listening task involves the detection of auditory signals, for example, sonar returns in maritime helicopter operations. An early study comparing active and passive systems showed that sine wave tone bursts could be detected by observers at significantly lower levels of presentation in a background of simulated helicopter noise when ANR was used (Ref. 1). What was not anticipated was that signal detection capability would be enhanced at frequencies well above the ANR operating bandwidth as shown in Figure 1, an outcome which could not have been predicted on the basis of active attenuation performance alone.

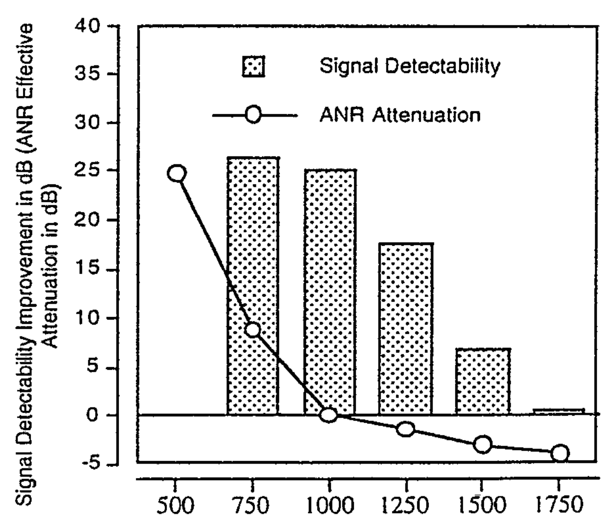

Fig.1. Improvement in Absolute Signal Detectability due to ANR Attenuation in a Background of Simulated Sea King Noise

It was presumed that the signal detection performance of the experimental observers was improved through the control of upward spread of auditory masking. This psycho-acoustic effect, sometimes called forward masking, refers to the capability of low-frequency high-amplitude sound energy to mask or hide sounds occurring at higher frequencies. Although most studies on forward masking have used mid-frequency tones or bandlimited noise as maskers (Refs. 3 and 4), there is also evidence that infrasound of sufficient amplitude is able to produce a similar effect (Ref. 5). An ongoing assessment of the noise levels at the ears of flight personnel using passive flight helmets in rotary-wing aircraft has shown that the intercom and radio sound levels are invariably higher than those considered necessary for adequate speech discrimination. This observation supports the probable occurrence of forward masking in real environments. It seems evident that the reduction of forward masking is one of the most important capabilities which can be attributed to ANR.

In flight environments, there is a tendency for ANR performance to be compromised through a combination of factors, including fitting difficulties with consequential sound leakage, and electro-mechanical limitations in the equipment itself which can lead to distortion, saturation or instability (Ref. 6). Anecdotal evidence suggests that these effects are commonly noted by flight crew, in spite of the potential of ANR to ameliorate forward masking through noise attenuation when properly applied. Consequently, there is a need to understand the low-frequency performance of personal ANR equipment and the factors on which performance depends, so that this emerging technology may be applied to the best possible advantage.

3. NEW STRATEGIES TO EVALUATE ANR

In recognition of these requirements, recent research at this laboratory has been aimed at developing a series of measurement strategies intended to isolate and quantify the factors contributing to the low-frequency performance of commercial ANR equipment (Ref. 7). One of the techniques to be described is a method which determines the limiting at-ear sound levels in which any given device will continue to function properly, and another assesses the attenuation properties of the ear shell and ear cushion in isolation from the effect of ANR. In the third, a technique is described in which overall attenuation performance is measured under both ideal and less-than-ideal conditions. In any selection process, these factors are considered in combination with the results of speech discrimination tests, an assessment of general suitability, and the nature of the sound field in which the system is to be used.

Measurement of Saturation Threshold

ANR system exposure to very high-amplitude low-frequency audible and sub-audible sound can lead to saturation or overload of the ANR electronics. This causes the system to generate extraneous noise at the ear, described variously as a clicking, popping or oil-canning sound. A technique was developed whereby the threshold or onset of overload could be determined experimentally through the direct excitation of the air volume confined within the ear cup of an ANR device.

A KEMAR acoustical mannequin headform with Zwislocki coupler artificial ears (Ref. 8) is modified by removing the couplers and mounting plates from the ear cavities. This provides 27 mm circular openings from the circumaural areas into the hollow headform. Calibrated 13 mm microphones are suspended in these openings such that their diaphragms are flush with the outer surface of the headform, allowing air to pass freely through the openings.

The hollow neck of the headform is attached to an opening in a loudspeaker enclosure containing a 200 mm low-frequency driver. Since there are no other openings in the enclosure, the back wave is acoustically coupled to the interior volume of the headform. When an ANR device is placed over the ear openings and the loudspeaker is driven by a very low-frequency pure tone, it is possible to excite the ear cavities to sound pressure levels exceeding 140 dB. The ANR system cannot distinguish between this type of excitation and that which would normally permeate the ear shells, thus the system under test will attempt to establish an opposing noise field. Since the measurement microphones are placed in proximity to the cancellation transducers, they "hear" the onset of distortion or overload in the form of extraneous noise. This is clearly audible over headphones used to monitor the microphones as the excitation sound level is varied in the region of the threshold. Alternatively, the onset of distortion can be monitored by connecting a signal analyzer to the measurement microphones and observing the rising pattern of sound energy above the excitation frequency as the threshold is exceeded.

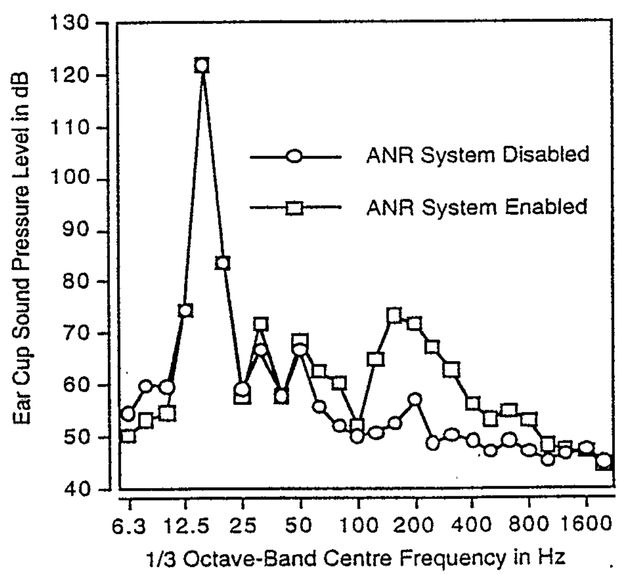

Fig.2. Typical Extraneous ANR System Noise Resulting from Presenting a 16-Hz Pure Tone at a Level 5 dB above the Saturation Threshold

A typical noise spectrum resulting from overload is shown in Figure 2, where the excitation is a 16-Hz pure tone presented

5 dB above the saturation threshold. For reference, the comparable spectrum with ANR defeated is also shown. The difference between the traces represents the extraneous noise which in this case is most pronounced at frequencies between 100 and 1000 Hz. This effect raises the possibility of interference with the lower portions of the speech band, and helps to explain the negative observations reported by flight personnel.

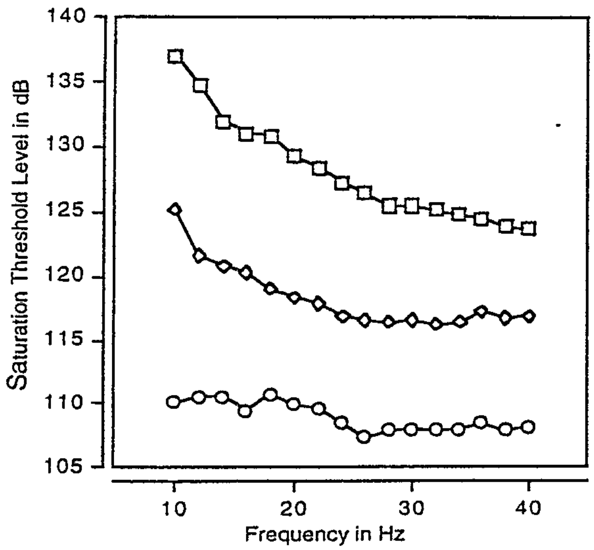

Fig.3. Saturation Thresholds for Three Typical ANR Systems

Whichever method of detection is used, the sound pressure levels registered by the microphones at the saturation threshold can be plotted as a function of frequency, as shown in Figure 3. A tendency towards lower thresholds is thought to be attributable to two compounding factors. Firstly, those systems capable of providing significant cancellation within this frequency range simply work hard in the presence of infrasound excitation. Secondly, hardware constraints such as the excursion limits of the cancellation transducers or the available drive power restrict the size of cancellation signal that can be generated.

Although a high overload threshold may indicate that the unit is particularly robust, it may also show that it is simply insensitive to energy in this frequency range. A review of the unit's active attenuation performance within the same frequency range will aid in making this distinction. It is noteworthy, however, that the devices having high cancellation capability in the infrasound region are perceived by the user as creating the best listening environment when operated below the overload threshold, in spite of the relative insensitivity of the human hearing system at these frequencies.

Ear Shell and Ear Cushion Attenuation

In any ANR system, the active attenuation due to electronic assist is complemented by the passive reduction provided by the ear shell assembly. Although the measurement of saturation threshold describes ANR behaviour within the ear cup at very low frequencies, it does not quantify the effect of the ear cushion or the seal against the side of the head. This information is needed to estimate the magnitude of an external sound field which will cause the overload threshold to be exceeded.

To study passive reduction capability, the entire ANR system is subjected to a low-frequency high-pressure sound field. The pressure vessel in which this test is carried out comprises a large sealed loudspeaker enclosure with a 300 mm driver. The driver is removable for access to the interior of the enclosure, which contains a heavy flat-plate coupler having a measurement microphone at its centre. The coupler is used to carry out insertion loss measurements of attenuation. A noise spectrum is obtained from the microphone as the coupler is pressed against one of the ear cushions and another is obtained with the cushion and coupler separated from each other, as the driver is excited by low-frequency pink noise. Passive attenuation is taken as the difference between the two spectra.

Experience has demonstrated (Ref. 9) that the fit of a protective device rarely approaches the quality of that obtainable against a flat plate coupler, thus it is acknowledged that the attenuation data obtained in this way should be thought of as ideal. It was therefore considered prudent to study the effect of a less-than-perfect seal to the coupler.

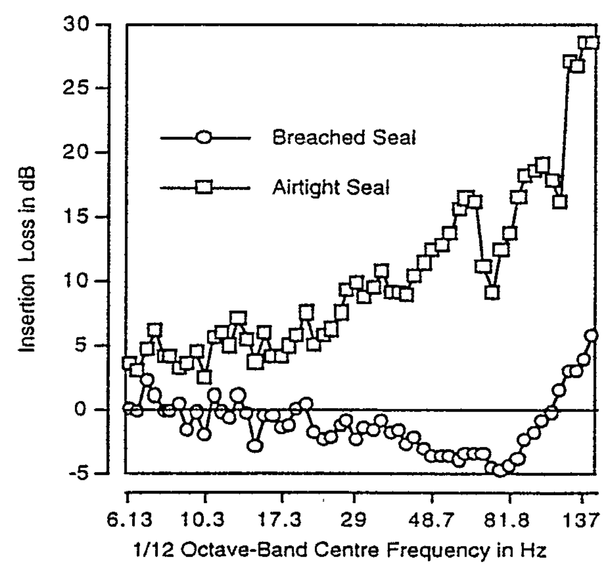

Fig.4. Sample Ear Cup / Ear Seal Insertion Loss with ANR Electronics Disabled

For this purpose, a tube 1.6 mm inside diameter x 25 mm length is inserted between the ear cushion and the coupler surface. It is embedded in a wedge of plasticine to prevent air movement around its periphery. The size of the tube was chosen to approximate the leakage cause by the insertion of a metal side frame of Canadian Forces issue sun glasses under the seal. In the absence of additional leakage, this represents a relatively small acoustical path.

The results of a typical low-frequency insertion-loss measurement with ANR in passive mode are shown in Figure 4. The upper trace shows the attenuation achieved with an ideal (airtight) seal against the flat-plate coupler containing the measurement microphone, and the lower trace the effect of breaching the seal into the ear cavity by means of the tube described above. The leakage path appears to act as a resonator with the enclosed air volume which amplifies sound energy in the 50 - 100 Hz region and generally nullifies any attenuation below 30 Hz.

Thus, for a given ANR system to perform satisfactorily in this helicopter, it needs to be capable of generating very high levels of infrasound.

Overall Performance Characteristics

The two techniques described above allow the separation of ANR function from the determination of low-frequency passive attenuation provided by the ear shell structure. One can also assess overall system performance by testing in an environment closely duplicating the noise in which the equipment might be used, for example to estimate hearing hazard. DCIEM has developed a noise simulation facility fully meeting these requirements, in which interior noise recorded in aircraft and in ground vehicles may be faithfully reproduced, in level, in bandwidth and in temporal pattern. The result is a test environment closely duplicating the actual noise encountered in the field. This capability allows testing under controlled and repeatable conditions and substantially lessens dependence on field trial resources for routine testing.

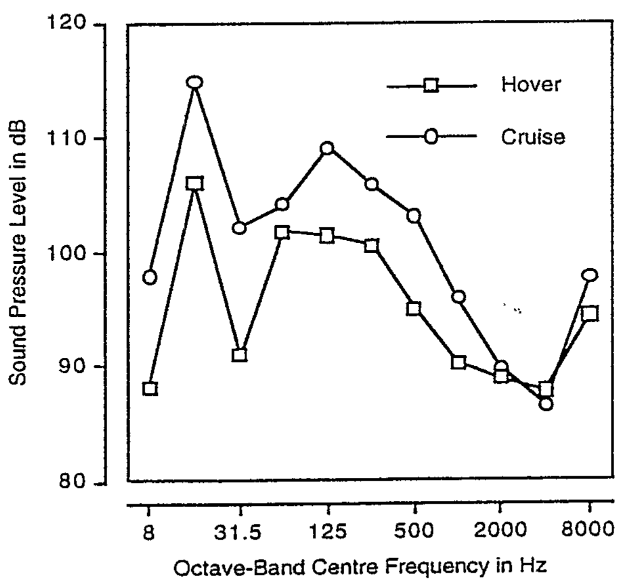

Fig.5. Ambient Sound Levels on the Flight Deck of the Sea King Helicopter

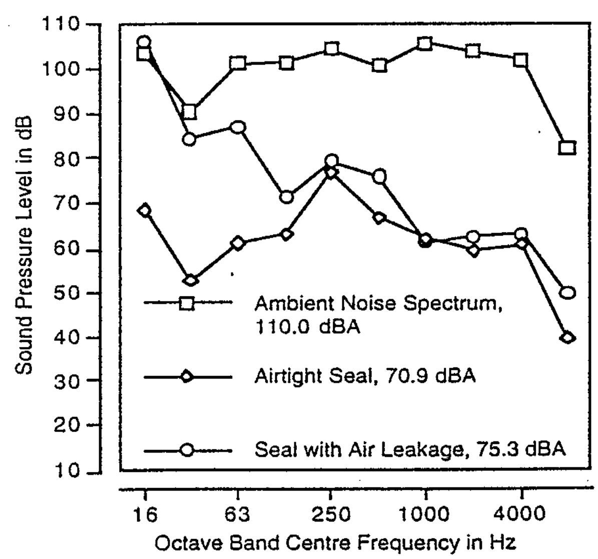

Fig.6. Attenuation Characteristics of Effective ANR System when operated against Flat Plate Coupler in Realistic Sea King Helicopter Noise

Acoustical leakage of this magnitude can be particularly troublesome in operational environments containing low-frequency sound energy. For example in the Canadian Forces Sea King maritime helicopter, the largest acoustical input to the cabin occurs at the main rotor blade-pass frequency, about 17 Hz, as shown in Figure 5. An air leak as small as that described above would force the ANR electronics to accommodate ambient (rather than attenuated) levels of infrasound, as well as higher-than-ambient levels of the 2nd - 5th order harmonics of rotor blade pass noise.

The results of some physical measurements carried out in this facility are given in Figures 6 and 7. The overall flat plate sound levels inside the ear cup of an effective wide-range ANR system is shown in Figure 6, together with the Sea King helicopter excitation spectrum measured via the coupler while separated from the ANR system. The difference between these curves represents the total attenuation of the device, that is, the passive attenuation as augmented by the action of ANR. Shown also is the dramatic effect of breaching the seal against the flat plate by means of the small tube described earlier. Notably, the performance decrement is considerably larger than would be predicted solely by the loss of passive attenuation. Clearly, leakage of this magnitude seriously compromises the intended effect of ANR.

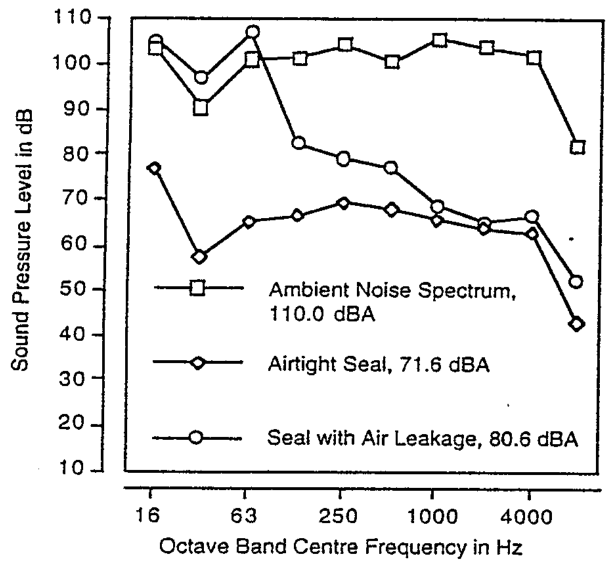

Fig.7. Attenuation Characteristics of Less Effective ANR System when operated against Flat Plate Coupler in Realistic Sea King Helicopter Noise

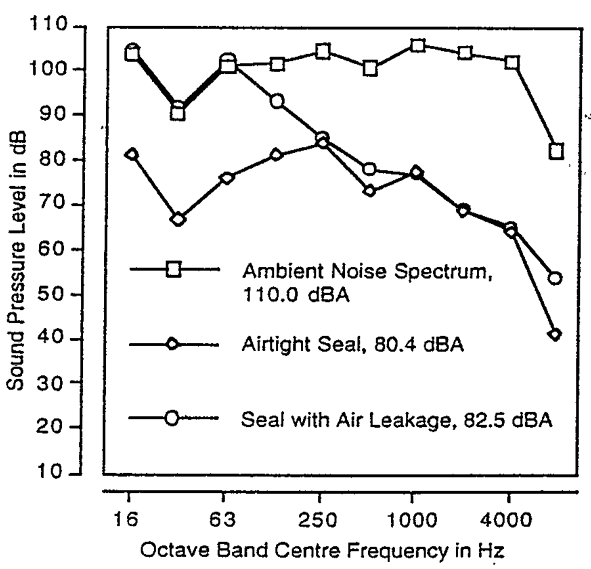

Fig.8. Attenuation Characteristics of Passive Communications Headset when operated against Flat Plate Coupler in Realistic Sea King Helicopter Noise

In Figure 7, the performance of a less effective system is shown for a measurement carried out under identical conditions. In both instances, there is general tendency for the leaky condition spectrum and the excitation spectrum to become asymptotic at low frequencies. This also occurs in devices not equipped with ANR, for example in Figure 8, although as expected, this headset provides less protection under airtight conditions than either of the active protectors.

4. IMPLICATIONS

Electro-Acoustic Limitations

It has been shown that commercial implementations of ANR differ considerably in their ability to operate effectively at very low frequencies. Built-in filter characteristics in some units permit operation in the infrasound region, usually with relatively low tolerance to overload, while others are relatively insensitive to infrasound. Subjectively however, the units which "sound best" are those with extended operating bandwidths, particularly when used in helicopter environments. Manufacturers are constrained by the size, excursion capability and power dissipation of transducers built into the ear cup. Larger, more powerful units would lessen the tendency to overload, particularly in the presence of sound leakage, but would remain restricted in providing additional attenuation because of their fixed filter and gain characteristics. A system capable of adaptation such as the one being developed by the National Research Council (Ref. 10) should lessen the overall dependence on effective fitting.

Fitting Limitations

The difficulties associated with adequate fitting of hearing-protective devices in field environments has been a significant health concern for many years (Ref. 9). Our own studies have indicated that the reception of radio and intercom messages is a significant component in the acquisition of noise dose, and improper fitting of helmets or headsets invariably requires higher intercom levels for adequate speech discrimination. Fitting difficulties are no different with ANR devices, except that the consequences are more severe in terms of loss of attenuation (see Figures 6, 7 and 8). Results such as these underscore the crucial importance of fitting, yet clearly indicate the performance potential achievable under ideal conditions. More work is required to assess performance on real subjects such that the inevitable decrement in performance due to fitting anomalies may be better understood.

5. SUMMARY

Environments in which ANR has the potential to provide the greatest benefits to the user often contain low-frequency noise of sufficient amplitude to cause ANR equipment to malfunction. ANR performance at very low frequencies appears to depend upon the capability to generate cancellation waveforms within this frequency range, upon hardware constraints such as transducer excursion limits and upon the integrity of the seal against the head. The data presented in this paper emphasize the importance of understanding the behaviour of ANR devices at extremely low frequencies and the relationship to the noise environment in which they will be used.

6. ACKNOWLEDGEMENTS

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