EAR CUP SELECTION FOR FEEDFORWARD ACTIVE NOISE REDUCTION HEARING PROTECTORS

Eric R. Bernstein[1], Anthony J. Brammer[1], Gongqiang Yu[1], Martin G. Cherniack[1], and Donald R. Peterson[1]
[1]Ergonomics Technology Center, Univ. of Connecticut Health Center, 263 Farmington Av., Farmington, CT, U.S.A., 06030

1. INTRODUCTION

Performance of an active noise reduction (ANR) hearing protector device (HPD) is significantly affected by the mechanical design of the ear cup. Two characteristics are of critical importance when evaluating a passive HPD design for potential modification into an active feedforward HPD: passive noise reduction and predicted active noise reduction with active control. Several commercially available passive HPDs have been evaluated using these metrics in order to select the ear cup that would offer the best performance with a feedforward ANR system.

Passive performance of the ear cup serves to augment the electronic control system in an active HPD. A well designed ear cup will compensate for the decreased attenuation provided by the active system at high frequencies as well as provide the maximum possible passive attenuation to improve the total attenuation of the complete system. Shaw and Thiessen (1965) detailed two important features that are necessary to maximize passive attenuation: the cushion must provide a high resistance to air leakage, and the volume underneath the ear cup should be as large as possible.

Active noise reduction systems improve the performance of an active HPD by attenuating low frequency noises whose wavelength approaches or exceeds the size of the ear cup. Simple estimation of the active noise reduction (ANR(ω)) possible with an optimal feedforward controller can be determined from the coherence function ($\gamma_{re}^2(\omega)$) between a reference microphone placed outside the ear cup and an error microphone at the desired point of cancellation inside the ear cup (Nelson and Elliot, 1992), $ANR(\omega)=1-\gamma_{re}^2(\omega)$. This method of estimation of active control system performance is ideal for ear cup selection because it does not require the presence of a secondary source loudspeaker or electronic controller, only the reference and error microphones located where they would ideally be positioned in a final device.

Caution should be exercised when using this equation in practice due to assumptions regarding the disturbance and the controller. First, this equation assumes a stationary disturbance, and thus controller performance could be better than predicted when using an adaptive controller with non-stationary signals. Second, the equation does not require the optimal controller to be causal and therefore may not be physically realizable. For a description of performance prediction with a causally constrained controller, see Elliott (2001).

2. METHOD

Ear cups were evaluated in a reverberation chamber possessing a reverberation time of between 1.5-4 sec over a frequency range of 100-8000 Hz. Tests were conducted using both a Head and Torso Simulator (HATS) (Brüel & Kjær Type 4128C) and human subjects. All subjects gave their informed consent to participate in the study, following the provisions of the ethics committee of the University of Connecticut Health Center.

HATS passive attenuation values were calculated as the difference between the power spectrums of a white noise signal presented with and without each ear cup recorded at the artificial eardrum microphone (Brüel & Kjær Type 4158C). Coherence was measured from a microphone (Knowles FG 23629-P16) placed on the surface of the ear cup along the axis of the ear canal to the artificial eardrum. Human subject passive attenuation and coherence testing were conducted similar to HATS procedures, however the artificial eardrum microphone was replaced with a custom probe microphone system designed to accurately replicate sound pressures at the subjects eardrum. The system uses custom fitted ear molds to allow repeated placement of the probe tip and has been shown to replicate signals of up to 6 kHz with an accuracy of ±2 dB, (Brammer 2009). Power spectrum and coherence were calculated and averaged over 50 measurement periods using a dynamic signal analyzer (Agilent 35670A). A signal bandwidth from 0-1600 Hz was used as coherence values were negligible above these frequencies and the level of passive attenuation remained approximately constant.

Predicted attenuation was used to select an optimal ear cup for conversion into an active HPD. Total noise reduction (TNR(ω)) was calculated using Eq. 1 by combining both the measured passive noise reduction (PNR(ω)) and active noise reduction predicted using the coherence function. The ear cup selected to provide the best predicted total attenuation was then modified into a feedforward ANR HPD using a floating-point DSP (Texas Instruments TMS320C6713).

$$TNR(\omega) = PNR(\omega) - 10 \cdot \log_{10}(1 - \gamma_{re}^2(\omega)) \qquad (1)$$

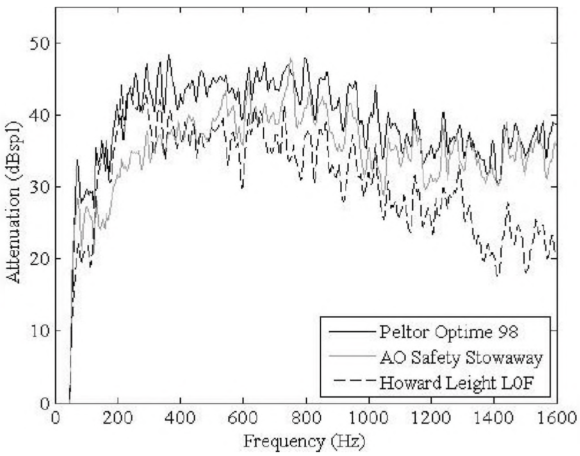

Fig 1. Predicted TNR(ω) of ear cups from human subject tests

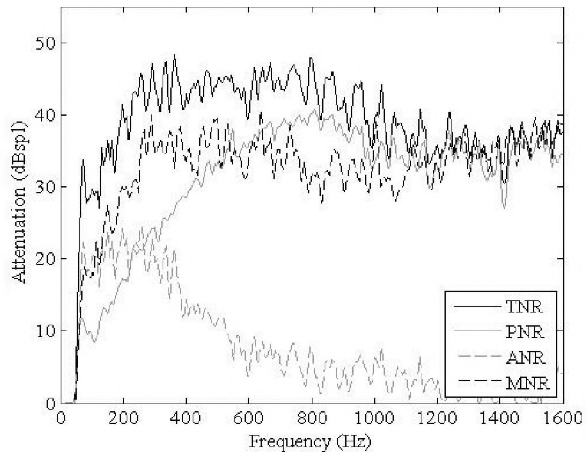

Fig 2. Noise reduction comparison of the Peltor Optime 98 ear muff before and after feedforward ANR modification

3. RESULTS AND DISCUSSION

Representative data from three diverse ear cup designs are included in Fig 1. The Peltor Optime 98 headset is a large volume ear muff intended to provide high levels of noise isolation in an industrial environment. The AO Safety Stowaway ear muff is designed for portability and has a teardrop shape to allow for part of the ear muff to sit underneath a hardhat yet still retain the volume necessary for high passive attenuation. The Howard Leight L0F ear muff is an ultra-slim ear muff that minimizes the storage size and volume underneath the ear cup.

The Peltor Optime 98 ear muff demonstrates exceptional performance over the entire frequency range of interest. Passive attenuation settles to approximately 35 dB at frequencies above 1.6 kHz and high coherence up to 400 Hz demonstrates that a feedforward system could add nearly 20 dB of active attenuation, see Fig 2. While the AO Safety Stowaway ear muff has a passive attenuation comparable to the Optime ear muff at high frequencies, the slight increase to the coherence at low frequencies cannot compensate for the loss of passive attenuation. Conversely, the small distance between the two microphones using the Howard Leight ear muff provides a very high coherence for active control, but the small volume leads to a significantly reduced noise reduction capacity at higher frequencies. Based on these results, the Optime ear muff was selected for modification into an active HPD. It should be noted that while the Peltor Optime 101 ear muff also tested provided slightly better total predicted performance than the Optime 98 ear muff, the Optime 98 ear muff was selected because it provided better coherence for design and testing of active feedforward noise control systems for future research.

When modifying the Peltor Optime 98 ear muff, the external reference microphone was positioned similar to the earlier coherence experiments. However, the error microphone was repositioned for better integration with the active headset. The differences between the TNR(ω) of the constructed system compared with the measured noise reduction (MNR(ω)) are illustrated in Fig 2. While the MNR(ω) closely follows the shape of the TNR(ω), a difference of approximately 10 dB is observed between 100-1000 Hz. This discrepancy can be explained by the modifications involved in installing a secondary source loudspeaker and repositioning the error microphone, which will affect both passive attenuation and coherence respectively. The relative agreement between the TNR(ω) and MNR(ω) curves indicate that this method is suitable for approximation of feedforward ANR HPD performance.

The results of this study suggest several guidelines for characteristics that make a particular ear cup design ideal for feedforward noise control. Comparing both the Peltor and AO Safety ear muffs, it is clear that a large volume underneath the ear cup is necessary for high passive attenuation. However, the coherence results from the AO Safety and Howard Leight ear muffs, not shown, indicate that the best predicted active attenuation is obtained when the distance between the external reference microphone and the error microphone is minimized. Future designs should emphasize an optimal balance between these two considerations to provide the best possible performance from feedforward HPD designs.

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ACKNOWLEDGEMENTS

This work was supported by NIOSH (R01 OH008669).