Hybrid Feedforward-Feedback Active Noise Control for Hearing Protection and Communication

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ABSTRACT

Research over the past decade has demonstrated substantial increases in noise reduction performance for circumaural hearing protectors through feedforward active noise reduction (ANR) based on least mean square (LMS) methods. However, commercialization of feedforward ANR hearing protection devices has yet to occur. This paper explores issues related to robust realization of feedforward ANR for hearing protection. Specifically, the dynamic range of noise sources, the potential for leakage around circumaural earcups, vibration conditions of high noise environments, and the need for communication requires ANR algorithms that are robust to large variations in the acoustical dynamics of hearing protectors. To meet this need, a hybrid ANR architecture that exhibits excellent stability margins and performance for both stationary and non-stationary noise sources is presented. The hybrid system is comprised of a Lyapunov-tuned leaky LMS feedforward component and a broadband digital feedback ANR system. The contribution of each component to ANR performance is adjusted by individual feedforward and feedback gain factors, and stability margins are defined by the net increase in these gains that can be accommodated while maintaining system stability. Stability and noise reduction performance of the hybrid system are validated experimentally using an earcup from a commercial circumaural hearing protector and using a prototype active earplug. Experiments are performed through flat plate or manikin testing using a DSP development system. Results demonstrate that stability margins are increased, in some cases, by several orders of magnitude.

1.0 INTRODUCTION

The need for improved hearing protection in the high noise fields present in military applications motivates the use of active noise reduction (ANR). Commercial ANR systems employ feedback control, in which an error microphone serves as the feedback signal from which a cancellation signal is produced. Traditional stability-performance tradeoffs that pose limitations on feedback control of noise are evident within commercial circumaural headsets; in feedback ANR, the cavity resonant behaviour forces low feedback gains and thus lower levels of active attenuation. Moreover, feedback circuitry often adds to the noise in the mid-frequency speech communication bands. Practical limitations in ANR performance and in improving speech intelligibility through feedback ANR have generated research in feedforward ANR using least-mean-square (LMS) adaptive filters [1-9]. These computationally simple filters are used widely for stationary noise cancellation. However, LMS filters have stability and performance tradeoffs caused by non-stationary, impulsive noise, finite precision, and measurement noise. Noise fields found in

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military settings – tanks, fixed and rotary winged aircraft, and environments served by ground crew –vary with operating conditions, posing significant noise reduction challenges.

References 7-8 introduced the Lyapunov-tuned LMS filter (LyLMS), developed in response to environments in which noise sources exhibit temporal variations over a large dynamic range. The Lyapunov-tuning method provides a *time-varying* leakage factor and adaptive step-size combination that optimizes LMS filter stability and noise reduction performance in response to time-varying SNR. The algorithm incurs minimal additional computation over a traditional leaky LMS filter, and it has the major advantage in eliminating empirical tuning. The Lyapunov-tuned leaky LMS filter can be further augmented with a filtered-X implementation, in which a non-constant cancellation path gain is accommodated [6].

Recent studies consider hybrid ANR for hearing protection [9-11]. In [10], a complex filtered-X LMS filter is combined with a commercial analog feedback controller to attenuate infrasonic noise due to the 17.7 Hz fundamental blade passage frequency in a helicopter and its harmonics. While the feedback system, combined with passive attenuation provided by the earcup, provides 20 dB broadband performance, reduction of the fundamental blade frequency is minimal. Addition of feedforward ANR reduces the fundamental blade passage frequency by an additional 20 dB. Reference [11] evaluates a hybrid system in both a reverberant sound field and a directional sound field, and explores the relation between ANR performance and forward path delay. The results show improved performance through hybrid ANR in a reverberant field, as compared with analog feedback alone, while a directional field, which affects the acoustic delay, degrades performance when the noise source does not face the reference microphone directly. In [9], two additional aspects of hybrid ANR are evaluated. A hybrid feedforward-feedback control architecture is shown to (1) improve noise reduction performance for nonstationary noise sources, and (2) increase stability margins. A digital feedback system provides low level, broadband performance, independent of the noise source. The feedforward system acts on the resulting error signal to further increase noise attenuation. Unlike previous studies, where feedforward ANR is hybridized with a commercial analog controller, [9] develops a broadband digital feedback compensator designed to work with the feedforward system. The presence of this feedback compensator increases the feedforward gain stability margin substantially and reduces sensitivity of overall performance to the temporal characteristics of the noise source.

These references show the benefit of hybrid ANR in retaining the positive characteristics of feedback control of providing good broadband performance irrespective of the noise source as well as the positive characteristics of feedforward control of achieving good tonal noise attenuation. Hybridization allows the use of lower feedback gain without sacrificing overall performance, providing positive benefits on stability margins. In this paper, the concept of a general hybrid ANR architecture is applied to two hearing protection devices, including circumaural earcup and an earplug.

2.0 HYBRID FEEDFORWARD-FEEDBACK ANR

Figure 1 shows the hybrid ANR system block diagram. The incoming noise *X(t)* is measured by a microphone embedded on the exterior of the hearing protector. The past L samples of $X(t)$ constitute the reference input X_k, where L is the filter length. Electronic and quantization noise enters as Q_{xk}. $X(t)$ passes through passive materials, an unknown acoustic process, to become noise signal $d(t)$. The LMS filter finds weight vector $W(z)$ modelling the unknown passive response and produces a cancellation signal $-y_k = W^T X_k$. An error microphone inside the hearing

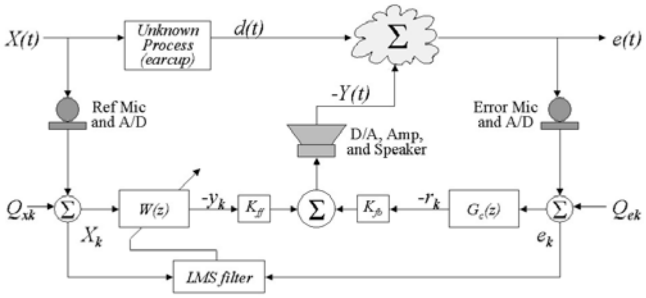
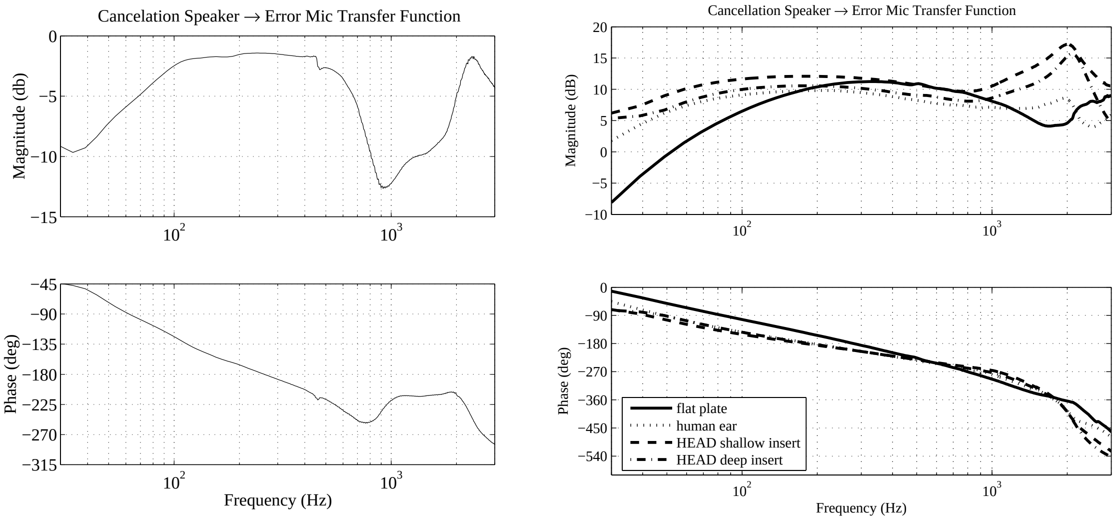


Figure 1: Hybrid ANR topology



(a) commercial circumaural earcup (b) earplug

Figure 2: Open loop response from input to cancellation speaker driver to output of error microphone amplifier for (a) earcup mounted on flat plate and (b) ANR earplug in flat plate, human ear, and manikin.

protector registers the residual noise e_k, subject to measurement noise Q_{ek}. e_k, adjusts the LMS filter and also passes through digital feedback compensator $G_c(z)$ creating a feedback cancellation signal $-r_k$. The two cancellation signals are scaled by gains K_{fb} and K_{ff}, summed, and passed to a D/A converter and amplifier to drive the cancellation speaker inside the earcup as $-Y(t)$. The residual noise, $e(t) = d(t) - Y(t)$, is what is “heard” by the error microphone. In an earcup, the error microphone is necessarily about one inch from the concha, while in an earplug, the error microphone is generally within the external auditory ear canal.

Figure 2 shows cancellation path responses from an internally generated cancellation signal to the error microphone for a commercial circumaural hearing protector and for several configurations of a commercial earphone modified for hybrid ANR. Both devices have good passive attenuation. Earplug data were collected within a flat plate (enclosing a volume comparable to that enclosed within human ear), on a manikin at two insertion depths, and in a human ear, showing different responses that can be elicited using common test configurations. The general characteristics of the cancellation path for these devices are similar, indicating that a common ANR architecture is viable. However, the variability in the cancellation path necessitates a system with good stability margins, which poses a design challenge for feedback and feedforward ANR individually. The non-constant cancellation path gain can be accommodated using a filtered-X implementation of the Lyapunov-tuned leaky LMS filter, in which either a finite-impulse response or infinite-impulse response filter shapes the reference input prior to the LMS filter update based on the cancellation path response [12]; however, to the extent that this path varies from user to user, the shaping filter needs either to be adaptive or robust to variations in the cancellation path. Similarly, the feedback system must also be robust to variations in the cancellation path response.

The hybrid architecture provides a means to retain performance while building in adequate stability margins in the face of these variations. For feedback ANR, a low-order digital feedback compensator $G_c(z)$ is designed to increase the frequency range in which the phase response is near -180°, such that the internally generated cancellation signal is 180° out of phase with the error signal e_k for a broad frequency range. Unlike commercial feedback ANR, which provides up to 20 dB of narrowband performance, this compensator provides lower level (5-10 dB), broadband attenuation. Since phase characteristics of various hearing protectors are similar, a common compensator structure is selected for feedback ANR. Feedforward ANR is based on the Lyapunov-tuned LMS (LyLMS) feedforward algorithm from [7,8], which is summarized here. $X_k \in \boldsymbol{R}^n$ is the reference input at time t_k, and is subject to noise Q_{xk}.

The unknown process produces output d_k. The LMS filter seeks a weight vector $W_k \in \mathbf{R}^n$ to minimize the mean-square-error. The optimum or Wiener solution is $W_0 = E[X_k X_k^T]^{-1} E[X_k d_k]$, where $E[]$ is the expected value and e_k, = d_k - $W^T X_k$.. A recursive update equation $W_{k+1} = W_k + \mu e_k X_k$ comprises the basic LMS filter. Convergence speed and stability depend on the step size μ, and a normalized step size μ_k is introduced to improve convergence. To improve stability in the face of measurement noise, the weight vector update equation is altered through a leakage factor, providing the leaky, normalized LMS (LNLMS) filter $W_{k+1} = \lambda W_k + \mu_k e_k X_k$. , where $0 \leq \lambda \leq 1$ for stability. The LNLMS filter forces a stability-performance tradeoff: for high performance λ should be close to unity, whereas stability requires leakage (lower λ). The optimum λ changes with signal strength and spectral composition. An adaptive leakage factor provides a solution to this tradeoff. The Lyapunov tuning method provides an adaptive leakage factor and step size combination to optimize both stability of the weight update equation and noise reduction performance. Tuning laws are detailed in [7,8].

3.0 EXPERIMENTAL EVALUATION

Experimental evaluation of the hybrid feedforward-feedback architecture was conducted in a Low Frequency Acoustic Test Cell (LFATC), described in [13], for the circumaural earcup, and for the earplug, a combination of test cell and manikin testing was performed. The LFATC, shown in Figure 3 has a flat acoustic frequency response from 10 to 200 Hz. Digital equalization extends this range to approximately 1000 Hz. A single earcup is secured over the base plate of the test cell. A 15.2 cm diameter 100 W speaker mounted in the top plate of the cell provides the noise signal and two Brüel & Kjær 4190 Type I microphones mounted through the sidewall and mounted axially in the base plate under the earcup provide source level and error signal, respectively. The microphone under the earcup represents the location of the external opening to the ear canal. Noise floors of these precision microphones average 50 dB in the measurement range 40-1250 Hz.

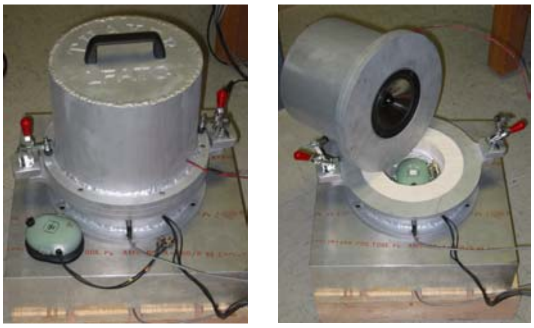


Figure 3: Low Frequency Acoustic Test Cell

Figure 4: HEAD Measuring System

The HEAD Acoustics Artificial Head Measurement System, shown in Fig. 4, reproduces head related transfer function characteristics in order to further evaluate the hearing protection system objectively at realistic source levels. This system provides an intermediate facility between that of the LFATC and human subject testing for evaluation of active hearing protection. In a quiet room with negligible building vibration and mechanical equipment, the noise floor of the HEAD microphones averages 55 dB.

The earcup was developed in-house from commercial components. Modification of a commercial feedback earcup for feedfoward ANR is described in [1]. The passive attenuation of the earcup is 5 dB at 50 Hz, increasing to 30 dB at 800 Hz [9]. The earplug consists of a commercial earphone for military applications modified for ANR. Knowles FG-3329 microphones are introduced for reference and error sensing. A foam tip provides good passive attenuation. Since earphone performance depends on the trapped volume of air, the cancellation path transfer function of the earplug is measured in the test cell (with an appropriate adaptor to insert the earphone into the flat plate above the B&K microphone), on the manikin, and on a human subject. While neither flat plate testing nor manikin testing represent the characteristics of a human ear, to first order, the cancellation path transfer function shown in Figure 2b is qualitatively similar to that of the earplug when inserted into a human ear.

A variety of noise sources were selected for the performance evaluation, depending on the device tested: (1) Individual tones at 1/3-octave band center frequencies, (2) a sum-of-tones signal, (3) F-16 cockpit noise, (4) Huey helicopter noise, and (5) UH-60A Blackhawk noise. Within the LFATC, signals are band limited 50-800 Hz. These noise sources can be viewed as increasingly less ideal operating conditions. F-16 aircraft noise is similar to band-limited pink noise. However, the two minute noise source recording used in experiments exhibits significant temporal variation as described in [8]. Huey helicopter noise also resembles pink noise, but with the addition of 55 Hz tonal components and associated harmonics and impulsive staccato components in the time domain from the rotor blades passing 10.7 times per second. Blackhawk noise has a similar broadband spectrum, but with high frequency tones due to gear whine and its harmonics. For earcup testing within the LFATC, sources are set to levels between 105 and 110 dB to avoid distortion in the cancellation speaker and saturation of the reference microphone. For earplug testing on a manikin, source levels are set at approximately 100 dB to permit a human to work in test area. All noise levels are reported in dB relative to a 20 μPa reference pressure.

The hybrid controller is implemented on a dSPACE DS1103 controller board. The controller board is based on a PowerPC 604e microprocessor running at 400 MHz. The dSPACE board provides on-board 16-bit A/D and 14-bit D/A converters. The hybrid system operates at an update frequency of 10 kHz for the earcup and 15 kHz for the earplug. Anti-aliasing filters are present on all microphone channels, and anti-imaging filters on all speaker driver channels. In the LFATC, performance data are given as the difference between the precision microphone outside of the earcup and the one inside in the base of the test cell, which accounts for the separation path between the noise source and the wearer's ear, or as the difference between the reference and error ANR microphones, which are calibrated to the precision B&K microphones. For earplug testing, performance is measured as the insertion loss at the manikin ear microphone, or as the difference between the reference and error ANR microphones, which are calibrated to B&K microphones.

4.0 EXPERIMENTAL RESULTS

4.1 Commercial Circumaural Earcup

The results for the earcup are summarized from [9]. Figure 5 shows the active attenuation of the sum-of-tones 50-800 Hz, F-16, and Huey helicopter noise sources, as measured by the B&K precision microphone located inside the earcup. *Active Attenuation* is the difference between the noise level with passive attenuation only and the noise level with both passive and active attenuation. For all three noise sources, the feedback system has low level (5-10 dB) but high bandwidth noise reduction capabilities. For tonal noise, the feedforward system performs exceptionally well in the range 80-400 Hz, with diminished performance above and below that range. Whereas both systems have only moderate to good attenuation below 100 Hz, the combined system is able to provide approximately 30 dB of active attenuation at these frequencies. Combining the two independent systems has resulted in performance that is greater than the sum of its parts, with total attenuation of the sum-of-tones of 36 to 51 dB in the 40-800 Hz band.

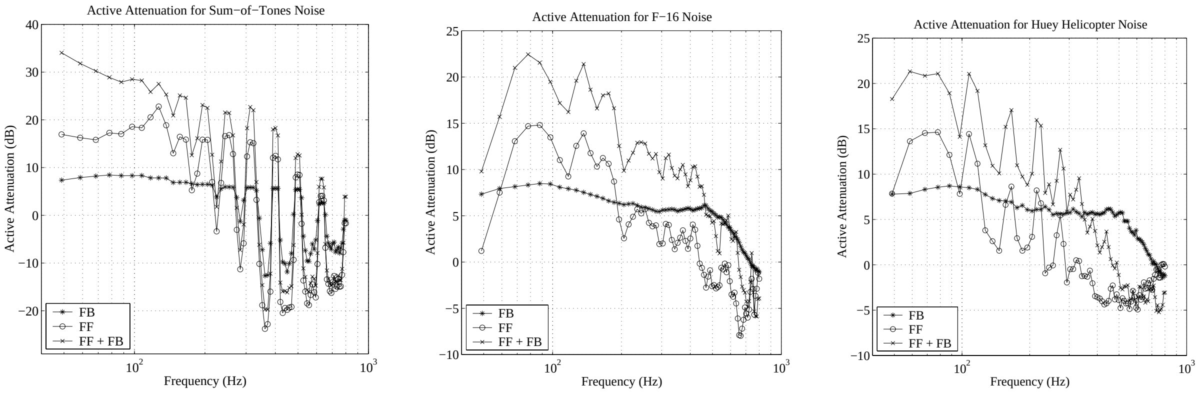


Figure 5: Active Attenuation performance of the hybrid ANR for a commercial circumaural earcup (a) Sum-of-Tones noise at 110 dB, (b) F-16 cockpit noise at 110 dB, and (c) Huey helicopter noise at 105 dB.

Table 1: Summary of performance for commercial earcup modified for hybrid ANR

Noise Source	Average Noise Level (dB)					Total Attenuation (dB)			Active Attenuation (dB)		
	Source	Passive	Feedb.	Feedf.	Hybrid	Feedb.	Feedf.	Hybrid	Feedb.	Feedf.	Hybrid
Sum-of-tones 50 - 800 Hz	110	98	90	81	71	20	29	40	8	17	27
F-16 Cockpit 50 - 800 Hz	110	95	88	86	78	23	25	32	8	10	17
Huey Cockpit 50 - 800 Hz	105	94	86	84	76	19	22	30	8	11	18

Total noise reduction, which include passive attenuation, causes the error microphone signal to approach its noise floor, thus the noise reduction performance approaches its physical limits. In this case, the feedforward and feedback gains assume one value for all frequencies, and the filtered-X algorithm is not implemented. Nevertheless, the average source level of 110 dB is successfully reduced to 71 dB.

The F-16 cockpit noise most closely resembles band-limited pink noise in that it contains no purely tonal content and, over long time periods, has a fairly uniform spectral component. However, during short periods of time its spectral content shifts considerably, which presents problems for traditional LMS filters. Despite this, the hybrid system provides an average active attenuation of 17 dB (32 dB total attenuation), reducing the 110 dB source level to 78 dB. Once again, the hybrid system has substantially greater performance than either of the independent systems acting alone, particularly for frequencies less than 200 Hz. Additionally, whereas the feedforward system alone *added* noise for frequencies above 500 Hz, the hybrid system largely avoided adding noise in the 50-800 Hz band.

Huey helicopter noise contains broadband nonstationary components like the F-16 noise, but also has a tonal component following a 55 Hz fundamental attributed to the tail rotor, and a temporal component due to blade passage that resembles a periodic broadband impulse. In order to keep the periodic impulse from forcing the ANR systems to over-drive the cancellation speaker, the source level is reduced to 105 dB. Active attenuation results are shown in Figure 5c. Once again, the addition of the feedback system to the feedforward system significantly improved the low-frequency attenuation, in this case by 5-10 dB. The tonal component is eliminated by both the feedforward and hybrid system, but is largely untouched by feedback ANR. The feedback system is unsuccessful in removing the temporal component of the helicopter noise; the feedforward system cannot completely remove it either. In contrast, the combined hybrid system is able to almost completely remove the periodic *thwt*, leaving behind a broadband background noise at an average level of 77 dB. Table 1 summarizes these performance results, showing average source, passive, active, and total noise reduction performance for each noise source for this earcup.

The hybrid system not only improves active performance, but it also improves the gain margin of the individual systems. In the feedback system, increasing the path gain, K_{fb}, generally increases the feedback attenuation. However, the gain that provides maximum noise attenuation is close to the threshold of instability, forcing a common stability-performance tradeoff. In a similar way, without a filtered-X LMS, there is a maximum feedforward gain, K_{ff}, above which the weight vector grows without bound, or overexcites certain frequencies. When the two systems are combined, both gains can be increased to levels that otherwise would cause instability, and the increased gain allows for higher overall active attenuation. Alternatively, the hybrid system can provide the same attenuation levels as individual feedforward and feedback components with larger stability margins. Larger stability margins provide a margin against uncertainty in the earcup transfer function or speaker performance. For the feedback system, adding the feedforward system allows K_{fb} to be increased by approximately 20% before instability reoccurs. However, the increased stability is

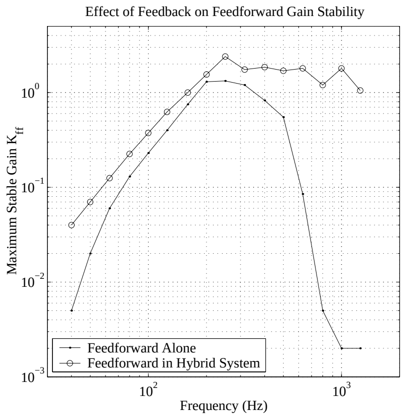


Figure 6: Maximum stable gain (K_{ff}) of the feedforward system for earcup

most notable in the feedforward system. Figure 6 shows the *maximum stable* (not necessarily optimal) feedforward gain K_{ff}, as determined experimentally, as a function of frequency. Figure 6 shows that by augmenting the feedforward system with feedback, the maximum stable K_{ff} can be increased by orders of magnitude at some frequencies.

4.2 Prototype ANR Earplug

Figure 7 shows the ANR earplug developed for evaluation of the hybrid architecture, with the earplug inserted in the left ear of the HEAD manikin. An unmodified communication earplug is inserted in the right ear. Manikin test results are reported for tonal noise, sum-of-tones at 1/3 octave band center frequencies 80-1250 Hz, and UH-60 helicopter cockpit noise. Passive and total ANR performance is measured as the insertion loss between the unoccluded ear and the occluded ear. In addition, total performance is provided as measured by the difference between the ANR reference microphone and the ANR error microphone, both of which are calibrated to the B&K microphones within the LFATC.

Figure 7: ANR earplug on manikin

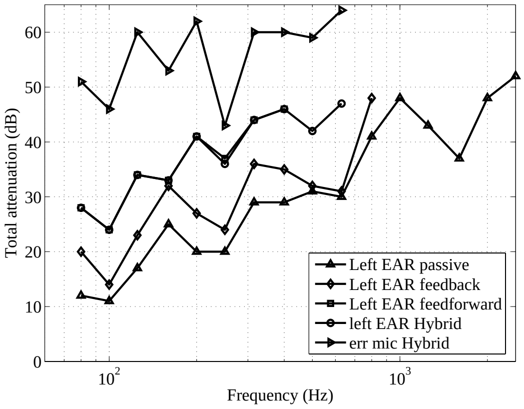


Figure 8: Pure tone performance of ANR modified earplug as measured by insertion loss at HEAD in-ear microphone and between ANR microphones.

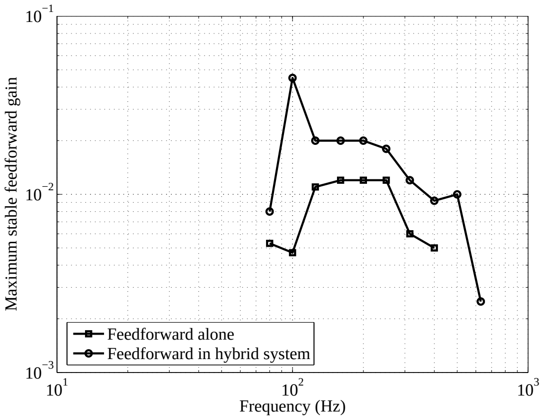
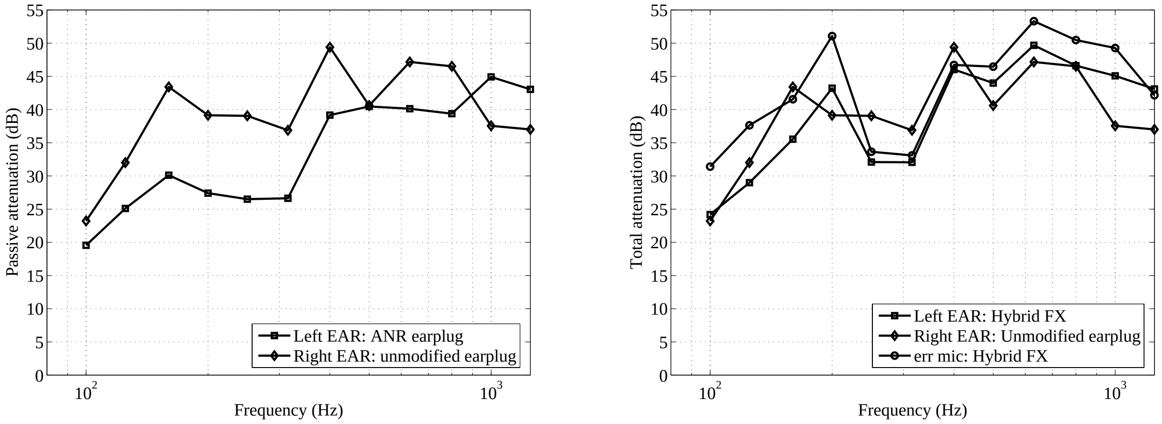


Figure 9: Maximum stable gain (K_{ff}) of the feedforward system for ANR earplug

Figure 8 shows passive performance of the ANR modified earplug, measured for pure tones, as well as the total (active+passive) performance for feedback, feedforward, and hybrid ANR measured at the manikin ear. Hybrid performance is also provided at the error microphone. Passive attenuation is reduced in the mid-frequency range by earplug modification, but high frequency passive attenuation is similar to the unmodified earplug. The feedback compensator gain is fixed at a value that provides a 6 dB gain margin and the feedforward compensator gain is tuned to maximize performance at each frequency. The feedback compensator provides a modest (2 to 6 dB) attenuation over the frequency range measured, while the feedforward compensator alone or hybridized with the feedback compensator provides an additional 8 to 15 dB from 80 to 630 Hz as measured at the in-ear microphone. However, for both the feedforward system alone and the hybrid system, the sound level at the ANR error microphone is reduced to its noise floor for all tones except 80 Hz and 160 Hz, thus at source levels tested, ANR performance is maximized at the error microphone. Total performance for tonal noise measured at the error microphone is 45 to 60 dB. For pure tone ANR experiments, after passive attenuation, the in ear microphones range from 0 (at 800 Hz) to 23 dB (at 200 Hz) above the 55 dB noise floor, thus at some frequencies there is insufficient signal-to-noise ratio to demonstrate ANR performance at the in-ear microphones.

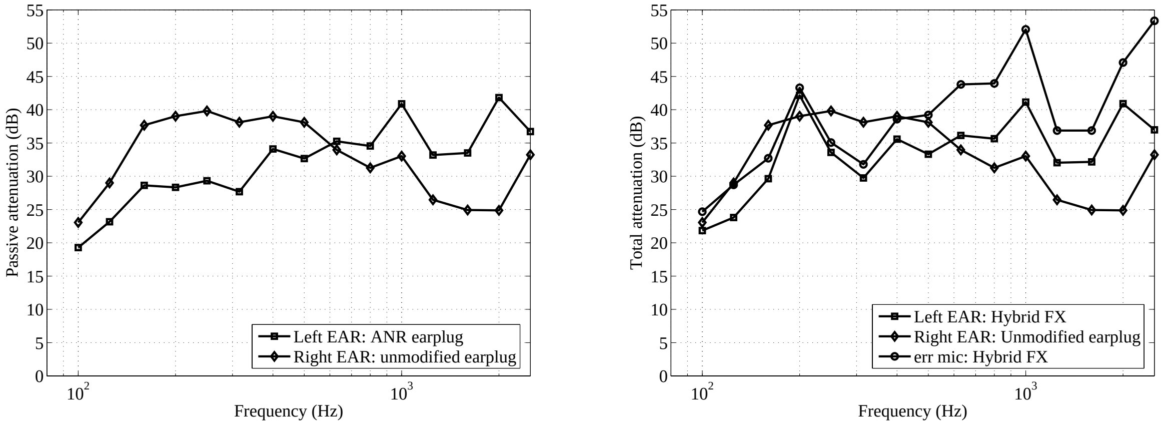
Although both feedforward and hybrid ANR can drive the error signal to its noise floor for single tones, as with the earcup, there is a stability benefit of hybrid ANR. Figure 9 shows the maximum stable feedforward gain for the feedforward system alone and for the hybrid system. The maximum stable feedforward gain changes sign above 400 Hz for the feedforward system alone. For the hybrid system, the crossover increases to 630 Hz. Figure 11 shows that the maximum stable feedforward gain increases by a factor of two to ten over the 80 to 630 Hz range through hybridization.

The variation in cancellation path gain requires the implementation of a filtered-X LyLMS filter for composite noise. The filter models the acoustic cancellation path of the manikin with a deep inserted ANR earplug. With the filtered-X LyLMS, a single feedforward gain is chosen to accommodate all frequencies of interest. Figure 10 shows passive and total ANR performance for sum-of-tone noise 80-1250 Hz for the ANR earplug and the unmodified earplug, and Figure 11 shows passive and total ANR performance for UH-60 helicopter noise. For sum-of-tone noise, the hybrid system provides a modest increase in performance of the ANR earplug over its passive performance of 0 dB (at 1250 Hz) to 19 dB (at 200 Hz) as measured at the ear microphone, with no spillover (negative attenuation). The ANR performance for the modified earplug is 0 to 25 dB at the error microphone for sum-of-tone noise and 0 to 15 dB for UH-60 noise.



(a) (b)

Figure 10: Performance of ANR earplug for sum-of-tones at 1/3 octave band center frequencies 80-1250 Hz, source level 102 dB, (a) passive attenuation of modified and unmodified earplug, (b) Total attenuation of ANR earplug.



(a) (b)

Figure 11: Attenuation performance of ANR earplug for UH-60 helicopter noise, source level 97 dB (a) passive attenuation of modified and unmodified earplug, (b) Total attenuation of ANR earplug.

Table 2: Summary of performance for communication earplug modified for hybrid ANR

	Average Noise Level (dB)					Total attenution (dB)		Active attenuation (dB)	
Noise Source	Source	Passive unmodified	Passive ANR	Feedb.	Hybrid	Feedb.	Hybrid	Feedb.	Hybrid
Sum-of-tones 80 - 1250 Hz	102	69	73	70	66	32	36	3	7
UH-60 cockpit noise	97	63	66	62	60	35	37	4	6

Table 2 summarizes manikin test results for the earplug showing that, on average, the ANR modified earplug loses 3-4 dB of passive attenuation through modification and gains 6-7 dB through active noise reduction at source levels tested. While the total attenuation of the ANR earplug remains below the passive attenuation of the unmodified earplug at some frequencies, a production earplug, in which the error microphone is integrated in the earplug body could retain good passive attenuation; hence, the projected total attenuation achievable by the active earplug is the sum of the passive performance of the unmodified earplug and the active performance of the ANR earplug. These results suggest that an ANR earplug that retains the passive performance of the unmodified earplug can achieve an average performance improvement of 9-11 dB using the present hybrid ANR algorithm at source levels tested. Unlike the earcup experiments within the LFATC, where source levels allowed operation significantly above the noise floor, source levels used for earplug testing do not permit operation at more than 5-18 dB above the noise floor of the manikin in-ear microphones, thus performance can be expected to improve as source level increases.

CONCLUSION

A hybrid ANR architecture has been evaluated for two hearing protection devices – a commercial circumaural earcup and a commercial communication earplug, both modified for feedforward ANR. The basic hybrid architecture comprised of a broadband feedback controller and a Lyapunov-tuned leaky LMS feedforward component provides increased stability margins over each control component acting alone. Experimental evaluation of the earcup through flat plate testing shows total performance ranging from 30 dB for Huey helicopter noise to 40 dB for sum-of-tone noise. For the ANR earplug, total performance is 36 to 37 dB for sum-of-tone noise and UH-60 helicopter noise. For both systems, stability margins increase through hybrid ANR, without a loss in ANR performance.

ACKNOWLEDGEMENTS

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