On Mitigating Acoustic Feedback in Hearing Aids with Frequency Warping by All-Pass Networks

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Abstract

Objective:

- To improve acoustic feedback reduction in hearing aids (HAs) with a new frequency warping technique based on all-pass networks for the Open Speech Platform (OSP): `http://openspeechplatform.ucsd.edu`.

Methods:

- "Freping" — a portmanteau for **fre**quency war**ping** — based on all-pass filters in a network [1].
- Cascade of 1st order IIR filters for nonlinear input-output frequency mapping of signals.
- Helps break both magnitude and phase conditions of Nyquist stability criterion (NSC) [2] and improves adaptive feedback cancellation (AFC), with minimal distortion in output speech quality.
- Objective quality metrics: the perceptual evaluation of speech quality (PESQ) and the hearing-aid speech quality index (HASQI) are used to evaluate the proposed method.

Results

- Quality improvements with freping:
  * **PESQ: 2.56 to 3.52 and HASQI: 0.65 to 0.78** for a basic AFC at a gain setting of 20.
  * **PESQ: 2.75 to 3.17 and HASQI: 0.66 to 0.73** for an advanced AFC at a gain setting of 30.
- Added stable gain (ASG) improvements with freping for a desired quality lower bound (e.g. HASQI = 0.8):
  * **2.5 dB for a basic AFC.**
  * **1.4 dB for an advanced AFC.**

1 Revisiting all-pass networks

The all-pass networks described in [1] realize a nonlinear mapping of the frequency axis controlled by a single warping parameter α. Let ω be the normalized angular frequency and $\hat{\omega}$ be the warped frequency. The mapping $\theta(\cdot)$ is according to:

$$\hat{\omega} = \theta(\omega) = \omega + 2\arctan\left(\frac{\alpha \sin\omega}{1-\alpha\cos\omega}\right), \quad -1 < \alpha < 1. \quad (1)$$

It can be shown that, this mapping between a signal $v(n)$ and its frequency-warped version $q(k)$ can be achieved by the network shown in Figure 1.

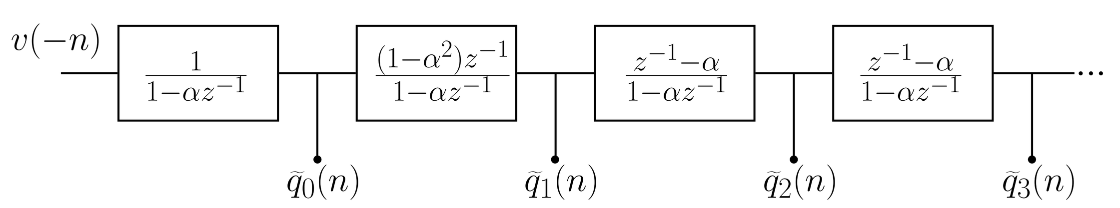

Figure 1: The all-pass network for frequency warping. The time-reversed signal $v(-n)$ is first passed through the network and then $q(k)$ is given by sampling $\tilde{q}_k(n)$ along the cascade chain at $n = 0$, i.e., $q(k) = \tilde{q}_k(0)$ [1].

2 Freping: real-time frequency warping

The all-pass networks described above are adopted for real-time frequency manipulations as illustrated in Figure 2.

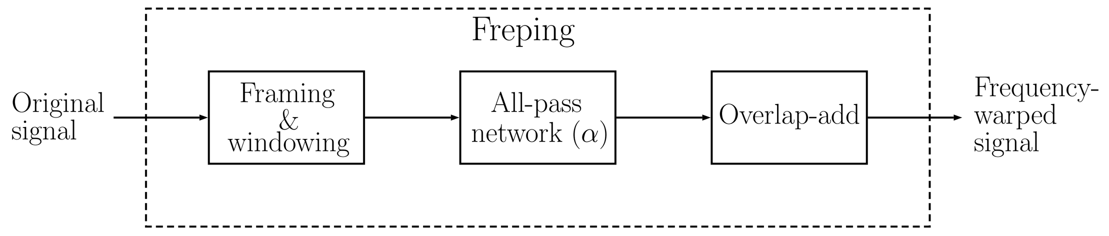

Figure 2: Short-time frequency warping using all-pass network. The input is first divided into overlapping frames followed by windowing. Each windowed segment then goes through the all-pass network to perform frequency warping with a specified warping parameter α. Finally, the overlap-add method is applied to produce the output.

To allow a more flexible way of manipulating spectral characteristics, we propose the multichannel freping as in Figure 3.

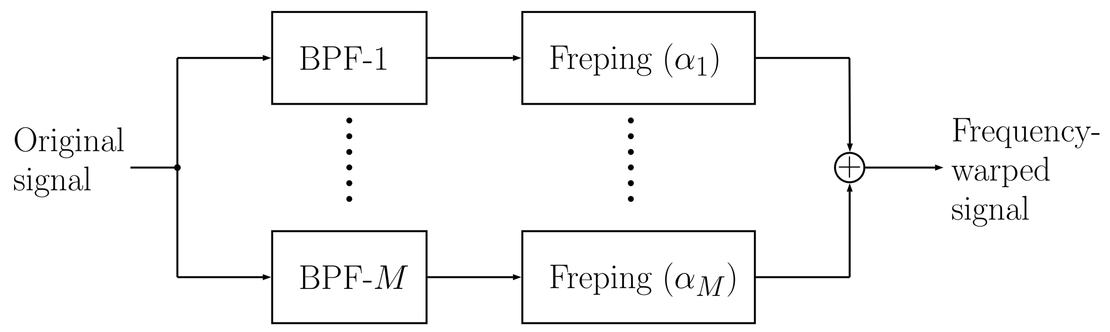

Figure 3: Multichannel freping. The system utilizes a set of band-pass filters (BPFs) which divide the input into M frequency bands. Each band goes through an independent all-pass network with the corresponding warping parameter α_i, for $i = 1, 2, ..., M$. The output of all the frequency bands are summed up to produce the final frequency-warped signal.

3 Freping for acoustic feedback reduction

3.1 Adaptive feedback cancellation (AFC) system

We adopt the AFC framework used in [3] as depicted in Figure 4.

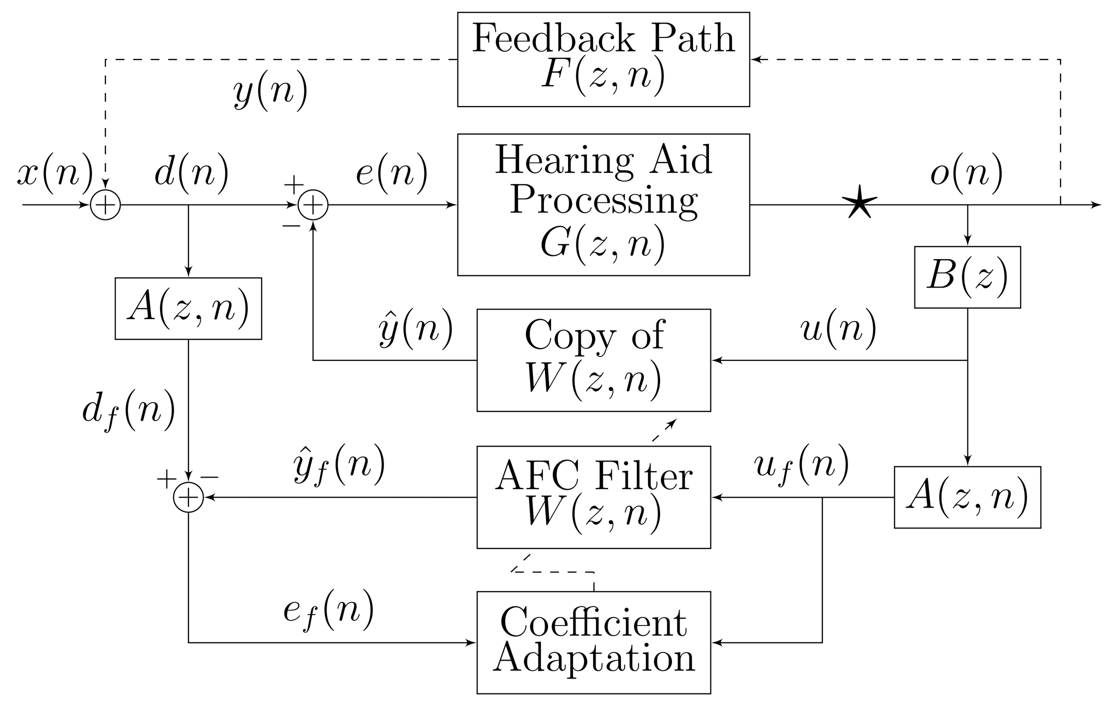

Figure 4: Block diagram of the AFC framework. The AFC filter $W(z,n)$, in parallel with the HA processing $G(z,n)$, continuously adjusts its coefficients to capture the time-varying nature of the acoustic feedback path $F(z,n)$. The microphone input $d(n)$ contains the clean signal $x(n)$ and the feedback signal $y(n)$ caused by the HA output $o(n)$ passing through the feedback path. $\hat{y}(n)$ is the feedback estimate and $e(n) = d(n) - \hat{y}(n)$ is the feedback-compensated signal. $A(z,n)$ is a time-varying pre-filter and $B(z)$ is a band-limited filter for decorrelation purpose. $\star$ represents the place for performing freping.

3.2 Mitigating Nyquist stability criterion (NSC)

The NSC [2] states that the closed-loop HA system becomes unstable whenever the following conditions are both fulfilled:

$$\begin{cases} \left|G(e^{j\omega},n)F(e^{j\omega},n)\right| \geq 1, & \text{(magnitude cond.)} \\ \angle G(e^{j\omega},n)F(e^{j\omega},n) = m2\pi,\ m \in \mathbb{Z} & \text{(phase cond.)} \end{cases}. \quad (2)$$

When employed in AFC, it becomes:

$$\begin{cases} \left|G(e^{j\omega},n)(F(e^{j\omega},n) - \hat{F}(e^{j\omega},n))\right| \geq 1, \\ \angle G(e^{j\omega},n)(F(e^{j\omega},n) - \hat{F}(e^{j\omega},n)) = m2\pi,\ m \in \mathbb{Z} \end{cases}, \quad (3)$$

where $\hat{F}(e^{j\omega},n) = B(e^{j\omega})W(e^{j\omega},n)$ is the feedback path estimate. Improvement to AFC is achievable by placing freping at $\star$ in Figure 4. Distortions introduced by freping appear to be perceptually benign based on informal subjective assessments.

4 Evaluation

4.1 Speech quality considerations

We directly performed freping on the speech signal and measured the frequency distortion at the output as shown in Figure 5.

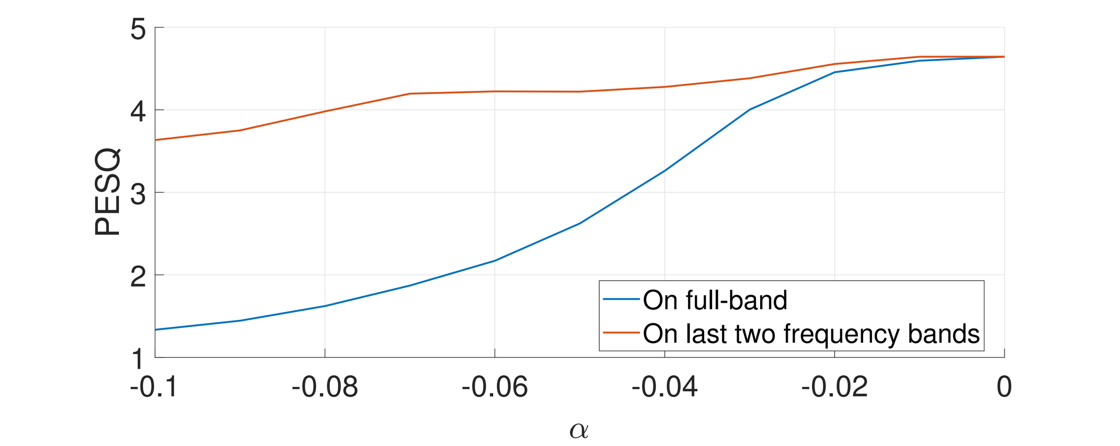

Figure 5: PESQ of freping output vs. warping parameter α. Freping only in the higher bands causes less degradation in speech quality. HAs tend resonate at higher frequencies due to feedback.

4.2 HA output quality

We study freping on top of the least mean square (LMS) (a basic AFC) and the sparsity promoting LMS (SLMS) of [3] (an advanced AFC) and the results are shown in Figure 6.

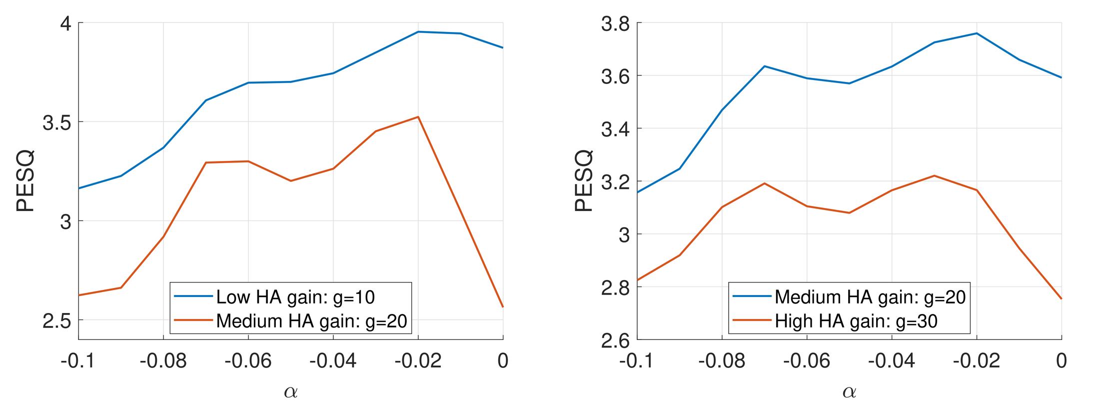

Figure 6: PESQ of HA output $o(n)$ as a function of α for AFC using LMS (left) and SLMS (right). $\alpha = -0.02$ improves AFC performance, while maintaining speech quality (see Figure 5).

4.3 Feedback reduction improvement

Figure 7 shows example spectrograms for demonstrating feedback reduction improvement with a speech input signal. Figure 8 compares the performance with an existing frequency shifting (FS) method of [4] in terms of HASQI. Table 1 compares the performance in terms of added stable gain (ASG).

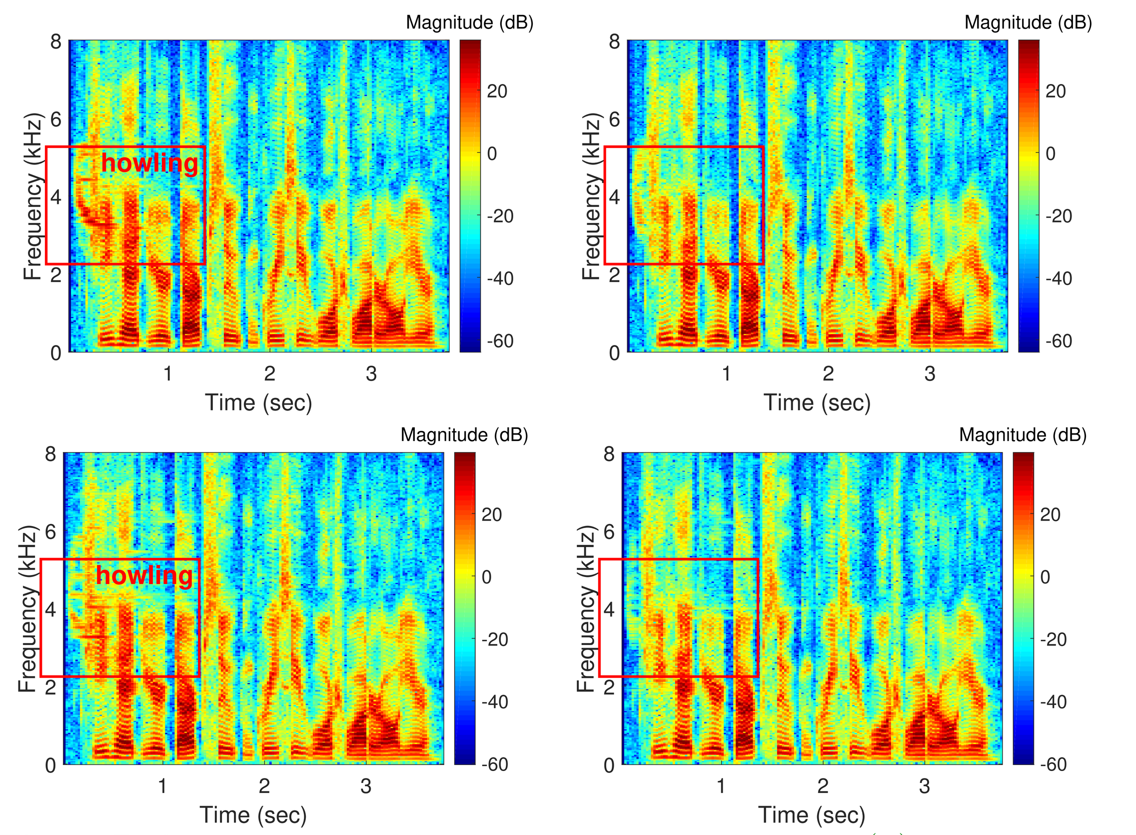

Figure 7: Spectrograms of feedback-compensated signal $e(n)$. The top row is for LMS with HA gain at 20 and the bottom row is for SLMS with HA gain at 30. Freping is disabled in the left column and enabled with $\alpha = -0.02$ in the right column.

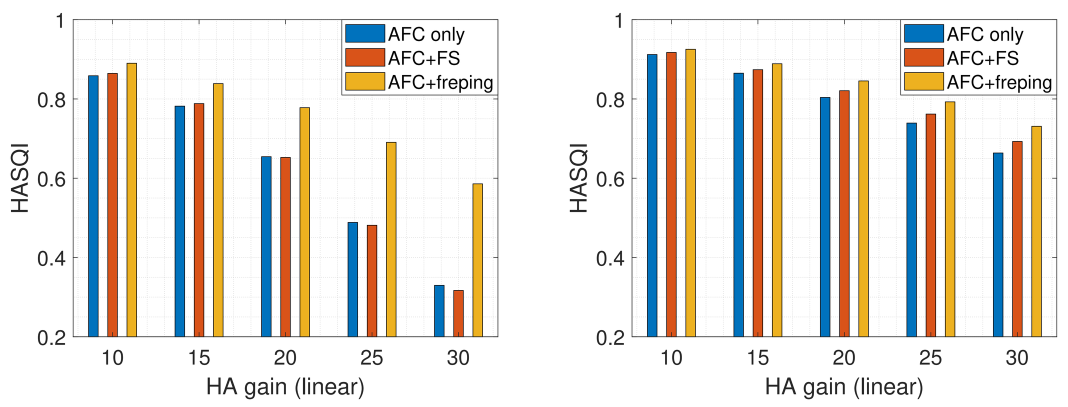

Figure 8: HASQI of feedback-compensated signal $e(n)$ for AFC using LMS (left) and SLMS (right). AFC+FS corresponds to the frequency shifting (FS) method described in [4].

Table 1: Added stable gain (ASG) comparison (in dB). Freping helps AFC algorithms achieve larger stability margin.

AFC algorithms	AFC only	AFC+FS	AFC+freping
LMS	14.41	15.05	**16.90**
SLMS	17.87	18.47	**19.31**

5 Conclusion

In this paper, we proposed and described real-time realization of multichannel "freping" for frequency warping in HAs and its use for breaking the NSC in acoustic feedback control. Experimental results demonstrate quality improvements with freping for basic and advanced AFC approaches.

6 Acknowledgements

This work was supported by NIH/NIDCD grants R01DC015436 and R33DC015046.

References

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