FREQUENCY SHIFTING FOR ACOUSTIC HOWLING SUPPRESSION

Edgar Berdahl
Center for Computer Research in Music and Acoustics (CCRMA), Stanford University
Stanford, CA, USA

Dan Harris
Sennheiser Research Laboratory
3239 El Camino Real, 3rd Floor
Palo Alto, CA, USA

ABSTRACT

Acoustic feedback is capable of driving an electroacoustic amplification system unstable. Inserting a frequency shifter into the feedback loop can increase the maximum stable gain before instability. In this paper, we explain how frequency shifting can effectively smooth out the feedback loop magnitude response and how this relates to the system stability. Then we describe measurements on real acoustic systems that we employ to study the practical performance. Although useful for stabilizing systems in reverberant environments, reasonably small amounts of frequency shifting do not provide a significant benefit for hearing aids. It can be helpful to employ a microphone with a focused directivity pattern, and we describe how the directivity pattern may affect the efficacy of frequency shifting.

1. INTRODUCTION

1.1. Motivation

The reader is probably familiar with a situation when someone placed a microphone too closely to a loudspeaker, causing the amplification system to begin "howling" unpleasantly. Figure 1 illustrates the signal flow for acoustic feedback. A person sings into a microphone, which sends an electrical signal to a controller with z-domain transfer function $K(z)$, which drives a loudspeaker accordingly. When the volume is increased, $|K(z)|$ is increased. $G(z)$ represents the acoustic feedback path from the loudspeaker back to the microphone. For convenience, we lump the microphone and loudspeaker transducer dynamic responses into $G(z)$.

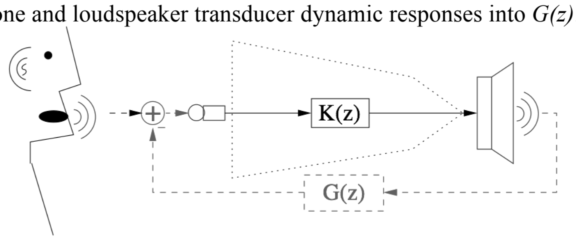

Figure 1: *Person singing into a microphone, whose signal is processed by an amplifier with transfer function K(z) and fed to a loudspeaker; acoustic path from loudspeaker to microphone represented by G(z)*

1.2. Linear Time-Invariant System Stability Criterion

Let the open-loop transfer function $L(z)=K(z)G(z)$. Then, if $L(z)$ is open-loop stable, then the feedback system is stable if [1]

$$|L(z_0)| < 1 \tag{1}$$

for all z_0 such that $|z_0|=1$ and

$$\angle L(z_0) = 180^\circ + n360^\circ. \tag{2}$$

Hence, a sufficient condition for the stability is for $|L(z)|$ to be less than unity at all frequencies.

1.3. Time-Varying Block For Frequency Mapping

One way to skirt the linear time-invariant system stability criterion is to make the system time-varying. A simple way to do so is to insert a time-varying block into the amplification block, as shown in Figure 2.

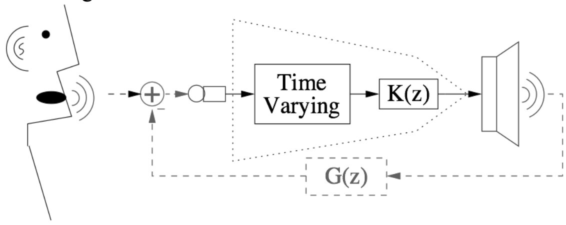

Figure 2: *Configuration in which the amplification block incorporates a time-varying block as well as filter K(z)*

1.4. Frequency Shifting Example For Time-Varying Block

We now introduce an example to demonstrate how the time-varying block can stabilize the system. Let us assume for now that the time-varying block implements a frequency shifter that shifts any input sinusoid up in frequency by Δf Hz. We assume also that it can do the same for any sum of sinusoids. The left-hand column of Figure 3 shows $|L(f)|$, $|L(f)|^2$, $|L(f)|^3$, and $|L(f)|^4$ from top to bottom, respectively. Consider an input sinusoid at a given frequency f in the worst case where $\angle L(z)|_{z=e^{-j2\pi f/f_S}} = 180^\circ + n360^\circ$ for some n and where f_S is the sampling rate in Hz. As the sinusoid travels around the loop, its magnitude is scaled each time by $|L(f)|$. If $|L(f)|$ is greater than 0dB, for instance in this case for f≈5.4kHz, then the sinusoid will increase in magnitude each trip around the loop (see Figure 3, left), destabilizing the system.

The right-hand column of Figure 3 shows $|L(f)|$, $|L(f)|\cdot|L(f+\Delta f)|$, $|L(f)|\cdot|L(f+\Delta f)|\cdot|L(f+2\Delta f)|$, and $|L(f)|\cdot|L(f+\Delta f)|\cdot|L(f+2\Delta f)|\cdot|L(f+3\Delta f)|$ from top to bottom, respectively. With each trip around the loop, a sinusoid with frequency f is shifted upward by Δf, in this case 12Hz. $|L(f)|$ contains many notches and peaks because $G(z)$ is reverberant, so frequency shifting has the effect of smoothing out the peaks and notches, allowing the energy to decay. Hence, frequency shifting stabilizes the system in this example, as indicated by the fact that the magnitude response in the lower right-hand corner is less than 0dB at all frequencies (see Figure 3). Note that because the magnitude criterion analogous to (1) is satisfied, the system is stable no matter what the phase response is.

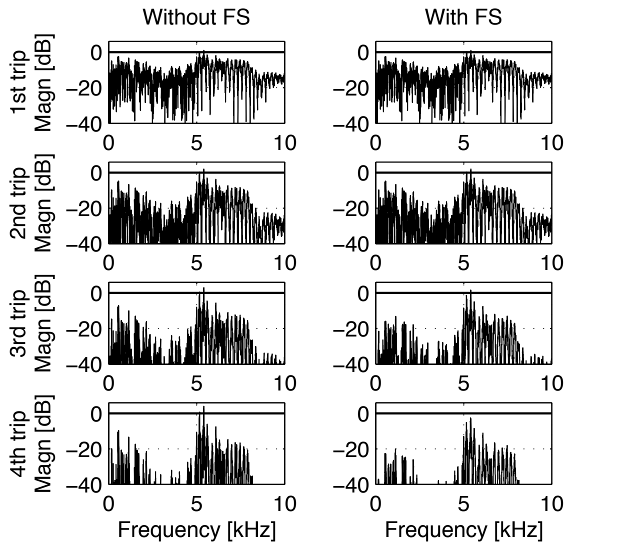

Figure 3: *Change in magnitude of an input sinusoid at frequency f as it travels around the loop*

1.5. Analysis

We now analyze the more general case where the time-varying block implements any arbitrary frequency mapping *F(f)*, and we assume that there is a low-pass filter in the feedback loop preventing aliasing. The sufficient condition for stability becomes more complicated:

$$\lim_{N\to\infty} L(e^{j2\pi F(f)/f_S})\cdot L(e^{j2\pi F^2(f)/f_S})\cdot\ldots\cdot L(e^{j2F^N(f)/f_S}) = 0, \quad (3)$$

where $F^N(f)$ denotes the function *F(f)* composed with itself *N* times. In other words, the time-varying block can smooth out the frequency response employed by the stability criterion. However, the energy has to go somewhere—the time-varying block does not eliminate it. For this reason, the time-varying block will not provide any practical benefit for a system with a flat open-loop magnitude response $|L(f)|$.

The time-varying block could be an *m*-semitone pitch shifter (PS) implementing the frequency mapping

$$F_{PS}(f) = f\cdot 2^{m/12}, \quad (4)$$

resulting in the stability criterion

$$\lim_{N\to\infty} L(e^{j2\pi f\cdot 2^{m/12}/f_S})\cdot L(e^{j2\pi f\cdot 2^{2m/12}/f_S})\cdot\ldots\cdot L(e^{j2\pi f\cdot 2^{Nm/12}/f_S}) = 0\cdot \quad (5)$$

However, pitch shifting does not provide adequate shifting at low frequencies, effectively limiting the performance of the howling suppression [2]. In contrast, a *frequency* shifter (FS) with frequency mapping

$$F_{FS}(f) = f + \Delta f \quad (6)$$

induces a constant frequency shift across the audio band. For frequency shifting, the stability criterion is

$$\lim_{N\to\infty} L(e^{j2\pi(f+\Delta f)/f_S})\cdot\ldots\cdot L(e^{j2\pi(f+N\Delta f)/f_S}) = 0\cdot \quad (7)$$

Other frequency mappings are of course possible and lead to other stability criteria. Other time-varying elements, such as delay modulation and phase modulation, can also increase the maximum stable gain. However, these techniques lead to frequency mappings that do not push the energy in the system monotonically away from the singer's input frequency components [3]. As a consequence, some of the energy can be mapped back onto the original frequency components, causing signal distortion without directly leading to an increase in stable gain.

1.6. Other Methods For Inhibiting Howling

Several other methods can be employed to inhibit howling; however, they either require a priori knowledge about *G(z),* much more computational power, arrays of transducers [4], or they require unusual transducers [5]. Nevertheless, frequency shifting is the simplest known approach, so we focus on it in this paper. Frequency shifting can be implemented with a two-step modulation approach [6], approximate Hilbert transformers [2], or a phase-vocoder [7], which allows for more complex frequency mappings *F(f)*.

To facilitate further study of the performance of frequency shifting, we employ a model that simulates the signal flow diagram shown in Figure 2. In Section 2, we describe the measurements we made for calibrating the model to real acoustic environments. In Section 3 we describe the simulation results, and finally in Section 4 we provide links to sound examples to help the reader gain more intuition into the perceptual artifacts caused by frequency shifting for public address system stabilization.

2. MEASUREMENTS

2.1. Room

Consider an application where a vocalist sings into a microphone, and a loudspeaker "monitor" sends an amplified acoustic wave back at the singer so that he or she can hear himself or herself. There is a serious danger of acoustic howling setting in because the microphone can also pick up the signal from the monitor. In response, microphone manufacturers have produced microphones with directional directivity patterns. For instance, an ideal cardiod microphone has a null in the directivity pattern that can be aimed at a monitor. In an anechoic chamber and in the absence of reflections off of other objects, the acoustic feedback from the monitor could be completely suppressed. However, in real configurations, room reflections will cause some feedback signal to be transduced by the microphone. We decided to make some measurements to help us quantify this effect. We employed the Sennheiser MKH 800 Twin microphone because its directivity pattern is adjustable. The two microphone signals correspond to cardiod directivity patterns pointing in opposite directions: one toward the front of the microphone and one toward the back.

We placed a monitor loudspeaker on a table, and measured the acoustic feedback transfer functions with the microphone placed at the 18 positions shown in Figure 4. Positions 1 though 8 were on axis with the loudspeaker (see the loudspeaker encircled in white in Figure 4). At each position, we measured the transfer function with the

- cardiod directivity pattern facing toward the monitor,
- cardiod directivity pattern facing away from the monitor,
- and an omnidirectional pattern, calculated by summing the transfer functions for the two cardiod patterns [8].

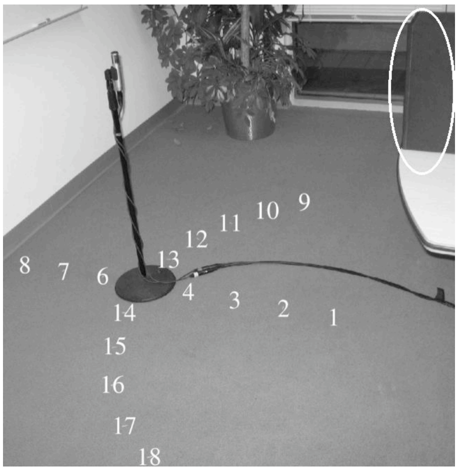

Figure 4: *Microphone positions for measuring feedback transfer functions in a typical room*

The cardiod directivity pattern pointing away from the loudspeaker successfully decreased the level of the feedback transfer function, especially at low frequencies. In order to produce a viewable figure, it was necessary to greatly smooth out the feedback transfer functions, which averaged out the peaks and notches due to room reverberation. (Refer to Figure 3, top as a reminder of what these sort of feedback transfer functions look like without smoothing.) Figure 5 shows the significantly smoothed feedback transfer function magnitudes for the three directivities as measured at position 5 as pictured in Figure 4. Beneath 6kHz, the cardiod directivity pattern aiming away from the loudspeaker decreased the average level of the feedback transfer function by the order of 10dB plus or minus about 5dB (see the thick, solid line in Figure 5). In contrast, the cardiod directivity pattern aiming at the loudspeaker was responsible for higher levels (see the dash-dotted line in Figure 5). Similarly, the thin, solid line in Figure 5 indicates that the omnidirectional response level was similar to the cardiod directivity pattern aiming at the loudspeaker. This was because the omnidirectional response was the complex sum of the two directivity patterns [8].

These measurements explain why it is desirable to employ a directional microphone for suppressing acoustic feedback, although for a cardiod directivity pattern, the increase in maximum stable gain will only be 5dB to 10dB in typical applications if the loudspeaker is placed in the null of the cardiod pattern. If the loudspeaker is not directly placed in the null, the increase in maximum stable gain will be even less in typical applications.

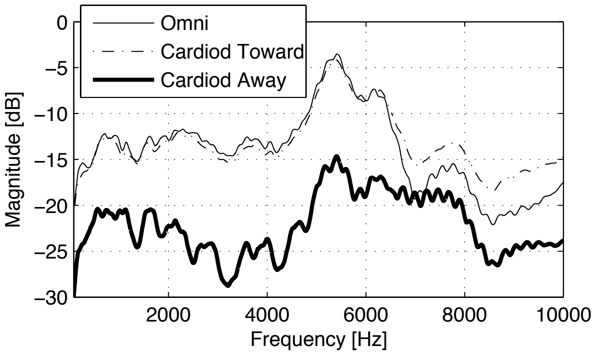

Figure 5: Smoothed *feedback transfer function magnitudes |L(f)| for real room measurements*

2.2. Hearing Aids

As far as we know, no prior papers in the literature studied the application of frequency shifting to stabilizing hearing aids, so we decided to include hearing aid feedback transfer functions in our simulations. We obtained 192 of these transfer functions from Johan Hellgren, who extensively studied how they change as a function of jaw movements, variations in the acoustics outside the ear, and variations in the hearing aid vent size [9]. We plot some example measured feedback transfer function magnitudes in Figure 6 for the Oticon Personic 425 behind-the-ear hearing aid. The magnitude depended on many factors, such as whether or not the hearing aid wearer was biting down, wearing a knitted cap that extended over the ears, or whether he or she was hugging someone. Because the microphone and loudspeaker of the hearing aid were so closely spaced, the hearing aid acoustic feedback transfer functions contained little influence from reverberation, which explains why in contrast with Figure 3, the feedback magnitude responses shown in see Figure 6 were *not* jagged.

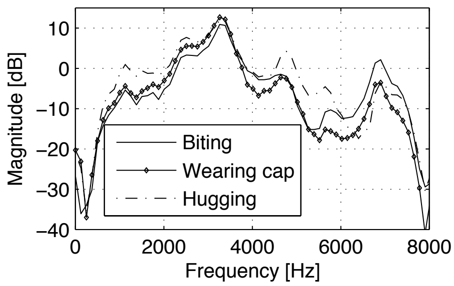

Figure 6: *Feedback magnitude responses for Oticon Personic 425 behind-the-ear hearing aid*

3. SIMULATIONS

3.1. Results

Using the measurements, we carried out a series of simulations in order to study the effect of the frequency shifting parameter Δf on the increase in maximum stable gain of the system described in Figure 2. The simulations employed a white noise excitation source and gradually increased the loop gain $K(z)=K$ until the envelope of the loudspeaker signal exceeded the envelope of the noise excitation signal by a factor of 4, approximately indicating the maximum stable gain. Figure 7 shows the increase in the maximum stable gain for the simulations, as computed by subtracting the difference between the maximum stable gain for frequency shifting of Δf Hz and frequency shifting of 0 Hz.

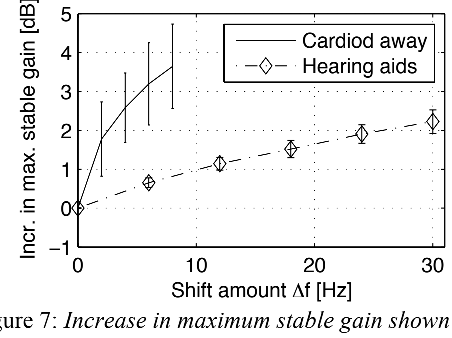

Figure 7: *Increase in maximum stable gain shown as a function of the frequency shift amount Δf*

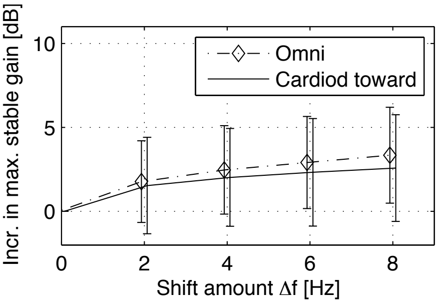

Figure 8: *Increase in maximum stable gain shown as a function of the frequency shift amount Δf*

3.2. Conclusions

3.2.1. *Larger Δf Means Larger Increase In Maximum Stable Gain On Average*

Choosing *Δf* larger increases the amount of smoothing of the feedback transfer function. Although it is possible to find an example where increasing *Δf* causes the maximum stable gain to decrease (not shown); this usually is not the case. As indicated by Figure 7 and Figure 8 for all of the simulated environments, choosing *Δf* larger made the *average* increase in the maximum stable gain larger. One standard deviation variation in the increase in the maximum stable gain is indicated using error bars (see Figure 7 and Figure 8).

3.2.2. *Frequency Shifting Less Effective For Hearing Aids*

As indicated by the dash-dotted plot in Figure 7, frequency shifting did not provide a significant improvement for small values of *Δf*. While it did provide up to 2dB of average increase in maximum stable gain, this was only for values of *Δf* on the order of 30Hz, and above. This reason for this was that the hearing aid feedback transfer functions contained little reverberation (compare the jaggedness of the magnitude responses shown in Figure 6, top with those in Figure 3), so much more significant frequency shifting was required to provide for significant stabilization effects. However, our informal listening indicated that the perceptual artifacts from such large frequency shifts outweighed the increase in maximum stable gain for most applications. Presumably this is the reason why the prior scientific literature does not provide any indication that frequency shifting is useful for stabilizing acoustic feedback in hearing aids.

3.2.3. *Effect of Directivity Pattern*

As indicated in Section 2.1, employing a microphone with a focused directivity pattern, such as a cardiod pattern aimed away from the loudspeaker, can help reduce the magnitude of the feedback transfer function, effectively increasing the maximum stable gain. Changing the directivity pattern also affects the increase in maximum stable gain due to frequency shifting. The cardiod pattern aimed away from the loudspeaker allowed larger average increases in maximum stable gain with lower variation (see the solid line in Figure 7) than the other two patterns as shown in Figure 8. This is a consequence of the increased diffuseness of the reverberation when the loudspeaker is placed in the null of the "cardiod away" pattern.

4. SOUND EXAMPLES

Members of the DAFx community are likely aware of the perceptual impacts of many effects, including pitch shifting; however, the effect of frequency shifting is more esoteric. As a consequence, we provide sample sounds of speech being frequency shifted by different amounts at the website:
`http://ccrma.stanford.edu/~eberdahl/Projects/FreqShift`

5. FINAL WORDS

We have provided sound examples and simulation data to help convey to the reader why frequency shifting is effective, and in what instances it may be useful. Inserting a frequency shifter into the feedback loop of an amplification system can significantly increase the maximum stable gain, but only if the acoustic feedback path is significantly reverberant. Otherwise, such large frequency shifting values *Δf* are required for significant increase in the maximum stable gain that the loudspeaker signal contains excessive artifacts. We believe that this is why hearing aid manufacturers do not report employing frequency shifting for acoustic feedback stabilization. We look forward to future work in evaluating the perceptual tradeoffs between increasing the degree of the impact of the time-varying block and the subjective sound of the loudspeaker signal.

6. REFERENCES

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