Head-related Crosstalk Cancelation on the Back of an Envelope

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The Set-Up

A high-quality crosstalk canceler is the core of Cooper Bauck ® Transaural ® Stereo. The basics of crosstalk cancelation for head-related stereophony can be presented quite simply, even though the implementation of a high-quality device is fraught with endless details and pitfalls. In this paper I will show the basic ideas and refer the interested reader to the references for a taste of the rest.

The *definition* of a crosstalk canceler is some process (circuit or algorithm) which causes the input signal P to appear exactly at one ear but also causes silence at the other ear. Unless stated otherwise, all signals will be expressed as frequency-domain quantities. The signal P is the input, or “program,” signal and E_1 and E_2 are the (acoustic) signals at the left and right ears, respectively. Thus, for crosstalk cancelation, we require $E_1 = P$ and $E_2 = 0$. The transfer functions of the loudspeakers are assumed to be unity. The acoustic transfer function to one loudspeaker to the ear on the same side is S and to the ear on the other (alternate) side is A; these are known in the literature as *head-related transfer functions*, or HRTFs, and have complicated shapes which depend strongly on the angle of the sound source relative the head and rather weakly on the distance of the sound source.

Consider Figure 1. We know that we want to change the (acoustic) signals at the ears of the listener. Since there are two ears, we will use all of our available “degrees of freedom” by inserting two filters with transfer functions X and Y between the input signal P and each of the loudspeakers. The object is to find X and Y in order to cause acoustic crosstalk to be canceled at one ear and the program signal to appear at the other ear. Don’t worry that we are using only one input signal; since the system is linear we can add the other signal with similar processing and simply add everything together (superposition).

The Take-Down

With the transfer function constraints as defined above, we can inspect the block diagram of Figure 1 and write down the equations that we need. Since we want $E_1/P = 1$, we can write the sums of the signals at the left and right ears from each loudspeaker, getting, respectively,

$$XS + YA = 1$$

$$XA + YS = 0$$

These are two linear equations for two unknowns, X and Y, which can be solved using high school algebra, giving us the desired filter transfer functions in terms of the available transfer functions S and A:

$$X = \frac{S}{S^2 + A^2}$$

$$Y = -\frac{A}{S^2 + A^2}$$

The Airhead

As a very crude example, consider a simplified situation in which there is no actual head but only two points in space which we want to pretend could be ears. This model ignores the subtleties of head diffraction and ear (pinna) diffraction, as well as propagation within the ear canal and the terminal impedance represented by the eardrum (which varies dynamically with the amplitude of the sound due to muscles in the inner ear acting as a very effective automatic gain control). With this assumption, we have, removing the overall delay common to both paths,

$$S = 1$$

$$A = ae^{-j\omega\tau}$$

where a represents a bit of $1/r$ attenuation and another bit of head shadowing, $|a| < 1$, and τ is the additional propagation delay due to the more distant ear. The filters become

$$X = \frac{1}{1 - a^2\exp\left(-j\omega 2\tau\right)}$$

$$Y = -\frac{\exp\left(-j\omega 2\tau\right)}{1 - a^2\exp\left(-j\omega 2\tau\right)}$$

How might we build filters with these transfer functions without breaking a sweat? Recall the classic feedback network, Figure 2, with input R, output C, feedforward gain H, and feedback gain G, and internal signals at the indicated nodes D and E. Writing down the signals for C, D, and E in terms of the input signal R and transfer functions H and G and performing three or four lines of algebra gives the possibly familiar result

$$\frac{C}{R} = \frac{H}{1 - GH}$$

$$\frac{D}{R} = \frac{1}{1 - GH}$$

This looks promising; all we need to do is to notice that using

$$H = G = -ae^{-j\omega\tau}$$

solves our filter design problem. These blocks are made by delaying the signal and attenuating it a little. The range of delays varies from 0 to about 600 µs depending on the angle of the loudspeakers from the (air)head. The crosstalk canceler for this example and one ear is shown in Figure 3.

What Just Happened?

There are several ways to interpret the results for the airhead-based crosstalk canceler, and some of them apply to a the crosstalk canceler for a realistic-model head. For example, the reader can verify by direct substitution of the results for H and G into the basic feedback model that $E_1/P = 1$ and $E_2/P = 0$. However, we will look at the results another way.

Consider the time-domain behavior of Figure 3. The form of the input signal isn't important, but it is helpful to imagine that it is a short pulse, say $p(t)$. Since we are disregarding the common propagation delay from the speakers L_1 and L_2, $p(t)$ reaches the left ear immediately. With a delay τ and attenuation a, it also reaches the right ear, where we want the signal to be zero. However, we need to add the signal that propagates from the right loudspeaker which has also been delayed by τ and attenuated by a, as well as inverted, thus canceling the crosstalk pulse from the left loudspeaker. However, this canceling pulse, $a\, p(t - \tau)$, now leaks around to the left ear where it appears delayed once more by the propagation, for a net signal of $-\,a^2\, p(t - 2\tau)$, disturbing the desired result that had just been established. But the upper path in the block diagram comes to the rescue, providing a signal to the left loudspeaker of $a^2\, p(t - 2\tau)$, and the desired result is once again established, if only temporarily. You can follow this infinite recursion around and around and see that the ping-ponging action of the crosstalk canceler provides exactly the correct canceling signals at each ear. Since the process is linear and since any signal can be made up out of a series of weighted and sufficiently short delayed pulses, this process can act as a crosstalk canceler for any signal P or $p(t)$.

Figures

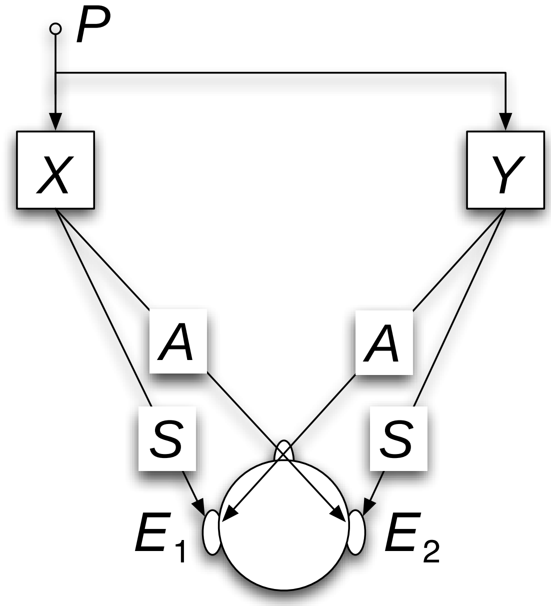

Figure 1. Block diagram for a one-ear crosstalk canceler.

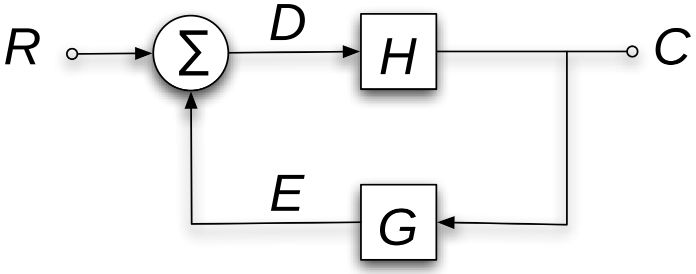

Figure 2. Block diagram of a feedback system.

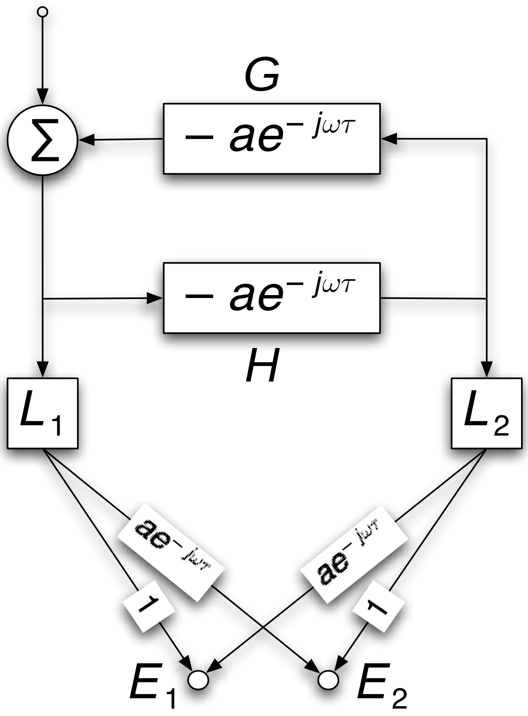

Figure 3. Block diagram of a one-ear crosstalk canceler for the airhead model. Loudspeakers L1 and L2 have unit transfer functions. The input signal appears at the left ear but not at the right ear.

Notes

More details on the theory and design of crosstalk cancelers can be found in “Prospects for Transaural Stereo,” by Duane H. Cooper and Jerry Bauck, published in the Journal of the Audio Engineering Society in January, 1989, and “Generalized Transaural Stereo Theory and Applications,” by Jerry Bauck and Duane H. Cooper in the Journal of the Audio Engineering Society in September, 1996. A related paper, “A Simple Loudspeaker Array and Associated Crosstalk Canceler for Improved 3D Audio,” appeared in the Journal of the Audio Engineering Society in January, 2001. These papers can be purchased for a small fee at www.aes.org. They are also available at www.transaural.com, along with some related Audio Engineering Society convention preprints and PowerPoint presentations.

This white paper is available at www.transaural.com.

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