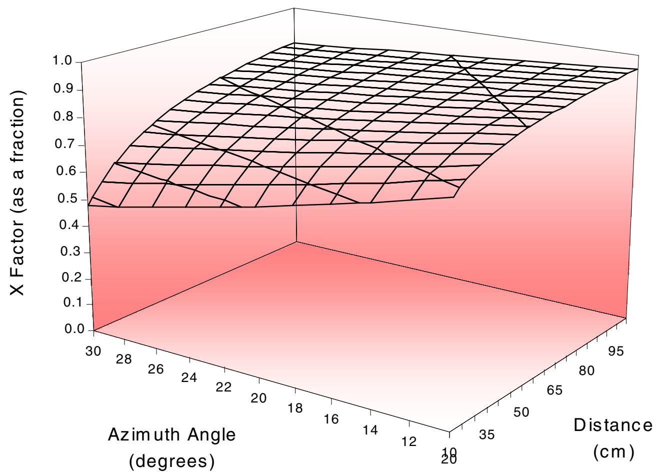
XTC™ crosstalk cancellation

by Alastair Sibbald



The cancellation of transaural acoustic crosstalk is an essential and critical feature of all head-related transfer function (HRTF) based 3D-sound synthesis systems when loudspeakers are used for listening. The foundations of transaural crosstalk cancellation were laid down by Atal and Schroeder[1] in 1962, when it was originally intended for hi-fi applications. By taking account of the angular placement of the loudspeakers, Schroeder[2] described clearly how appropriate signal processing filters could be devised for effective crosstalk cancellation.

However, present-day multimedia loudspeaker configurations differ from conventional hi-fi arrangements in that the speakers are much closer to the listener. This means that the crosstalk signal level is relatively smaller with respect to the primary signal than it would be, say, at two metres distance. Consequently, an effective transaural crosstalk cancellation method must take account of the *distance* of the loudspeaker from the listener, in addition to its azimuth angle. Sensaura XTC™ is the first distance-dependent transaural crosstalk system. The proprietary XTC algorithm uses both the distance and angle of the loudspeakers to calculate precisely the transaural crosstalk level and then generates a very accurate cancellation signal. The algorithm is user-configurable for custom loudspeaker set-ups and can be used with multiple speaker systems (Sensaura MultiDrive™).

1 Introduction

Several complementary technical papers in this series describe the synthesis of three-dimensional sound for reproduction via two loudspeakers, in which the cancellation of transaural acoustic crosstalk is essential. The paper *Transaural acoustic crosstalk cancellation* describes in detail the principles and methodology behind such systems and includes an account of the proprietary Sensaura algorithm which enables the cancellation of differing relative amounts of transaural crosstalk.

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This paper describes further details of the Sensaura crosstalk cancellation scheme (Sensaura XTC) in which the cancellation is precisely specified as a function of both loudspeaker distance and angle. This is not to be confused with the simple use of the appropriate azimuth angle **A** and **S** functions for crosstalk cancellation, which is implicit and well known (for example, the use of 30° functions for speakers at ±30°; 15° functions for speakers at ±15° and so on).

As described in the technical paper *Transaural acoustic crosstalk cancellation*, the fundamental HRTF characteristics which are required to implement such a scheme[1,2] are the left- and right-ear transfer functions associated with the azimuth angle at which the loudspeakers are situated (Figure 1). For most applications, this is commonly accepted to be ±30°.

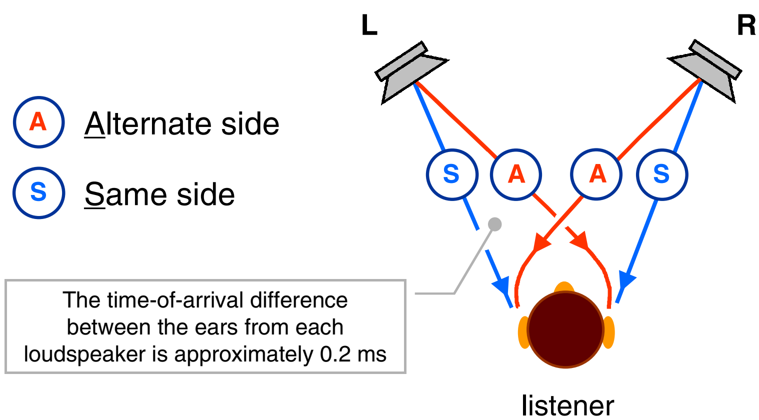

Figure 1: Transfer functions related to two-speaker stereo listening

The near-ear function is sometimes referred to as the *same* side, or **S**, function and the far-ear function as the *alternate* side, or **A**, function. These **A** and **S** characteristics form the basis of all transaural crosstalk cancellation schemes and, from the previous paper, it can be observed that the **A** and **S** functions are combined to form filter blocks of the form:

$$\left(\frac{1}{1-C^2}\right) \qquad (1)$$

(where **C = (-A/S)**)

and

$$\left(\frac{1}{S}\right) \qquad (2)$$

These terms, when compounded together, simplify to form:

$$\left(\frac{S}{S^2-A^2}\right) \qquad (3)$$

It is not easy to obtain reliable measurements of HRTF data (**A** and **S**) at low frequencies for several reasons. These include the poor low frequency (LF) response of the measurement loudspeaker, the presence of standing waves (even in an anechoic chamber) and various LF limitations of the impulse measurement methods which are used.

Consequently, raw HRTF measurements do not contain LF information. Hence, the missing LF properties must be replaced in order to create valid HRTFs. This is conveniently done by extrapolating the amplitude data at the lowest valid frequency (typically 200 Hz) back to 0 Hz (or, in practise, back to the lowest practical frequency, say 10 Hz). If there are any LF errors present in the audio processing chain, they can cause significant audio quality problems. Thus, it is the usual practise to converge both near- and far-ear characteristics of the HRTF to the same value at around 200 Hz and then to extend this same value to the lower frequencies. This provides a flat response below 200 Hz, with similar or identical values for the near-ear and far-ear functions.

2 TCC factor

When a sound wave arrives at the head of the listener from a loudspeaker, it encounters the near ear first, creating a primary signal. It then traverses the head to the far ear, thus creating an unwanted crosstalk signal. The crosstalk signal intensity can be expressed as a fraction of the primary signal intensity in the form of a *crosstalk factor*, **X**. This is largely independent of frequency below several hundred hertz, where diffraction and resonance effects are not significant.

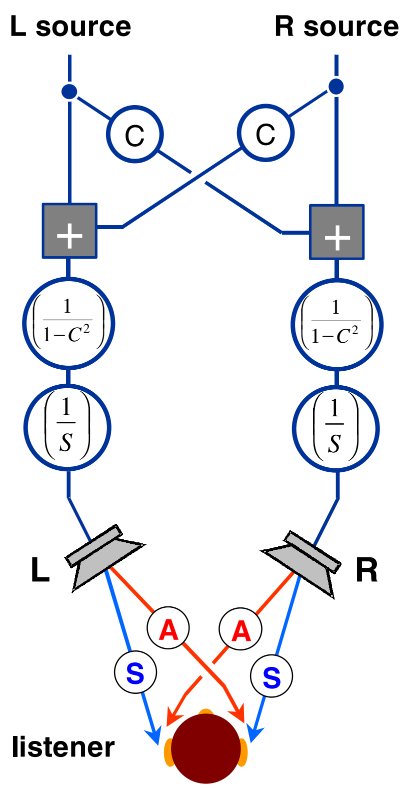

Figure 2: Conventional transaural crosstalk cancellation scheme (Schroeder[2])

As described above, it is standard procedure in conventional transaural crosstalk cancellation schemes (Figure 2) to employ **A** and **S** functions which are artificially forced to converge at several hundred hertz and to be virtually identical at frequencies below this value. This corresponds to a crosstalk factor, **X**, of 100% (i.e. **A** = 100% of **S** at LF). This is reasonable for loudspeakers that are several metres or more away from the listener, as is the case for conventional hi-fi systems. **However, such conventional crosstalk cancellation arrangements are not valid for relatively close loudspeakers, because X is distance dependent (and this distance dependency is also a function of angular position).**

When loudspeakers are closer than several metres to the listener, conventional crosstalk cancellation systems create significantly excessive cancellation signals and therefore the transaural crosstalk is overcancelled, hence reducing the overall effectiveness. For multimedia speakers at 0.6 m distance, the overcancellation error can be as high as 30%.

As an illustration of the effects of using a relatively close loudspeaker, first consider the relative intensities at the far and near ear. When a lateral sound source moves towards the head from, say, 1 m distance, the distance ratio (far ear to sound source vs. near ear to sound source) becomes greater. For example, at 45° azimuth in the horizontal plane, at a distance of 1 m from the centre of the head, the near ear is about 0.95 m distant and the far ear around 1.06 m. This gives a distance ratio of (0.95 / 1.06) = 0.90. When the sound source moves closer, to a distance of 0.5 m, then the ratio becomes (0.45 / 0.57) = 0.79. When the distance is only 20 cm, then the ratio is approximately (0.16 / 0.27) = 0.59. The intensity of a sound source diminishes with distance as the energy of the propagating wave is spread over an increasing area, the wave front being similar to an expanding bubble. Thus, the energy density is related to the surface area of the propagating wave front, which in turn is related by a square law to the distance travelled (the radius of the bubble). Hence, the intensity ratios of left and right channels are related to the ratio of the squares of the distances. The intensity ratios for the above examples at distances of 1 m, 0.5 m and 0.2 m are approximately 0.80, 0.62 and 0.35 respectively. In dB units, these ratios are -0.97 dB, -2.08 dB and -4.56 dB respectively.

It is also important to note that the intensity ratio differences are position dependent. For example, if the aforementioned situation were repeated for a frontal sound source (azimuth 0°) approaching the head, then there would be no difference between the left and right channel intensities because of symmetry. In this instance, the intensity level at both ears would increase simply according to the $1/r^2$ law.

3 Sensaura XTC

Sensaura XTC provides optimal transaural crosstalk cancellation for users of PC-based multimedia systems in which the loudspeakers are relatively close to the listener and might be at a variety of angles and distances, depending on the individual user's set-up configuration and preferences. This has been achieved by deriving a mathematical function for the distance and angle dependency of the transaural crosstalk factor, **X**, such that it can be calculated for any given loudspeaker distance and angle (Figure 3). This, in turn, can be used to control the amount of crosstalk cancellation that is implemented.

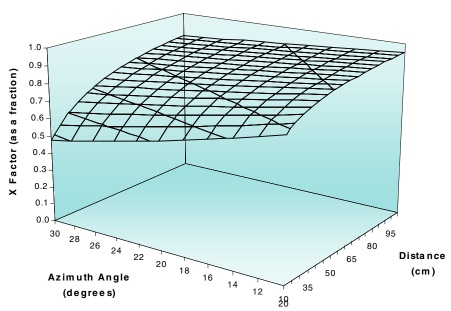

Figure 3: Surface plot of Sensaura XTC transaural crosstalk factor

As described in the paper *Transaural acoustic crosstalk cancellation*, the crosstalk factor, **X**, is incorporated into the overall design architecture (Figure 4) and used with *standard* 1 m **A** and **S** functions. This allows a range of different crosstalk cancellation filters to be created with differing values of **X** for a range of speaker configurations. The end user can then select the most appropriate one for their particular speaker configuration. For example, a range of filters for **X** values in the range, say, 0.5 to 1.0 in 0.05 increments (11 filters) covers most situations, including a hi-fi system, a desktop PC and a laptop PC.

Alternatively, the crosstalk cancellation factor can be used to define the LF asymptote difference of the **A** and **S** function pair, which can then be used in a conventional crosstalk cancellation scheme to the same effect.

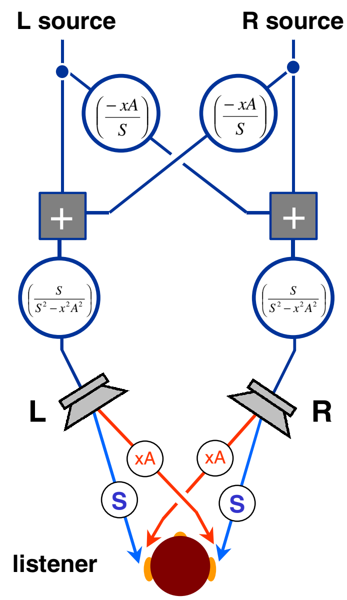

Figure 4: Sensaura XTC transaural crosstalk cancellation scheme (unity-gain option)

Sensaura XTC operates seamlessly with the latest '98 PC operating system. This includes the provision to select a variety of different loudspeaker set-ups, allowing the user to specify the distance between speakers and the distance from head to speaker centre-line. With this information, the software can then determine the optimal transaural crosstalk filtering arrangements.

4 References

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   (Bell Telephone Labs., filed 1962).

2. Models of hearing.
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