A Four-Channel Dynamic Cross-Talk Cancellation System

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Introduction

To reproduce a binaural signal using loudspeakers, a cross-talk cancellation (ctc) system is needed. It is based on the transfer functions from each loudspeaker to each ear. To produce filters for a static cross-talk cancellation system, the four transfer functions are measured with an artificial head. Afterwards the filter set is calculated and used to cancel the cross-talk at the point the artificial head was positioned during the measurement. The filter is valid only in this one point. This fact limits the systems applicability.

An adaptive cross-talk cancellation for a moving listener requires a system being able to provide a valid filter set for each position [3]. With an increase of computation power it is now possible to calculate cross-talk cancellation filters online using an HRTF-Database (Head Related Transfer Functions) and a head tracking system to detect the listener's current position.

A dynamic cross-talk cancellation system using two speakers is already implemented [4] and achieves good results. But head rotation is possible only within the angle spanned by the loudspeakers. Aim of this work is to implement a dynamic four speaker cross-talk cancellation to provide a full head rotation of the user.

Cross-talk cancellation

The problem of loudspeaker reproduction is the cross-talk between the channels that destroys the three dimensional cues of the binaural signal. The requirement for a correct binaural presentation is that the right channel of the signal is audible only in the right ear and the left one is audible only in the left ear [1][2]. This problem can be solved by a cross-talk cancellation filter, which is shown in Figure 1.The four transfer functions are labelled H_{LL}, H_{LR}, H_{RL} and H_{RR}. H_{LR} and H_{RL} indicate the cross-talk paths, which have to be cancelled by the system. The ear signals Z_L and Z_R can be described as:

$$Z_L = Y_L \cdot H_{LL} + Y_R \cdot H_{RL} = X_L \quad (1)$$

$$Z_R = Y_R \cdot H_{RR} + Y_L \cdot H_{LR} = X_R \quad (2)$$

The solution of equation (1) and (2) can be written as:

$$Y_L = \left[\underbrace{\frac{H_{RR}}{H_{LL} \cdot H_{RR} - H_{LR} \cdot H_{RL}}}_{Ctc\_LL} \cdot X_L - \underbrace{\frac{H_{RL}}{H_{LL} \cdot H_{RR} - H_{LR} \cdot H_{RL}}}_{Ctc\_RL} \cdot X_R \right] \quad (3)$$

$$Y_R = \left[\underbrace{\frac{H_{LL}}{H_{LL} \cdot H_{RR} - H_{LR} \cdot H_{RL}}}_{Ctc\_RR} \cdot X_R - \underbrace{\frac{H_{LR}}{H_{LL} \cdot H_{RR} - H_{LR} \cdot H_{RL}}}_{Ctc\_LR} \cdot X_L \right] \quad (4)$$

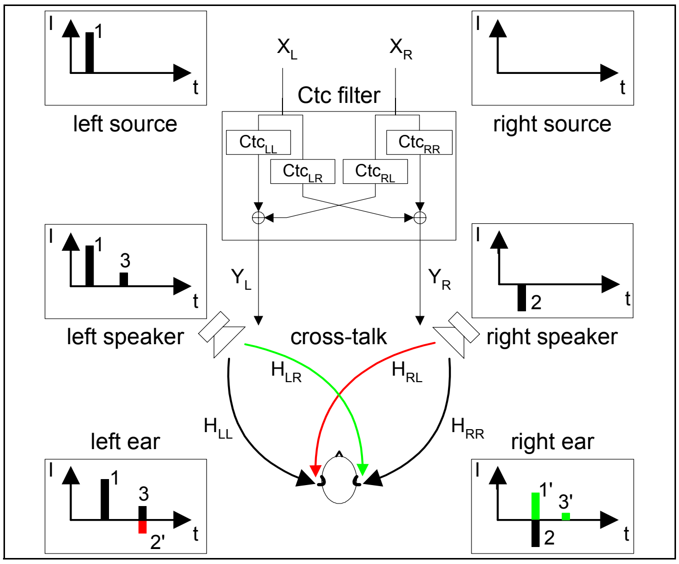

Figure 1: Principle of cross-talk cancellation

The parts labelled with brackets of equation (3) and (4) representing the four ctc-filters shown in Figure 1.

Stability

Tests showed that a dynamic cancellation works only in the angle spanned by the loudspeakers. This behaviour becomes clear looking at the denominator (5) of the filter equations (3) and (4).

$$D = H_{LL} \cdot H_{RR} - H_{LR} \cdot H_{RL} \quad (5)$$

If any frequency of $H_{LL} \cdot H_{RR}$ becomes equal to $H_{LR} \cdot H_{RL}$, the denominator is zero and the filter is not stable anymore. Even when the result is not exactly but almost zero, the resulting filter reaches a very high amplitude, which may result in ringing or even range overflow at the sound output device. Dividing the two parts of the denominator causes a relative scaling (equation (6)) without the need to take the absolute amplitude of the transfer functions into account.

$$K = \frac{H_{LL} \cdot H_{RR}}{H_{LR} \cdot H_{RL}} \quad (6)$$

To detect possible singularities, K was calculated for every head direction. Afterwards the algorithm searches the value closest to 1 in each filter and stores the value for the current head position. Figure 2 shows the results of searching critical values of K over a complete head rotation. On the left a ±45° speaker configuration was used, in the right plot it was ±90°. Plot a) reveals that a stable cross-talk cancellation is possible in a range of approximately ±40°, in plot b), the ±90° configuration, the valid area is about ±75°.

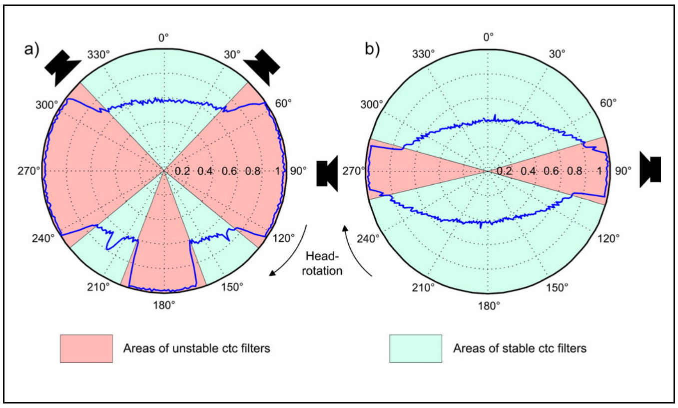

Figure 2: Plot of critical values of K for each direction. a) ±45°- and b) ±90°-speaker configuration

Switching between areas

To provide a complete head rotation, it is necessary to use a stable configuration at every possible viewpoint of the user and this leads to a four speaker environment, which makes it possible to combine the ±45° and ±90° configuration in the same setup. Depending on the current viewpoint, the system automatically chooses the valid configuration.

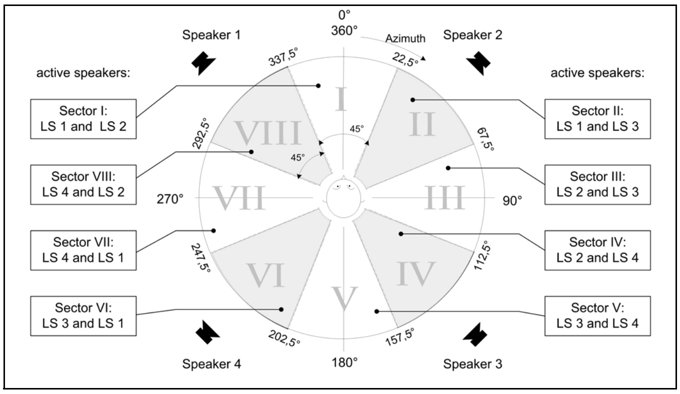

Figure 3: Grey: Areas for ±90° configuration, white areas for ±45° configuration

Measurements and listening tests showed that the cancellation achieves good results inside the particular areas, but switching between areas is still audible as a "click". Comparing ctc filters one step before and one step after switching the filters reveal some differences in particular at high frequencies. Inaccuracies in the speaker placement and the determination of the head position by the head tracker can cause a mismatch in the time alignment so that a sufficient consistent cancellation is not possible.

Cross-fading between areas

To reduce the interfering "clicks" a more smooth changeover from one sector to the next is needed. Due to the fact that the cross-talk cancellation filter structure is a linear time invariant system, a linear superposition of two classical 2-speaker systems is possible. To describe the procedure the following indexing will be used:

Speakers in the active area are labelled with A and B, speakers in the destination area are labelled with A an C. For example fading from sector *I* to *II* (Figure 3) speaker 1 and 2 (A, B) are active and after fading is complete, speaker 1 and 3 (A, C) are active. With this indexing a generally applicable system of equations can be established.

$$Z_L = Y_A \cdot H_{AL} + Y_B \cdot H_{BL} + Y_C \cdot H_{CL} = X_L \qquad (7)$$

$$Z_R = Y_A \cdot H_{AR} + Y_B \cdot H_{BR} + Y_C \cdot H_{CR} = X_R \qquad (8)$$

This set contains three unknowns, but only two equations which makes a closed solution impossible. Taking account of the boundary conditions before and after fading, this set of equations is reduced to two independent cancellation problems, as shown in (1) and (2), which will be superposed. To fade from one sector to the next a position dependent weighting factor controls the fading from one 2-speaker setup to the next in between a small 10° sector.

Figure 4 shows the complete cross-talk cancellation filter structure of a three speaker solution. To provide full rotation the ±45° and ±90° configuration alternate, as well as practiced by the switching method, only in between two sectors both configurations are active at the same time.

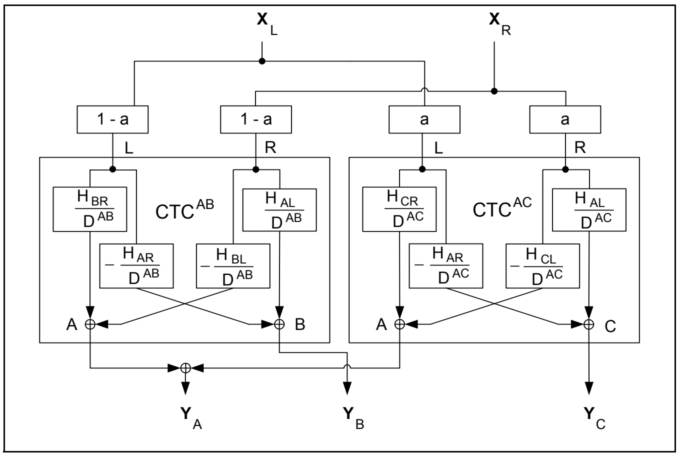

Figure 4: Dynamic three channel cross-talk cancellation filter structure with cross-fade

Listening tests using this fading method showed that "clicks" are apparently not audible anymore. With this system an efficient cross-talk cancellation can be established in the full space around the user and is especially suited to enhance virtual reality systems like a Cave (VR video projection) with spatial audio to combine visual and acoustical stimuli in an excellent way.

References

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