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reproduced through loudspeakers

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CANCELLATION OF CROSSTALK IN ARTIFICIAL HEAD RECORDINGS REPRODUCED
THROUGH LOUDSPEAKERS

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1. INTRODUCTION

The basic concept of the artificial head recording technique is well-
known. In any listening situation the input to the hearing mechanism con-
sists of two one-dimensional signals, e.g. the sound pressure at the two
eardrums. If a set of recording/playback equipment is able to create the
same sound pressure at the eardrums of a listener as would have been in
the concert hall, then the acoustic experience is reproduced correctly,
including directional aspects, reflections, reverberation etc.

In practice, recordings are made with microphones in the ear canals of a
carefully designed model of a human head, including pinnae. Reproduction
is carried out through headphones, which ensures that each channel is
only reproduced in one ear.

2. REPRODUCTION THROUGH LOUDSPEAKERS

The good directional characteristics of an artificial head recording are
destroyed if it is reproduced through loudspeakers. This is due to the
crosstalk which is introduced in any free field listening. Crosstalk
means that the right speaker is heard not only with the right ear but
also with the left ear and vice versa.

However, it can be shown that it is possible to add an artificial cross-
talk which cancels out the natural crosstalk. This principle is shown in
the following.

X_{left} and X_{right} denote the two channels which are to be reproduced as
sound pressure at the eardrums. Y_{left} and Y_{right} are the signals presen-
ted to the loudspeaker terminals. Z_{left} and Z_{right} denote the sound pres-
sure at the two eardrums. X and Y have the unit V, while the unit of Z
is Pa. The transfer functions from Y to Z are denoted with H as indica-
ted in Figure 1. H has the unit Pa/V.
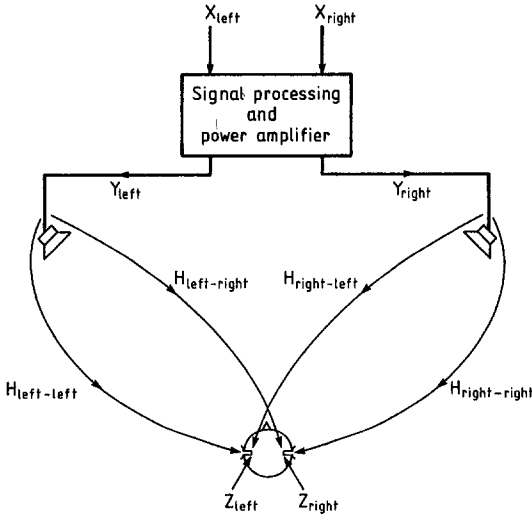
Figure 1. Principal diagram showing the transmission from recording to sound pressure at the eardrums.

Now we have

$$Z_{left} = H_{left-left} \cdot Y_{left} + H_{right-left} \cdot Y_{right} \qquad (1)$$

$$Z_{right} = H_{left-right} \cdot Y_{left} + H_{right-right} \cdot Y_{right} \qquad (2)$$

What we want, is that

$$Z_{left} = k \cdot X_{left} \qquad (3)$$

$$Z_{right} = k \cdot X_{right} \qquad (4)$$

k being constant of unit Pa/V. If we combine (1) with (3), (2) with (4), and solve with respect to Y, we get

$$Y_{left} = k \cdot (H_{right-right} \cdot X_{left} - H_{right-left} \cdot X_{right})/D \qquad (5)$$

$$Y_{right} = k \cdot (H_{left-left} \cdot X_{right} - H_{left-right} \cdot X_{left})/D \qquad (6)$$

$$D = H_{left-left} \cdot H_{right-right} - H_{left-right} \cdot H_{right-left} \qquad (7)$$

Some further manipulation is appropriate.

The loudspeaker frequency response is isolated through introduction of P, the sound pressure at the centre of the head, but with no head present. Then

$$H_{left-left} \approx \left.\frac{Z_{left}}{Y_{left}}\right|_{Y_{right}=0} = \left.\frac{Z_{left}}{P}\right|_{Y_{right}=0} \quad \left.\frac{P}{Y_{left}}\right|_{Y_{right}=0} \tag{8}$$

$$\left.\frac{Z_{left}}{P}\right|_{Y_{right}=0} = FFC_{left-left} \tag{9}$$

could be denoted Free-Field-Correction of the head for a sound origina- ting from the left loudspeaker and reaching the left ear. The unit in Pa/Pa.

$$\left.\frac{P}{Y_{left}}\right|_{Y_{right}=0} = LFFR_{left} \tag{10}$$

is the Loudspeaker Free-Field-Response for the left loudspeaker. The unit is Pa/V. Now (8) can be written as (11) and similar expressions can be found for the other H as given in (12), (13) and (14).

$$H_{left-left} = FFC_{left-left} \cdot LFFR_{left} \tag{11}$$

$$H_{left-right} = FFC_{left-right} \cdot LFFR_{left} \tag{12}$$

$$H_{right-left} = FFC_{right-left} \cdot LFFR_{right} \tag{13}$$

$$H_{right-right} = FFC_{right-right} \cdot LFFR_{right} \tag{14}$$

If symmetri is assumed, then

$$LFFR_{left} = LFFR_{right} = C \tag{15}$$

$$FFC_{left-left} = FFC_{right-right} = A \tag{16}$$

$$FFC_{left-right} = FFC_{right-left} = B \tag{17}$$

(5) and (6) can now be rewritten

$$Y_{left} = \frac{A}{A^2 - B^2} \cdot (X_{left} - X_{right} \cdot \frac{B}{A}) \cdot \frac{k}{C} \tag{18}$$

$$Y_{right} = \frac{A}{A^2 - B^2} \cdot (X_{right} - X_{left} \cdot \frac{B}{A}) \cdot \frac{k}{C} \tag{19}$$

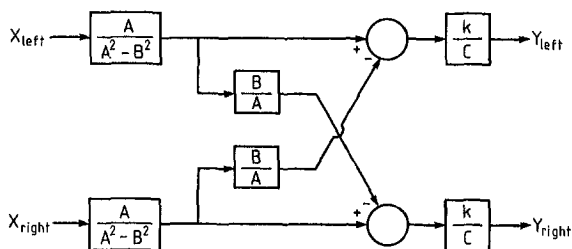This signal processing is shown in block diagram form in Figure 2.

Figure 2. The signal processing of equations (18) and (19) shown in
          block diagram form.

The blocks to the right perform a gain control and an equalization of
the loudspeakers. The left blocks are similarly introduced in the direct
signal path of both channels and thus also perform an equalization.
Among other things this compensates for the fact, that the ear canal ap-
pears two times in the transmission path: once at the recording and once
at playback.

The real suppression of the crosstalk is carried out by the crosscoup-
ling of the two centre blocks.

3. REALIZATION

The above given functions were measured on a Neumann Type KU80 i artifi-
cial head, see Figure 3.

Until now the effort has been concentrated on realization of the cross-
coupling B/A as shown in Figur 3c. A possible way will be to approximate
B/A with an analogue filter or a recursive digital filter. However, as
accuracy is expected to be essential, it has been realized as a Finite
Impulse Response filter using Motorola XSP 56200 processors. The impulse
response of the filter, calculated as the inverse Fourier transform of
B/A is shown in Figure 4. At the time of printing, the blocks k/C and
$A/(A^2 - B^2)$ have not been realized.

4. ASSESSMENT

The suppression of crosstalk is very effectively demonstrated in an an-
echoic room. With pink noise applied to both channels, the listener per-
ceives the sound as being located in the head, like when listening with
headphones. When the noise is applied to only one channel, the listener
gets the impression of listening to a sound source located immediately
outside the appropriate ear. If this ear is closed with a finger or an
earplug, the listener is able to clearly indicate the correct position
of the head by searching for minimum sound level at the opposite ear.

At present the reproduction of processed artificial head recordings have
only been subjectively evaluated. In general, listeners agree that the
directional reproduction is at least as good as with headphones. Many
listeners even indicate a better spatial discrimination, especially in
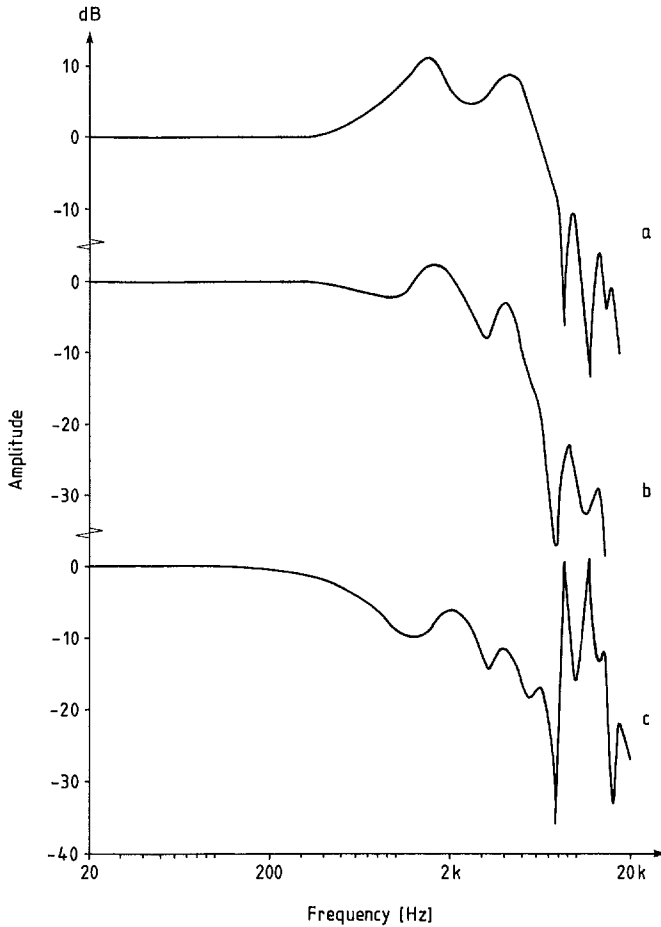
Figur 3. Magnitude of transfer functions:
   a) A (Free Field Correction for the ear for sound coming from
      the same side as the ear),
   b) B (Free Field Correction for the ear for sound coming from
      the opposite side),
   c) B/A
      All curves are given for sound in the horizontal plane,
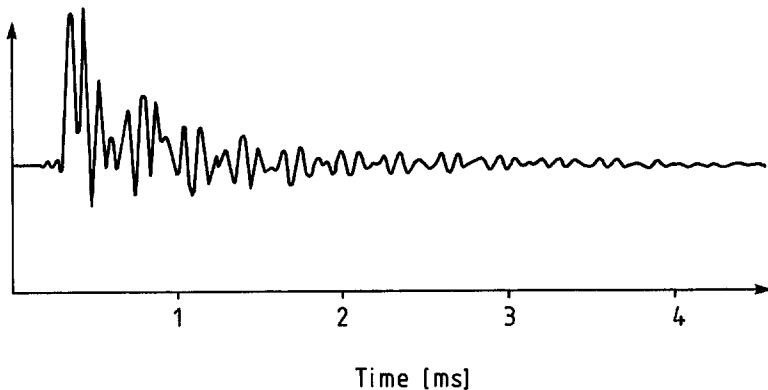 45^0 off-frontal incidence.

Figure 4.   Impulse response of B/A.

the front region. The effect of the system is unexpectedly independent of head position, when only the distances to the two speakers are kept equal.

5. FUTURE WORK

Further investigations have been planned on the following matters:

a) Quantitative and objective evaluation of the observations given above in Section 4.

b) Evaluation of the significance of the blocks $A(A^2 - B^2)$ and k/C.

c) Significance of impulse duration in the realization of filters.

d) The possibility of realizing the blocks of Figure 2, using recursive Infinite Impulse Response filters.

e) The possibility of using a normal listening room. The system is not formally limited to anechoic rooms, but for normal living rooms much longer impulse responses occur, and more computing power is needed.

f) The construction of the artificial head. Figure 5 shows a principal diagram of the signal path from the sound field without a listener present to the sound pressure at the eardrum. It can be argued that full directional information is present in the open circuit Thevenin sound pressure at the entrance to the ear canal. If this pressure is recorded rather than the pressure at the eardrum, all transfer functions are more regular, and the blocks of Figure 2 become easier to realize. Furthermore, the final reproduction is less influenced by differences between the artificial ear and the ear of the listener, since a smaller part of the artificial ear is used. Recording with Neumann Type KU81 i artificial head is expected to approach this situation.
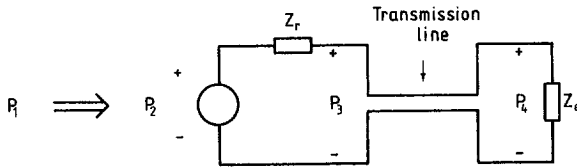
Figure 5. Principal diagram of the signal path from the sound field without a listener present to the sound pressure at one eardrum. P_1 denotes the pressure without a listener, P_2 the open circuit Thevenin pressure at the entrance to the ear canal, P_3 the actual pressure at the entrance to the ear canal, and P_4 the pressure at the eardrum. Z_r is the radiation impedance seen from the ear canal, and Z_e is the impedance of the eardrum. The ear canal is represented by a transmission line. Only the transmission from P_1 to P_2 is dependent on the angle of incidence and the distance of the sound source. Thus, it can be argued that P_2 contains full spatial information.

g) Problems at frequencies where A and B are approximately equal, and thus D is close to zero. This happens especially at low frequencies.

6. ACKNOWLEDGEMENTS