On the audibility of spatial reflection changes in relation to WFS

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Introduction

A sound field in an enclosed space can basically be divided into components that are related to the direct sound, the early reflections and the reverberation [1]. This concept holds for real sound fields as for instance occurring during a musical performance in a hall, but it also holds for the reproduction of sound. Depending on the recording and reproduction system this sound field may or may not give a natural spatial impression of the musical performance. A very realistic reproduction method may be obtained with a wave field synthesis (WFS) system [2], where the required reflection patterns are obtained from impulse response measurements or perceptual generation of impulse responses with which the dry source signals can be convolved. It is well known that the early reflections depend much on the (intended) source position and that differences in the early reflection patterns are used by the human brain to localize the source position. Hence, it may be necessary for a high quality sound reproduction with artificial or convolutional reflections and reverberation, to differentiate the reverb processing for different source positions. In this paper the results of a preliminary investigation are presented to learn how sensitive the human ear is for variations in early reflections and hence to know if we can use the same reflection processing for sources that are not too far apart so that an easier and less expensive processing can be carried out without perceptual loss in quality. Although this investigation was inspired by our WFS method of reproduction, the results are as well applicable to other kinds of reproduction where artificial reflections (or measured impulse responses) are involved.

Test configuration

In a natural enclosed surrounding the sound field of a source is a complex mix of the direct sound field, the early reflections and the reverberation. As discussed in the Introduction, the early reflections may differ considerably for different source positions. Our question is now whether these differences are audible. If they are audible, a reproduction system that distinguishes between these situations may give a more natural reproduction than one which does not. It is easily verified with a simple image source model that variation of a source position also leads to variation in the position of the reflections. It is plausible that the audibility of spatial changes in a single reflection can easier be noticed if that reflection occurs only together with the direct sound, without other reflections that could give some kind of masking. On the other hand, if a lot of reflections are observed together, and these reflections all change when the source moves, the total change may easier be noticed. In this preliminary investigation we decided to make the testing environment as simple as possible and to investigate only the audibility of spatial changes in a single reflection together with a direct sound. In that way the problem reduces to the estimation of the audibility threshold of spatial changes in one single reflection. To simplify the test conditions even further, we made a test setup where only the position of the single reflection was changed, leaving the source at the same position. In our experiments the source was always positioned in front of the listeners (the test persons) and the early reflection was delayed by 30 ms relative to the source and given a direction of 25.5°, 44.0° or 70.3° relative to the front. The level of the reflection was always made equal to that of the direct sound. The choice of the test signal has a major influence on the audibility of reflections and hence also on spatial variations of the reflections. Using impulsive sounds would give results that give a low threshold, which may be too critical for general use. Continuous noise would possibly give too high thresholds. These thoughts were confirmed by some preliminary experiments. It was then decided to use speech samples, because they give a natural compromise between the extremes of impulses and continuous noise. A change in the position of the reflection will result in changes in delay times with the direct sound and in changes in the interaural time differences (ITD) and the interaural level differences (ILD). Hence it makes sense to conduct the experiments in such a way that a threshold for variations in the travel time (related to the distance of the image source) and the angle is estimated.

Measurement method

Because the aim of the subjective tests was to find the threshold in position changes of a single reflection, a two-alternate forced choice (2AFC) test method was applied to find the threshold between a reference (R) and a test (T) signal, where both signals were the same in the direct sound, coming from the front of the listener, but the distance or angle of the single reflection was different. The test sequences RRRT or RTRR were presented to the test persons and they had to answer if a difference was noticed in the second or the fourth signal in the sequence. If no distinguishing was noticeable they had to guess. Hence, the response was 50% of correct answers far below the threshold. The threshold was defined at 75% correct answers. The amounts of variations in the signals (the reflection distance or its angle) had to be chosen such that the threshold could be estimated efficiently from a small number of trials. For that purpose the PEST-method was used (Parameter Estimation by Sequential Testing) [3]. After a given number of trials (in our experiments we used 30 trials) a best fit of the psychometric function was calculated with the maximum likelihood (ML) method [4].

In a 2AFC experiment the psychometric function – giving the fraction of correct answers – can be written as:

$$\psi(x;\alpha,\beta) = 0.5 + 0.5F(x;\alpha,\beta) \quad . \qquad (1)$$

Often the function $F(x;\alpha,\beta)$ is chosen to be the cumulative Gaussian probability function. Here we decided to use the Weibull distribution, which according to Harvey [5] is the best choice in forced choice experiments. The Weibull distribution is given by:

$$F(x;\alpha,\beta) = 1 - \exp\left(-\left(\frac{x}{\alpha}\right)^{\beta}\right) \quad . \qquad (2)$$

The parameters α and β were estimated with the ML-method and next the 75% threshold was computed.

Results

Delay variation experiment

A set-up was chosen with the direct sound coming from a loudspeaker at a distance of several meters in front of the listener. A second loudspeaker was placed at a comparable distance to produce the single reflection at an angle of φ_1 = 25.5°, φ_2 = 44.0° and φ_3 = 70.3° with the front. The environment was semi-anechoic, i.e. a room with strongly damped walls and ceiling and the level of the single reflection was made equal to that of the direct sound. For the reference signal, the reflection had a delay of 30 ms in relation to the direct sound.

The threshold of audibility of changes in the delay of the reflection was estimated for the three angles in the direction of smaller delays and in the direction of larger delays, giving 6 different thresholds. The averaged thresholds in delay variation and the corresponding change in reflection distance are given in table 1.

angle	threshold in delays in ms	threshold in distances in m
25.5°	-5.4 / +5.1	-1.9 / +1.7
44.0°	-5.1 / +5.0	-1.8 / + 1.7
70.3°	-3.4 / +3.6	-1.2 / + 1.2

Table 1 Delay and distance thresholds

Angle variation experiment

In this experiment the reference signals were the same as with the delay variation experiment, but now the threshold of audibility was determined of a change in the angle of the reflection. This experiment was more difficult to conduct, because a change of signal angle is more difficult to accomplish than a change in delay. In this experiment an array of loudspeakers was used and an automated switch was included to choose the appropriate loudspeaker.

The results of these experiments are summarized in table 2.

angle	threshold in angles
25.5°	-4.8° / +9.0°
44.0°	-9.2° / +4.7°
70.3°	-9.7° / +13.7°

Table 2 Angular thresholds

Discussion and conclusion

From our results the preliminary conclusion can be drawn that variations in distance (or latency) of a single reflection can easier be noticed from a lateral direction than from a frontal direction. This is probably caused by the fact that the direct signal was also coming from the front in these experiments. On the other side it can be concluded that variations in angle of the reflection are easier detected for frontal directions than for lateral directions. This behavior is identical to the localization uncertainty that is known from direct signals. This can be understood from the different values of the interaural time differences (ITD) and the sensitivity differences of ITD for different directions [6].

In conclusion it can be stated that the minimum audible spatial variation of a single reflection is 1 – 2 m or 5 – 10 degrees, whichever is the largest. This knowledge can be taken into account for recording and synthesis purposes in WFS rendering and other spatial reproduction systems.

References

[1] H. Kuttruff, "Room Acoustics", Applied Science Publ., London, 1973.

[2] A. J. Berkhout, "A Holographic Approach to Acoustic Control," J. Audio Eng. Soc., vol. 36, pp. 977-995, 1988.

[3] M.M. Taylor and C.D. Creelman, "PEST: Efficient estimates on probability functions", J. Acoust. Soc. Am., 41, 728-787, 1967.

[4] J.L. Hall, "Maximum-likelihood sequential procedure for estimation of psychometric functions", J. Acoust. Soc. Am., 44, 370, 1968.

[5] L.O. Harvey Jr., "Efficient estimation of sensory thresholds with ML-PEST", Spatial Vision 11, 121-128, 1968.

[6] J. Blauert, "Spatial hearing, the psychophysics of human sound localization", MIT Press, Cambridge MA, 1997.