ARCHIVES OF ACOUSTICS
16, 2, 295–303 (1991)

PREDICTION OF THE EARLY PART OF ECHOGRAMS INDISPENSABLE IN COMPUTER SIMULATION IN ROOMS

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The paper discusses the possiblility of an optimal selection of the early part of the room echogram during its calculation in computer simulation.

The existence of two such time segments in the echogram has been found.

In the first time segment it is necessary to follow precisely successive reflections. In the second time segment the reflections can be treated stochastically.

1. Introduction

Numerous works on speech acoustics, room acoustics, electroacoustics and psychoacoustics indicated the influence of transients on properties of transmitted sound signals [2, 3, 6, 7, 8, 9, 10, 14, 15, 16, 25, 26, 27]. Room acoustics employs a number of criteria for the evaluation of rooms. The criteria can be determined on the basis of their so-called room impulse response (echogram) [5]. The criteria differ with respect to the value of the early part of the echogram, if one considers the usefulness of successive reflections and the function of their weight [4, 11, 12, 13, 21].

In computer simulation of echograms of closed rooms it is very important to determine the size of the early part of the said echogram used to evaluate rooms, as it determines the calculation time [23]; there is no need to calculate the entire room echogram (theoretically during an indefinitely long time); it suffices to calculate its early part. Without going into details about the relations between particular criteria and whether or not they could be used in computer simulation [4, 24], we attempted to estimate the border temporal value of the early part of the echogram, in view of a change of an acoustic signal, perceived in subjective evaluation, connected with early parts of an echogram (of a different length) through the convolution function.

In order to accomplish the task specified above, speech and music signals recorded under the conditions of a free field, following their sampling, were fed into the computer. Having undergone the convolution operation there with the early parts of the room echogram (of a different length), obtained through computer simulation, following their digital-analog conversion, the signals were recorded at the computer output in the tape-recorder system.

The acoustic signals prepared as described above have been evaluated subjectively.

2. Recommended values of the time limit of the echogram's early part

Determination of the echogram of a real room requires that the following two factors be taken into consideration: disturbances which overlap the echogram (room's own noises, noises of the transmission track – the said problems are absent in computer simulation), and, on the other hand, the fact that it is practically possible to determine an echogram at a finite time T_i while its definition requires $T_i = \infty$.

Since an exponential function approximates the envelope of the decaying echogram, the value of time determined by the signal dynamics can be assumed to be the maximal time limit T_i. Given signal dynamics equal to 40 dB:

$$T_i = \frac{2}{3} T \qquad (1), [14]$$

where: T — room reverberation time.

In a cuboidal room with reflecting walls, the number of reflections ΔN per time unit Δt grows along with time square t:

$$\Delta N = \frac{4\pi c^2}{V} \cdot t^2 \, \Delta t \qquad (2), [5]$$

where: c — sound propagation speed [m/s] V— room volume [m^3].
Designating the temporal density of reflections as

$$\bar{m} = \frac{\Delta N}{\Delta t} \quad [s^{-1}], \qquad (3)$$

we can determine time t from Eq. (2):

$$t = \sqrt{\frac{V}{4\pi c^2} \cdot \bar{m}} \quad [s] \qquad (4)$$

Substituting for $\bar{m}$ in the expression (4) the limit value resulting from the inability of the hearing organ to distinguish signals consisting of a number of impulses per second greater than $\bar{m}_{max}$, we get

$$t_{st} = \sqrt{\frac{V}{4\pi c^2} \cdot \bar{m}_{max}} \quad [s] \qquad (5)$$

CREMER [5] has interpreted the limit value t_{st} as the time of the beginning of static reverberation; for time values greater than t_{st} there is no point in precise studying of the amplitude-temporal structure of the room echogram. Substituting the value of 340 m/s for c in Eq. (5) we obtain

$$t_{st} = 4.5 \cdot 10^{-2} \sqrt{V \cdot \bar{m}_{\max}} \text{ [ms]} \tag{6}$$

The values of $\bar{m}_{\max}$ given in the literature, depending on the methodology of the investigations, are within the range of $\bar{m}_{\max} = 2000 \div 2800$ [s^{-1}] [5, 19, 13].

Assuming successive values of $\bar{m}_{\max} = 2000$ s^{-1}, and then $\bar{m}_{\max} = 2800$ s^{-1},

$$t_{st} = 2\sqrt{V} \text{ [ms]} \tag{7}$$

and

$$t_{st} = 2.4\sqrt{V} \text{ [ms]} \tag{8}$$

However the time limit which separates the useful echo from the useless one, in the sense of the disappearance of its perception, has been set by many authors at $40 \div 90$ ms. The value depends on the energy of all echoes coming from a given direction, the difference in the levels of the direct and reflected sounds, sound direction, the place of the sound reception in the room, the room reverberation time, the kind of sound signal (speech, music) [1, 5, 15, 18, 20, 22].

Hence we can state that there are two notions which define the early parts of the echogram from the standpoint of their psychoacoustic evaluation, T_i and t_{st}. The former defines echogram time T_i of the early part of the echogram, necessary for stabilized subjective evaluation of the acoustic sensation in a given room – an increase in the time segment T_i does not change this sensation. The latter defined duration t_{st} of the early part of the echogram, which is only a certain segment of the fragment limited by time T_i ($t_{st} < T_i$), in which a detailed amplitude-temporal structure of reflections must be taken into account. After this time t_{st} there is no need to take into account the detailed structure of the reflections; its stochastic distribution up to time T_i is sufficient.

In computer simulation of the room echogram detailed calculations are necessary within the time range of up to value t_{st}. The calculations relate to successive reflections approaching the signal registration point. Over t_{st} only a segment with a stochastic distribution of amplitude and duration ($T_i - t_{st}$) can be added to the echogram with time t_{st}. This distinction between time T_i and t_{st} helps considerably shorten the calculation time in computer simulation of the room echogram as well as the calculation time of the convolution function of the said echogram with a selected fragment of the acoustic signal.

Consequently, the procedure speeds up investigations with respect to the evaluation of the acoustic properties of rooms. Real signals of speech or music are evaluated in a computer simulated room whose physical parameters can be changed quickly and without any restrictions.

3. Computer simulation of room echogram

An attempt at the verification of the hypothesis about the possibility of distinguishing time T_i and t_{st} in an echogram, obtained by computer simulation of the distribution of the acoustic field in a room has been made. The method of virtual images has been applied.

An echogram was calculated for a room for which simultaneous binaural registration in the artificial head was simulated; the transfer response of the external ear was taken into account [17]. It was also possible to stimulate the change of the position of both the source and reception points of the sound.

The early parts of the room echogram obtained in the calculations, each of a different length, we convolved with a sampled test signal recorded under the conditions of a free field.

The test signal consisted of a fragment of speech (a sentence in German) or a fragment of music a (violin concerto) each lasting 10 s.

The evaluation of the acoustic signals, recorded at the computer output, following their digital-analog conversion, was conducted by the present authors through ear-phones. The main task was to determine whether the pairs of acoustic signals are different or not. The successive pairs of acoustic signals consisted of randomly combined signals, each of a different (growing) time T_i and then of a signal of a set time T_i combined with a signal of a different (growing) time t_{st}. Each pair was evaluated by each author ten times. The results of the measurements were analysed statistically.

4. Results

Three cuboidal rooms A, B and C were computer-simulated. Their dimensions, reverberation times and values of critical radius are given in Table 1.

During the first stage of investigations the initial fragment of the room echogram was calculated at the set localization of the sound source and reception point, for $T_i = (50, 100, 150, 200, 250, 300)$ ms; Fig. 1.

Figure 2 shows results of the calculations for $T_i = 100$ ms and Fig. 3 for $T_i = 300$ ms.

The difference in the subjective evaluation of musical signals of $T_i = 50$ and 200 ms is very clear and greater than that between 100 and 150 ms or 150 and 200 ms. The comparison of signals $T_i = 200$ and 250 ms and then of $T_i = 250$ and 300 ms indicates that the difference between them is imperceptible. The border value of the initial time of a fragment of the echogram T_i was estimated to be $T_i = 250$ ms.

In the case of speech signals, the general tendency in the evaluation of the differences is similar. One perceives not only differences in the global evaluation of signals but also with respect to specific attributes, e.g., spaciousness or timbre.

The investigations were repeated for room B of the same dimensions as room A but with a reduced reverberation time T.

Table 1. Values of reverberation time T and critical radius r in octave bands for computer simulated rooms, A, B, C

Room	Dimensions $b \times l \times h$ [m]		Octave mid frequencies [Hz]						
			125	250	500	1000	2000	4000	8000
A	15x20x5	Reverberation time [ms]	1033	1641	910	1669	1569	1309	1144
		Critical radius r [m]	2.2	1.7	2.3	1.7	1.8	1.9	2.1
B	15x20x5	Reverberation time [ms]	806	674	716	787	683	616	615
		Critical radius r [m]	2.5	2.7	2.6	2.5	2.7	2.8	2.8
C	13x20x4.5	Reverberation time [ms]	728	613	649	726	718	558	583
		Critical radius r [m]	2.3	2.5	2.4	2.3	2.5	2.6	2.7

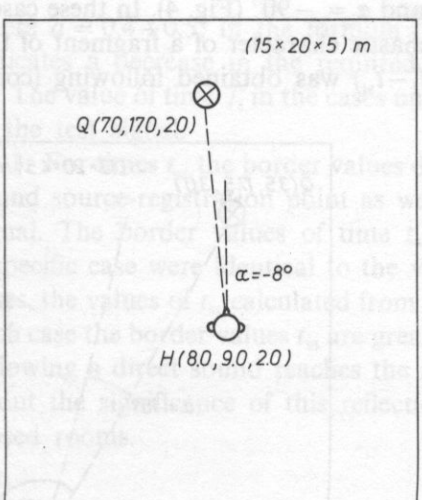

FIG. 1. Room A with source point Q and reception point H.

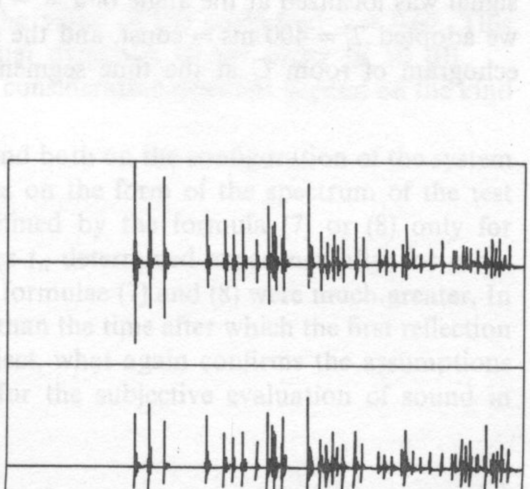

FIG. 2. Echogram of room A, at $T_i = 100$ ms.

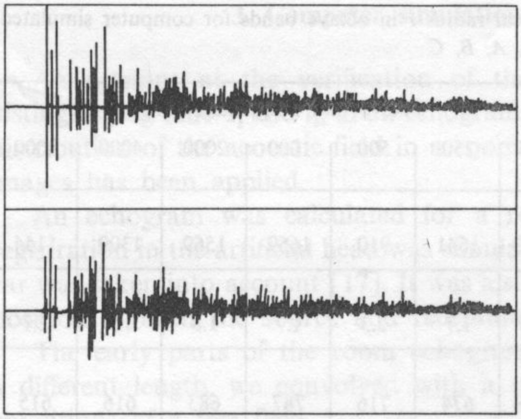

FIG. 3. Echogram of room A, at $T_i = 300$ ms.

Comparison of border values T_i with values of the rooms reverberation time T (Table 1) indicates that for the cuboidal room in question and for the given speech and music signals, the border values T_i are smaller than the values resulting from the formula (1): for example, in the octave band 500 Hz for room A — $T_i = 607$ ms, for room B — $T_i = 311$ ms.

In the second stage of the investigations the early parts of the echogram of room C were calculated (Table 1). The reciprocal configuration of the signal source and its reception point was such that the source with respect to the binaurally registered signal was localized at the angle of $\alpha = -15°$ and $\alpha = -90°$ (Fig. 4). In these cases, we adopted $T_i = 400$ ms = const, and the stochastic character of a fragment of the echogram of room C at the time segment $(T_i - t_{st})$ was obtained following (com-

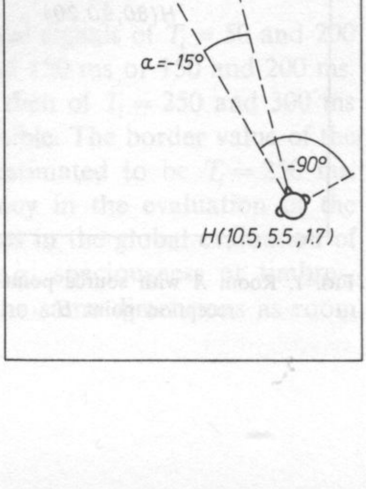

FIG. 4. Room C with source point Q and reception point H.

putational) alteration of the channels in the system of binaural registration after time $t_{st} = (5, 10, 15, 20, 25, 30, 50, 80, 100)$ ms. A subjective evaluation comparing acoustic signals obtained as a result of the convolution of test signals with fragments of echograms with different times t_{st}, after which they assumed stochastic character, showed that the border values of time t_{st} are within the range of $t_{st} = (80 \div 100)$ ms for speech signals and $t_{st} = (5 \div 10)$ ms for music signals — when $\alpha = -15°$. For $\alpha = -90°$, border values of $t_{st} = (5 \div 10)$ ms were obtained for both speech and music signals. The comparison of the border values of t_{st} with values of t_{st} resulting from the formula (7) — $t_{st} = 68$ ms and (8) — $t_{st} = 82$ ms indicates the lack of their uniform compatibility or incompatibility.

5. Final conclusions

The investigations help formulate the following conclusions:

1. The hypothesis about the possibility of distinguishing two early parts of the echogram with border times T_i and t_{st} was confirmed in the subjective evaluation of the acoustic signal prepered in computer simulation of the distribution of the acoustic field in a room.

2. The border numerical values of T_i indicates a possibility of modification of the formula (1) by the formula (9):

$$T_i = a \cdot T \tag{9}$$

where $a = 0.4 \div 0.5$; in the formula (1) the value of the coefficient $a = 0.67$. This indicates a decrease in the required signal dynamics to the order of 30 dB.

The value of time T_i in the cases under consideration does not depend on the kind of the test signal.

3. For times t_{st} the border values depend both on the configuration of the system sound source-registration point as well as on the form of the spectrum of the test signal. The border values of time t_{st} defined by the formula (7) or (8) only for a specific case were identical to the values t_{st} determined experimentally; for other cases, the values of t_{st} calculated from the formulae (7) and (8) were much greater. In each case the border values t_{st} are greater than the time after which the first reflection following a direct sound reaches the subject, what again confirms the assumptions about the significance of this reflection for the subjective evaluation of sound in closed rooms.

6. Conclusion

The problem of the estimation of the required duration of a fragment of the room echogram in computer simulation of the distribution of the acoustic wave in the same room is closely connected with the optimization of the conditions of such a simulation.

The results of the investigations indicate the possibility of distinguishing between two early time segments in the room echogram.

In the first segment, up to time point t_{st}, it is necessary to follow precisely successive reflection from room boundaries. At the time segment $T_i - t_{st}$, the reflections can be treated stochastically.

The formulae (1), (7), and (8) used to determine the value of time T_i and t_{st} generally give values much greater than the border values of these times obtained in the investigations under discussion.

Systematic investigations into the problem, which has only been outlined in the present paper, are necessary. They would help minimize the calculation time in computer simulation of acoustic processes in a closed room.

Acknowledgements

The authors would like to thank Prof. J. BLAUERT for his participation in discussions held during the investigations.

E. HOJAN extends his gratitude to the von Humboldt Foundation for providing funds to cover the cost of his stay in Bochum.

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Received February 14, 1989