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OPTIMIZATION OF THE DURATION OF AN ECHOGRAM RESULTING FROM COMPUTER SIMULATION OF THE ACOUSTIC PROPERTIES OF A ROOM

R. GOŁĘBIEWSKI, E. HOJAN, M. WOJTCZAK and P. PĘKALA

Institute of Acoustics,
Adam Mickiewicz University
(60-769 Poznań, ul. Matejki 48/49)

The authors of this paper investigated the ways to decrease the time of calculating an echogram in the computer simulation of the distribution of the sound field in a room. The authors emphasize the existence of a limiting moment t_{st} up to which the simulation must be completed. The remaining part of the echogram may be treated as a stochastic amplitude (temporal distribution). The authors related the moment t_{st} to the reverberation time RT and the early decay time, EDT, of a room.

1. Introduction

The implementation of computer systems in acoustics allowed, among other things, a more precise prediction of acoustic properties of real rooms and room designs.

Studies based on computer simulation aim at a maximum fidelity of the representation of the actual conditions. In the case of the simulation of auditory rooms, it becomes possible to evaluate their acoustical properties already at the design stage. In simulation methods it is very easy to correct the positions of the walls, the source of sound, the observation point, etc.

Computer simulation leads to an echogram (a transient response of the room) which provides a collection of data for both objective and subjective evaluation of the acoustic properties of a room.

Basing on an echogram, a number of acoustic parameters may be determined yielding objective characteristics of a room. On the other hand, the convolution of the echogram with the function of a discretionarily selected signal allows the subjective evaluation of the quality of a sound in the simulated room.

Although computers of high processor capacity are used for this task, the time of simulation of an echogram is still too long. Therefore, scientists look for methods of decreasing the time necessary for the calculation of an echogram.

The literature of the subject often postulates that in the process of evaluating the acoustic properties of a room only the early part of the echogram is important. Basing on this postulate, it was proposed by HOJAN and PÖSSELT [2] that the simulation of the entire echogram is not necessary. It is sufficient to simulate it up to a certain moment T_i. The relation between T_i and the duration of the entire echogram, T, is

$$T_i = \alpha T, \tag{1}$$

where $\alpha = 0.4 \div 0.5$ as results from Hojan and Pösselt's experiment. Moreover, it turned out that it is important to simulate only the very early part of the actual echogram provided that its further distribution, resulting from simulation of the entire echogram, is then replaced by a stochastic distribution of the sound amplitude decaying exponentially with time. In order to prove this hypothesis, a subjective evaluation of signals of music and speech was performed after convoluting the signals with the entire simulated echograms. The results of this procedure were compared with echograms consisting of the early parts of the actual echogram and the stochastic parts decaying exponentially. In each case, the duration of the echograms "produced artificially" (with addition of the stochastic parts) was the same as that of the entire simulated echogram, but the durations of the part of the accurate echogram and the stochastic part were varied during the experiment.

The aim of our experiments was to specify the time limit up to which an echogram should be simulated in order to obtain a subjective evaluation of a signal (convoluted with the early part of the echogram) being identical with that of this signal convoluted with the entire echogram. The evaluation was accomplished using sound signals and echograms different from those used in the experiment described by HOJAN and PÖSSELT [2].

The ultimate purpose of the experiment was to generalize the relations between the minimum time required for an accurate computer simulation of the echogram and the selected acoustic parameters of the room and, when applicable, the type of the sound signal to be evaluated after the convolution operation.

2. Computer simulation

The authors of this paper used a computer program that allowed to simulate the acoustic properties of a room. The program had been developed at the Institute of Acoustics of the Adam Mickiewicz University and implemented into a so-called cone-tracing method.

The sound energy decrease caused by the sound absorption accompanying reflections of acoustic waves from the walls was taken into account in the calculation of the echogram. The absorption of sound by the medium was disregarded because of the negligible influence of this factor on the value of the acoustic energy in the considered range of distances between the source and the sound receiver.

The directional characteristics of the human ear, a factor which produces some difference in the sound signal pressure registered by each ear, were also taken into consideration in the program.

3. Echogram

An echogram is a temporal record of the acoustic pressure at a given point in the room following a pulse stimulation of acoustic vibrations in this room. This temporal distribution of the pressure is, in fact, an impulse response of the room recorded at a specific observation point for a given specific position of the source of the sound. In view of the limited capacity of the computer memory, a histogram is used as an approximation of the echogram. The histogram is plotted by dividing the period of observation into a finite number of ranges and calculating the sum of sound intensities within each range. Thus, the histogram is a set of bars numbered from 1 to $k_{\max}$ (where $k_{\max}$ is the ordinal number of the last temporal range). The height of each bar corresponds to the value of the sum of squared acoustic pressures received at the observation point during the time indicated by the width of the bar.

The height of the i-th bar p_i^2 ($i = 1, 2, ..., k_{\max}$) may be expressed by the equation

$$p_i^2 = \sum_t p^2(t), \tag{2}$$

where $t \in \langle t_i, t_{i+1} \rangle$, and

$$t_k = (k-1)\frac{T_{\max}}{k_{\max}}, \tag{3}$$

where k – ordinal number of the bar, $T_{\max}$ – duration of the histogram, $k_{\max}$ – total number of bars in the histogram.

In the calculation of the histogram, the above-mentioned energy decrease due to reflections of acoustic waves from the walls of the room is taken into account. Hence, the values of the squared pressure corresponding to individual cones "emitted" by the source are multiplied by the factor

$$\prod_{i=1}^{N} (1-\alpha_i), \tag{4}$$

where N – number of reflections of the observed cone from the walls of the room, α_i – absorption coefficient of the i-th wall.

4. Parameters calculated on the basis of an echogram

An echogram provides the basis for the calculation of a number of parameters which allows an objective acoustic evaluation of the room. The criterion in the selection of objective parameters was their correlation with subjective evaluations of selected sound attributes, while the heed was paid particularly to the aim of this paper, i.e. to the specification of the limiting value t_{st}.

All parameters were calculated assuming both the monaural and binaural perception of sound. The calculated parameters are as follows:

• the reverberation time RT, basing on the histogram transformed into the Schroeder's curve,

• the early decay time EDT, basing on the histogram transformed into the Schroeder's curve,
• the sound pressure level L_p,
• the temporal centre of the echogram t_s,
• the articulation (Deutlichkeit) D,
• the clarity C.

Schroeder's curve, which is the basis for calculation of all the parameters mentioned above is defined by the following equation

$$R_{db}(k') = 10\mathrm{Lg}\frac{\sum\limits_{k=k'}^{k_{\max}} p_{lk}p_{pk}}{\sum\limits_{k=1}^{k_{\max}} p_{lk}p_{pk}} \quad [\mathrm{dB}], \tag{5}$$

where p_{lk}, p_{pk} – total values of the RMS for the left and the right ear in the k-th range, respectively, $k_{\max}$ – ordinal number of the last temporal range, k – ordinal number of the temporal range (k, $k' = 1, 2, ..., k_{\max}$).

4.1. Reverberation time

In the range of $t \in (0, T_{\max})$, the function $R(t)$ is a continuous and non-growing function which allows the calculation of the reverberation time from the equation

$$RT = 3|t_{-5} - t_{-25}|, \tag{6}$$

where t_{-5} denotes the time corresponding to the value of -5 dB on the Schroeder's curve, t_{-25} denotes the time corresponding to the value of -25 dB on the Schroeder's curve.

A discretization of equation (6) produces

$$RT_d = 3|k_{-5} - k_{-25}|, \tag{7}$$

where k_{-5} denotes the ordinal number of the temporal range corresponding to the value of -5 dB on Schroeder's curve, k_{-25} denotes the ordinal number of the temporal range corresponding to the value of -25 dB on Schroeder's curve.

4.2. Early decay time

The EDT is calculated on the basis of the reverberation curve (5) using the relation

$$EDT = 6k_{-10}, \tag{8}$$

where k_{-10} is the ordinal number of the temporal range corresponding to the value of -10 dB on the Schroeder's curve.

Since no consistent correspondence was found between the time limits t_{st} and other acoustic parameters of the room, except RT and EDT, they are not defined in this paper.

5. Convolution function

A subjective evaluation of signals in the simulated room was possible by applying a convolution function defined as follows:

$$f(t) = \int_{-\infty}^{\infty} f_1(\tau) f_2(t-\tau)\, d\tau\,, \tag{9}$$

where $f_1(\tau)$ – impulse response of the room, i.e., in this case, the echogram resulting from simulation, $f_2(t-\tau)$ – signal of music or speech to be submitted to the subjective evaluation in the simulated room.

In order to eliminate the influence of any other rooms on the signal to be evaluated in the simulated one, it was recorded under anechoic conditions using a digital tape recorder. Subsequently, the signal was put into the computer via an analog-digital converter, at a sampling frequency eliminating the so-called "aliasing" effect, and the convolution operation of the recorded signals with entire or "produced artificially" echograms was then carried out. The output signal, after its analog-digital conversion, was recorded again using a digital tape recorder and then reproduced via headphones in order to present it to the listener for the subjective evaluation.

6. Test signals

The two echograms used in the experiment were obtained by means of a computer simaulation of the interior of a church under two different acoustic conditions. The signals were speech (a sentence in Polish), guitar music and violoncello-and-violin music. All signals were recorded in an anechoic chamber. The duration of each signal did not exceed 10 s.

Echogram 1, of duration of 600 ms, was convolved with the signal of speech and the signal of guitar music. Echogram 2, of duration of 1000 ms, was convolved with the signal of speech (the same as in the case of echogram 1) and the signal of violoncello-and-violin music.

After convolution with the echograms, the signals were recorded using a digital tape recorder and submitted to subjective evaluation by means of earphone listening applying constant stimuli method.

The process of "artificial production" of the echograms comprised the removal of their final parts (of various duration) and the addition of a stochastically distributed amplitude decaying exponentially with time. While producing such compounded echograms, the problem arose how to relate the last bar of the echogram (after the removal of its final part) to the first one of the stochastic part. In the present work it was assumed that the amplitude of the last bar of the actual echogram was identical with that of the first one of the stochastic part; following the latter, the value of the sound amplitude decayed exponentially with time.

Table 1. Initial parameters for computer simulation.

		Echogram 1	Echogram 2
1.	Number of rays	12.000	10.000
2.	Duration of the echogram	600 ms	1000 ms
3.	Maximum order of the ray	8	12

7. Experiment

The experiment was divided into several stages. The first one was the preparation of echograms, i.e. the removal of their final parts and the addition of the stochastic part; the duration of the removed part was each time increased by 20 ms. The stochastic part was generated anew after each removal.

The duration of the echogram with the stochastic part added was identical to that of the actual echogram. All such echograms were subsequently convolved with a selected signal.

The next stage was the preparation of pilot experiments in order to assess preliminarily the limiting moment t_{st} of the computer simulation of the echogram. These experiments were conducted in a downgoing series with signals grouped in pairs. Each pair consisted of a signal convolved with an entire echogram (the standard signal) and a signal convolved with an echogram with a part removed (the test signal). The sequence of signals in a pair was random. Each subsequent pair of signals differed from the previous one by the duration of the removed part of the echogram in the test signal. The duration of the removed part was increased each time by 20 ms. The intervals between the signals in a pair did not exceed 1 s, and those between pairs did not exceed 5 s.

The pilot experiments were conducted with the participation of 6 listeners. The same listeners participated in the main experiments in which the constant stimuli method was applied as well. The listeners aged from 21 to 29 and had no musical education. At most two listening session were caried out within a day (with an hour's intermission). The prepared listening tests were recorded by means of a digital tape recorder and reproduced via earphones.

A listening test using the constant stimuli method included 3 to 5 series (depending on the duration of the signal and the number of pairs in a series). From 12 up to 14 pairs of signals were presented to the subject in each series. The number of pairs in a series depended on the accuracy margin of the assumed time values t_{st} in the individual listeners responses. Hence, in order to fill the "transition range" around the assumed temporal limit, more pairs of signals had to be presented. As in the pilot experiments, the sequence of signals in a pair was random. .

Each series contained the same pairs of signals arranged randomly within each series. The sequence of series at each listening session was also random. One listening session lasted at most 20 minutes.

After the listening session, the number of affirmative responses of each listener was counted. The results were presented in the form of a psychometric curve of a single listener. Subsequently, the numbers of affirmative responses of all listeners were avaraged; they are presented in the form of a psychometric curve (see Fig. 1).

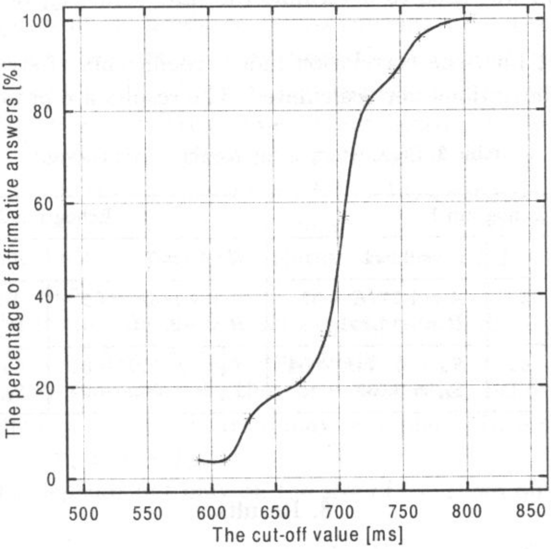

Fig. 1. Psychometric curve of the results for all the listeners (signal of speech, echogram 2).

Using a table of conversions of the values of the psychometric curve p to values projected along the straight line with ordinates z, the results were presented in the form of a straight line from which the values of the time limit t_{st} were read (see Fig. 2).

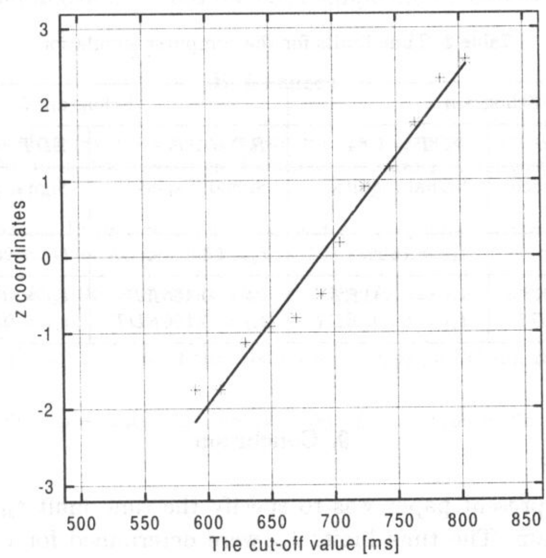

Fig. 2. The straight line resulting from the conversion of p values to z values, for all the listeners (signal of speech, echogram 2).

The value of t_{st} corresponds to the abscissa of the point on the line whose ordinate is equal to zero.

A similar method was used to determine the time values t_{st} of all signals and both the echograms.

For each straight line, the correlation index, coefficients of straight lines A and B and their standard deviations were calculated. The results are presented in Table 2.

Table 2. Parameters of the psychometric curves.

Echogram 1		Echogram 2	
$K = 0.983$	$K = 0.994$	$K = 0.997$	$K = 0.982$
$A = 2.138E-02$ $B = -14.747$	$A = 1.777E-02$ $B = -14.851$	$A = 1.115E-02$ $B = -2.701$	$A = 1.011E-02$ $B = -3.733$
$S_A = 1.321E-03$ $S_B = 0.912$	$S_A = 6.344E-04$ $S_B = 0.537$	$S_A = 2.932E-04$ $S_B = 7.604E-02$	$S_A = 5.6E-04$ $S_B = 0.223$

8. Results

In Table 3, the values of t_{st} obtained in the experiments for two echograms are presented. The values are also related to the reverberation time RT and the early decay time EDT of the simulated room for either echogram and for two types of signals convolved with either echogram.

Our data did not support the extant relationship between the time value t_{st} and other acoustic parameters of the room, mentioned previously (Sec. 4 of this paper).

Table 3. Time limits for the computer simulation.

Echogram 1		Echogram 2	
$RT = 0.79$ s	$EDT = 1.84$ s	$RT = 1.17$ s	$EDT = 1.78$ s
Signal : speech	Signal : guitar	Signal : speech	Signal : violin and violoncello
$t_{st} = 320$ ms	$t_{st} = 165$ ms	$t_{st} = 360$ ms	$t_{st} = 230$ ms
$t_{st} = 0.279RT$ $t_{st} = 0.18EDT$	$t_{st} = 0.141RT$ $t_{st} = 0.092EDT$	$t_{st} = 0.465RT$ $t_{st} = 0.196EDT$	$t_{st} = 0.291RT$ $t_{st} = 0.125EDT$

9. Conclusion

The aim of the present paper was to specify the time limit t_{st} of computer simulation of an echogram. The time limits t_{st} were determined for two echograms characterizing a simulated church under various acoustic conditions and with the same shape of the church. The signals used in the experiment were speech, guitar music and violoncello-and-violin music. The determined time values t_{st} are shown in Table 3. The subjective evaluation of the signals of speech produced time values t_{st} larger than those in the case of music signals. It was due presumably to a certain amount of reverberation inherent in the sound of music produced by instruments with a resonance box. There were no significant objective differences between the magnitude spectra of the signal convoluted with "compounded" echogram and that convoluted with the entire simulated echogram, although such differences were easily heard in the subjective evaluation.

Table 3 contains values of the time limit t_{st} obtained during the experiment and shows their relation to the reverberation time RT and the early decay time EDT of the simulated room. As shown in Table 3, the values of t_{st} are scattered between $0.141\,RT$ and $0.465\,RT$, whereas, in the case of the relation to their EDT, the scatter is smaller: from $0.092\,EDT$ to $0.196\,EDT$.

Comparison of the results obtained in our experiments to those presented in a paper by HOJAN and PÖSSELT [2] leads to following conlusions:

1. It is necessary to simulate only the early part of an echogram limited by the time moment t_{st}. The rest of the echogram may be replaced by a stochastic amplitude distribution of a duration of $(T_i - t_{st})$,

2. The value of t_{st} depends not only on the size of the room but also on the type of the signal,

3. The t_{st} values are always smaller for signals of music than for those of speech,

4. The time limit values t_{st} may be related to the reverberation time RT and the early decay time EDT. Any change of the experimental conditions (such as, e.g., a change of total absorption in a room) alters the relation between t_{st} and RT. Therefore, the parameter EDT seems to be more useful as an objective measure of reverberation in the computer simulation of a room.

All the statements above are valid for both simple and complex rooms.

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