ARCHIVES OF ACOUSTICS
16, 2, 355–367 (1991)

APPLICATION OF CORRELATION METHODS FOR AN INVESTIGATION OF THE ACOUSTIC FIELD IN A ROOM

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The aim of the present work is presenting the possibilities of applying the autocorrelation function of a room defined by Kuttruff for the estimation of some acoustic properties of rooms with various geometries. Within the work measurements tending to specify and perfect Kuttruff's method of autocorrelation function measurement of a room were carried out.

The authors focused, first of all, on the determination of the effect of frequency bandwidth of the signal used for room excitation on the autocorrelation function measured there. The work also presents the measurement results of temporal diffusion Δ – the parameter introduced by Kutruff for a quantitative estimation of autocorrelograms registered in the room. The measurements were varried out in three different rooms.

The investigation prove that the autocorrelation function measurement is particularly useful in the estimation of the number and of the time distribution of strong reflections or sequences of reflections, subjectively perceived as echo, flutter echo or sound coloration. It allows also to determine the degree of sound dispersion in a room and thus it may help to estimate the quality of the reverberation decay of sound energy in the room.

Celem niniejszej pracy było wykazanie możliwości zastosowania funkcji autokorelacji pomieszczenia, zdefiniowanej przez Kuttruffa, do oceny niektórych własności akustycznych wnętrz o różnej geometrii. W ramach pracy przeprowadzono badania mające na celu uściślenie i udoskonalenie metody Kuttruffa pomiaru funkcji autokorelacji pomieszczenia.

Skoncentrowano się przede wszystkim na określeniu wpływu szerokości pasma częstotliwości sygnału używanego do pobudzenia pomieszczenia na mierzoną w tym pomieszczeniu funkcję autokorelacji. W pracy przedstawiono również wyniki pomiarów dyfuzyjności czasowej Δ – parametru wprowadzonego przez Kuttruffa dla ilościowej oceny rejestrowanych w pomieszczeniu autokorelogramów. Pomiary te wykonano w trzech różnych pomieszczeniach.

Na podstawie przeprowadzonych badań stwierdzono, że pomiar funkcji autokorelacji szczególnie przydatny jest do oceny liczby i rozkładu czasowego silnych odbić czy też ciągów odbić, odczuwanych subiektywnie jako echo, echo drżące lub zmiana barwy dźwięku. Pozwala również na określenie stopnia rozproszenia dźwięku w pomieszczeniu a zatem służyć może do oceny jakości pogłosowego zaniku energii dźwiękowej w pomieszczeniu.

1. Introduction

An important parameter determinig the acoustic quality of a room is the degree of sound diffusion in a room as well as the amplitude and time structure of subsequent reflections, particularly early ones, reaching the listener [7, 5]. Both characteristics can be found by measuring the autocorrelation function of acoustic signals in a room. This function, as one of four statistic functions, describes the main properties of random signals such as sound of music or speech spreading around the room.

In 1966 KUTTRUFF [9] suggested the application of the defined by him autocorrelation function of a room to investigations of the time structure of the room response to pulse excitation. The introduced by him parameter – "temporal diffusion" Δ was to determine the degree of sound diffusion in a room basing on the measured autocorrelation function of a room. Further works by BILSEN [8] using the assumptions of Kuttruff's theory and the results of investigations made by SCHRODER, ATAL and KUTTRUFF [4] allowed to find the hearing threshold of the disadvantageous phenomena subjectively perceived as sound coloration, echo or flutter echo.

In recent years, due to the fast development of modern measurement techniques, based on digital analysis of acoustic signals, it has become possible to intensify the investigations concerning the application of autocorrelation function in room acoustics. The progress is reflected particularly in ANDO's works [1, 2, 3] who, basing on subjective investigations, introduced correlation criteria of time structure preference of early reflections reaching the listener and optimal reverberation time.

The investigation undertaken by the authors have in view a verification and specification of Kuttruff's method of autocorrelation function measurement of a room with a particular regard to the effect of frequency bandwidth of the signal exciting the room on the measured autocorrelation function.

The results of these investigations are presented in the first part of the present work. The second part is an attempt of showing some possibilities of the application of autocorrelation function to estimate some acoustic properties of selected rooms.

2. Main assumptions

2.1. Autocorrelation function of a room

Let us assume that the investigated room can be treated as a linear, stationary dynamic system. While exciting it with a short duration pulse, theoretically determined e.g. by Dirac pulse $\delta(t)$, we obtain the response of the room as:

$$h_0(t)=\sum_k a_k \delta(t-t_k) \tag{2.1}$$

where t_k – time moments in which pulse reflections from the surfaces limiting the room reach the measurement point. They are of stochastic character and the more randomly located they are on the time axis, the more advantageous it is for a good acoustics of the room. (We assume at the moment that the reflected pulses do not undergo frequency deformation and are merely amplitude weakened – factor a_k is the measure of this weakening).

The autocorrelation function of the room has been defined by KUTTRUFF [9] and described by the formula:

$$\phi(t) = \int_{-\infty}^{+\infty} h_0(\tau)h_0(\tau+t)d\tau = \int_{-\infty}^{+\infty} h_0(-\tau)h_0(t-\tau)d\tau \tag{2.2}$$

Substituting Eq. (2.1) into Eq. (2.2) we can determine the autocorrelation function by the following dependence:

$$\phi(t) = \sigma(t)\sum_k a_k^2 + \sum_{k \neq l}\sum a_k a_l \delta(t+t_k-t_l) = \phi_1(t)+\phi_2(t) \tag{2.3}$$

The above equation presents the sum of subsequent multiple reflections of the signal $\delta(t)$. Component $\phi_1(t)$ determines the main maximum of autocorrelation function for $t = 0$ whose height amounts to $\sum a_k^2$ and $\phi_2(t)$ expresses the remaining part of the autocorrelogram, the so called "tail" of the autocorrelation function with mean height $\overline{a_k \cdot a_l}$; it is absolutely valid for completely stochastic reflections.

In the case of reflections of the character determined in the autocorrelogram (multiple reflections in intervals $t_l - t_k$) apart from the main maximum, lateral maxima will appear for $t = t_l - t_k$. It is quite obvious because of the properties of autocorrelation function due to which we can separate the periodic component from the random signal.

Thus the autocorrelation of the pulse response of a room for a given point of the field perfectly accounts for the time structure of this response. For the quantitative estimation of the time structure of the room response to pulse excitation Kuttruff introduced the parameter "temporal diffusion" and its measure – the ratio of the main maximum $\phi_1(t)$ for $t = 0$ to the subsequent magnitude maximum, belonging to $\phi_2(t)$ [9]:

$$\Delta = \frac{\phi_1(0)}{\mathrm{Max}(\phi_2)} \tag{2.4}$$

Equation (2.2) is equivalent to the following dependence [6], [10]:

$$\phi(t) = \mathscr{F}^{-1}\{S(f)\} \tag{2.5}$$

where $S(f)$ is the power spectrum of a time signal $h_0(t)$ and $\mathscr{F}^{-1}$ – the inverse Fourier transform. The power spectrum $S(f)$ is found here as the squared modulus of Fourier transform of the signal $h_0(t)$:

$$S(f) = |\mathscr{F}\{h_0(t)\}|^2 \tag{2.6}$$

The method of finding the autocorrelation function basing on Eq. (2.2) is a conventional one, while the method using Eq. (2.5) is an indirect method consisting in, first of all, the calculation of the power spectrum by means of the forward Fourier transformation and then calculation of the inverse Fourier transform of the power spectrum.

3. Experiment

3.1. The investigated rooms

In the investigations concerning the verification of Kuttruff's method of autocorrelation function measurement of a room and in those concerning the possibility of the application of autocorrelation function for the estimation of some acoustic properties of rooms, three rooms were used: the room of the Mathematics-Physics-Chemistry Department Council of Gdańsk University (room A), Auditorium 3 of Physics Institute (room B), and Auditorium I of the Electronics Department of Gdańsk Technical University (room C).

Room A of volume 204 m^3 has perpendicular walls, its length — 10.3 m, width — 5.65 m, height — 3.5. It is a typical conference room whose scheme and the location of measurement points is presented in Fig. 1 The recommended value of reverberation time T for such room amounts to 0.75 s (± 10%) and should be constant in the frequency function [7].

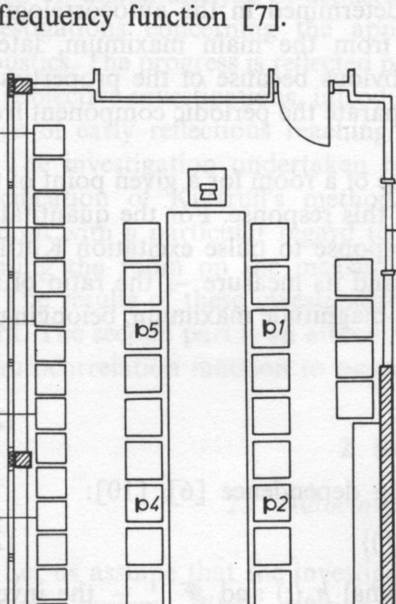

FIG. 1. Horizontal section of room A

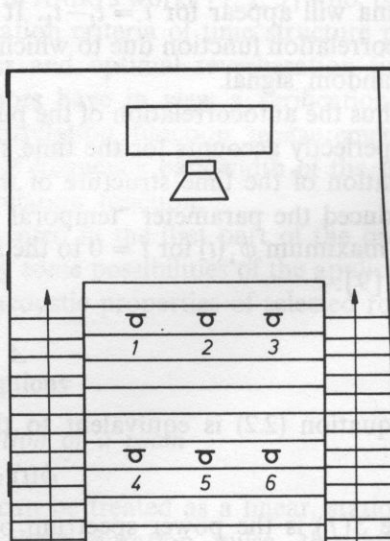

FIG. 2. Horizontal section of room B

Room B of volume 876 m^3 is amphitheatric. Its length amounts to 17.65 m, width in the widest place – 10 m, in the narrowest one – 9,4 m. The height on zero level (at the entrance) amounts to 2.85 m. The floor slopes down reaching the level of – 3.35 m on the opposite side of the room. The scheme and measurement points location is presented in Fig. 2. The recommended value of reverberation time for such room amounts to 0.8 s ($\pm 10\%$).

Room C of volume 1195 m^3 is also amphitheatric. Its length – 13.5 m, width in the widest place – 17.5 m, in the narrowest 12 m. The height on zero level (at the entrance) amounts to 3.5 m. The floor slopes down reaching the level of – 3 m on the opposite side of the room.

The scheme with the measurement points is presented in Fig. 3 The recommended value of reverberation time for such room is 0.85 s ($\pm 10\%$).

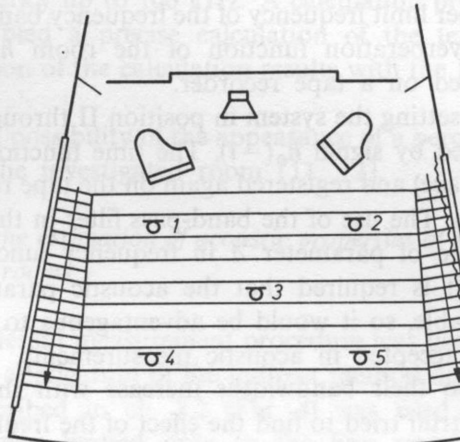

FIG. 3. Horizontal section of room C

3.2. Measurement procedure applied to verification of Kuttruff's theory of autocorrelation function estimation

The measurement of autocorrelation function in the investigated room by Kuttruff's method can be carried out in a simple way. The autocorrelation function is registered on a tape recorder just at a given measurement point as a response of the room to the signal being the reciprocal of the pulse response $h_0(-t)$ registered earlier at this measurement point. So, Kuttruff's metod is a conventional one (Eq. (2.2)) in which the investigated room plays the role of a correlator.

The schematic diagram of the instrumentation for the registration of the autocorrelation function by Kuttruff's method is presented in Fig. 4.

The first stage of the measurement is carried out in the position of connections I. The rectangular pulse from the generator is transferred to a band-pass filter and a loudspeaker.

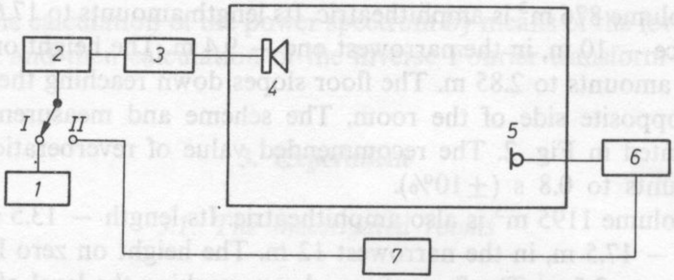

FIG. 4. Schematic diagram of instrumentation used in autocorrelation function measurement (Kuttruff's method): 1 — pulse generator, 2 — band-pass filter, 3 — power amplifier, 4 — isotropic sound source, 5 — condenser microphone, 6 — measuring amplifier, 7 — tape recorder.

The pulse duration should be shorter than a half of the period corresponding to the upper limit frequency of the frequency band of the filter used in the measurement. The reverberation function of the room h_0 (t) received by the microphone is registered on a tape recorder.

On setting the system in position II through the filter and loudspeaker the room is excited by signal $h_0(-t)$. The time function received by the microphone (in the same place) and registered again on the tape recorder is the required autocorrelation function. The use of the band-pass filter in the measurement system enables to find the value of parameter Δ in frequency function.

As it is required that the acoustic parameters of the room should be easily measurable, so it would be adventageous to use filters of width 1/1 or 1/3 octave widely accepted in acoustic measurements. Those filters are constant percentage filters so their bandwidths increase with the increasing measurement frequency.

Kuttruff tried to find the effect of the frequency-band-widening on the measured autocorrelation function. His theoretical formula [9]:

$$S = \sqrt{\frac{B'}{B}} \tag{3.1}$$

where B and B' are widths of the successive frequency bands of the filter used in the measurement, determines this effect in the case of an almost ideal sound diffusion. Values Δ obtained for higher frequencies should then be corrected — i.e. divided by coefficient S to compare them with values Δ obtained for lower frequencies.

In order to work out a univocal method of temporal diffusion measurement so that it can be widely used for objective estimations of subjectively perceived phenomena in rooms, it was necessary to carry out experiments which could specify the dependence of coefficient Δ on the bandwidth of the signal exciting the room. These investigations were made in room B.

The measurements were made with band filters of centre frequencies $f_0 = 500$, 1000, 2000 and 4000 Hz. For each measurement frequency the bandwidth B of the used filter was changed. The values B used in the investigations are presented in Table 1. The analysis of the room autocorelation functions was made by means of an

Table 1

Center frequency of band-pass filter f_0 [Hz]	Frequency bandwidth of filter used in measurements B [Hz]				
500	65	115	200	350	620
1000	130	230	400	700	1230
2000	260	460	800	1400	2500
4000	530	920	1600	2800	4900

MSM microcomputer (compatible with IBM XI) coupled with a 12-bit analogue--to-digital converter of sampling frequency up to 100 kHz. A calculation programme has been worked out which enabled a precise calculation of the temporal diffusion value Δ as well as a comparison of the calculation results with the Bilsen's weighting function [8].

On that basis, we could determine a possibility of the appearance of a perceptible flutter echo or sound coloration in the investigated room [11, 12].

3.3. Measurement procedure applied to the estimation of acoustic properties of selected rooms

In these investigations a slightly different measurement procedure was used than that described in ch. 3.2 basing on the application of the indirect method described by Eq. 2.5 [13]. The apparatus described in ch. 3.2 (Fig. 4) was used in the investigations but the measurement was limited only to the first stage which corresponds with the connection system marked by I in Fig. 4. Thus in the investigated room a registration of the room response to pulse excitation h_0 (t) was made and then a computer estimation of autocorrelation function by FFT method was carried out.

The worked out calculation programme for the estimation of autocorrelation function also enabled a precise analysis of the obtained autocorrelograms. The above investigations were carried out in rooms A, B and C. The investigated rooms were band-excited at each measurement point while the centre frequencies of the used 1/3 and 1/1 octave filters amounted to: 500, 1000, 2000 and 4000 Hz.

4. Results of investigations

4.1. Measurement of the dependence of temporal diffusion value Δ on the frequency bandwidth of the exciting signal

The dependence of the parameter value Δ on the bandwidth of the signal used for the excitation of the room for selected measurement points and frequencies is

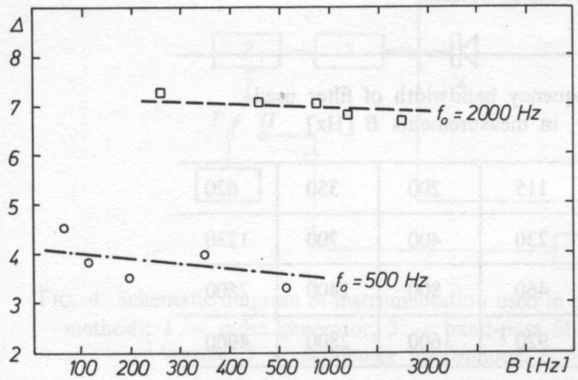

FIG. 5. Dependence of temporal diffusion Δ on the frequency bandwidth of signal used for room excitation (room B, measuring point 3). ○: $f_0 = 500$ Hz, □: $f_0 = 2000$ Hz

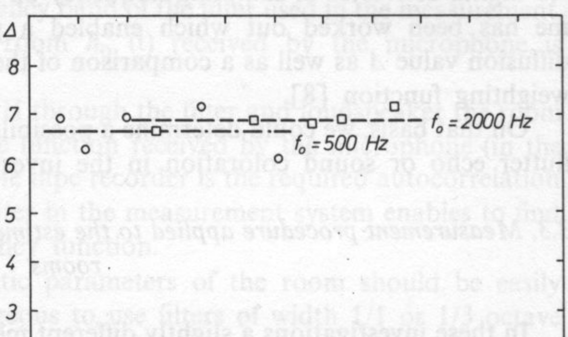

FIG. 6. Dependence of temporal diffusion Δ on the frequency bandwidth of signal used for room excitation (room B, measuring point 6). ○: $f_0 = 500$ Hz, □: $f_0 = 2000$ Hz

presented in Fig. 5 and 6. This choice has been conditioned by the assumptions of Kuttruff's theory [9] according to which formula (3.1) is valid for a large temporal diffusion of the room. Kuttruff suggested a correction of the measured values of the temporal diffusion coefficient for $\Delta > 3.5$.

From the dependencies presented in Fig. 5 and 6 we can see a clearly insignificant effect of the bandwidth of the signal exciting the room on the value of temporal diffusion for the same measurement frequency. In the case of the measurements points and frequencies for which Δ was smaller than 3, the dependences of temporal diffusion values on the frequency bandwidth of the exciting signal were similar. Apparently it agrees with Kuttruff's theory according to which formula (3.1) in not valid for small temporal diffusion of the room.

4.2. Application of autocorrelation function for the estimation of acoustic properties of selected rooms

The results of investigations concerning the above subject are presented in Fig. 7. Each figure contains mean values of temporal diffusion Δ in frequency function for

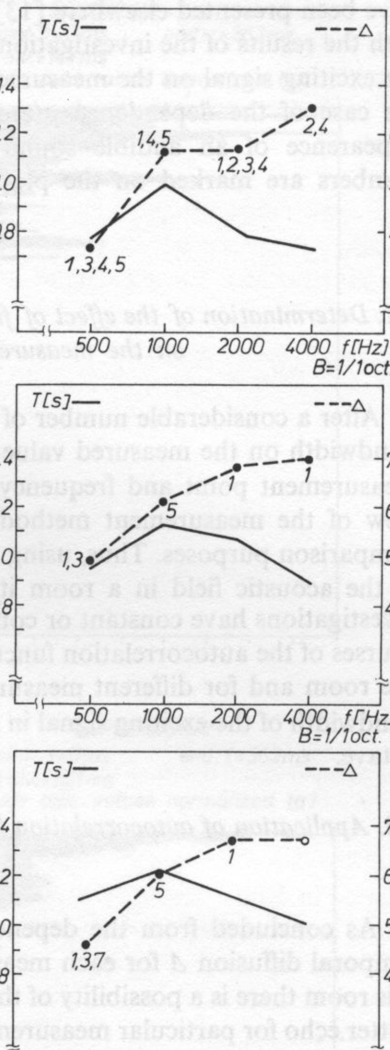

FIG. 7. Reverberation time T and temporal diffusion Δ in octave bands: a) room A, b) room C, c) room B.

each investigated room (rooms A, B, C). On each figure there are also plotted mean values of reverberation time T found from the pulse responses registered in the room. The values of the coefficient Δ and reverberation time T presented in the schemes are arithmetic means of values Δ and T measured at each measurement point of the investigated rooms (Fig. 1, 2, 3). Only in the case of room B the values presented in Fig. 7 are arithmetic means of the values measured only at measurement points 1, 3, 5, 7 and 9.

The dependence presented in Fig. 7 are plotted for octave bands. The respective values of temporal diffusion Δ and reverberation time T found for 1/3 octave bands have been presented elsewhere [13]. The differences are slight which is in agreement with the results of the investigations concerning the effect of frequency bandwidth of the exciting signal on the measured autocorrelation function presented in ch. 4.1. In the case of the dependence presented in Fig. 7 black circles mark the possible appearence of an audible sound coloration at the measurement points whose numbers are marked on the plot.

5. Conclusions

5.1. Determination of the effect of frequency bandwidth of the signal exciting the room on the measured value of temporal diffusion

After a considerable number of measurements carried out, no effect of frequency bandwidth on the measured value of temporal diffusion was observed for the same measurement point and frequency. It is an essential conclusion from the point of view of the measurement method and the procedure of finding coefficient Δ for comparison purposes. Thus, using the autocorrelation function for the investigation of the acoustic field in a room it is not essential whether the filters used in the investigations have constant or constant percentage bandwidth. When analysing the courses of the autocorrelation function for different bandwidths of the signal exciting the room and for different measurement frequencies it was found that the optimal bandwidth of the exciting signal in measurement of this type is the width equal to 1/1 octave.

5.2. Application of autocorrelation function for the estimation of acoustic properties of rooms

As concluded from the dependences presented in Fig. 7, the largest values of temporal diffusion Δ for each measurement frequency were obtained in room C. In this room there is a possibility of the appearance of a perceptible sound coloration or flutter echo for particular measurement points. A reverse situation occurs in room. A. The reason of it can be the poor geometry of room A.

While analyzing the frequency characteristics of reverberation time and temporal diffusion Δ we should state that coefficient Δ in the investigated rooms reaches high values for bands of centre frequency 2000 and 4000 Hz for which the values of reverberation time approach the recommended values. Still in the case of the band of centre frequency 500 Hz for which the values of reverberation time also approach the recommended values, the value of temporal diffusion decreases. It is observed particularly in the case of room A.

So, we may suppose that the value of temporal diffusion is not so much connected with the value of reverberation time but rather with its "quality" — the bigger the temporal diffusion coefficient, the higher the quality of reverberation course, that is, the course of sound energy decay in the room is smoother, more

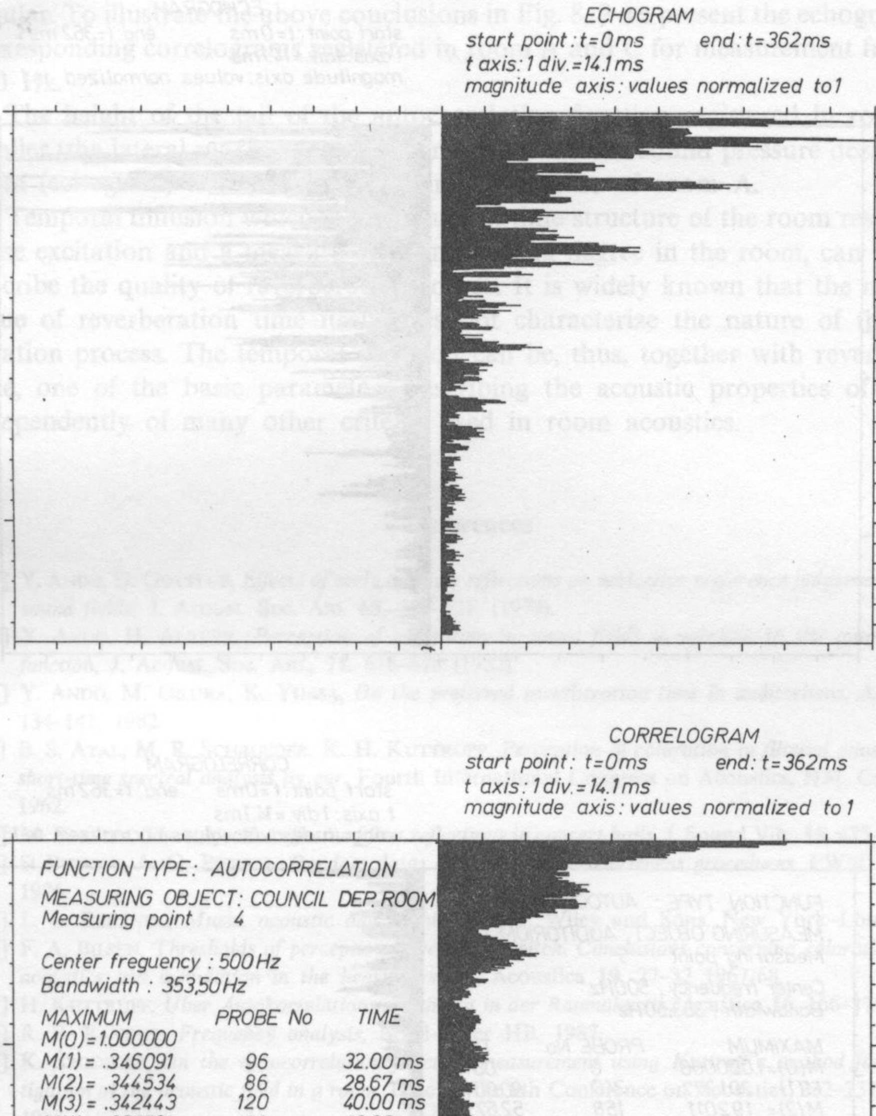

FIG. 8. Echogram and correlogram obtained from the response of room A.

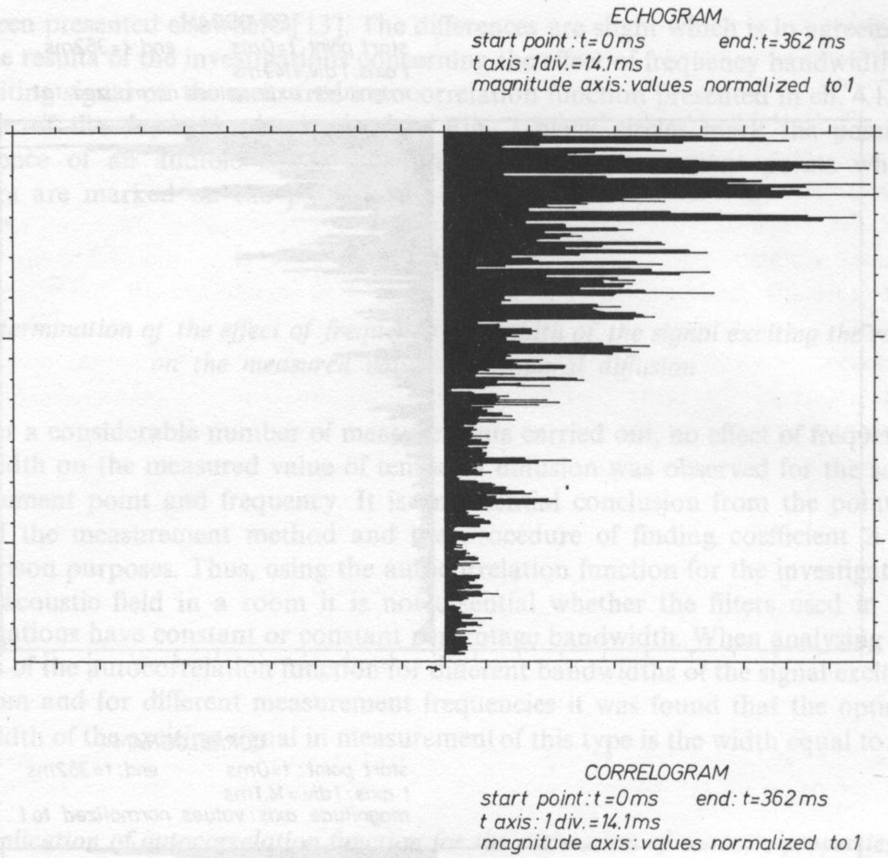

FIG. 9. Echogram and correlogram obtained from the response of room C.

regular. To illustrate the above conclusions in Fig. 8, 9 we present the echograms and corresponding correlograms registered in room A and C for measurement frequency 500 Hz.

The height of the tail of the autocorrelation function registered in room C is smaller (the lateral maxima are less significant) and the sound pressure decay in the room (echogram) is more regular than in the case of room A.

Temporal diffusion which is a measure of time structure of the room response to pulse excitation and a measure of sound mixing degree in the room, can precisely describe the quality of reverberation course. It is widely known that the measured value of reverberation time itself does not characterize the nature of the reverberation process. The temporal diffusion can be, thus, together with reverberation time, one of the basic parameters describing the acoustic properties of a room independently of many other criteria used in room acoustics.

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This work was carried out under Polish Central Project for Fundamental Research CPBP 02.03.

Received September 12, 1989