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APPLICATION OF SIMULATION METHODS TO EVALUATION OF ACOUSTIC FEATURES AND DESIGN OF ADAPTATION OF THE CONCERT HALL OF CRACOW PHILHARMONIC ORCHESTRA

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The publication presents the problems of application of digital methods of simulation of acoustic field to the evaluation of the acoustic characteristic and adaptation of the concert hall of the Cracow Philharmonic Orchestra. The measurement method based on an advanced technique of signal processing and the results obtained have been described. The evaluation of acoustic properties of the hall was carried out according to the Beranek Scale. A geometric model of acoustic field has been presented, as well as the acoustic parameters determined. An assessment method according to Ando has been discussed. This method has been applied in order to determine the influence of the changes in stage arrangement and kind of the music performed on the hearing conditions. Directions of further research based on the experimental and digital simulation methods have been proposed.

1. Introduction

Reconstruction of the concert hall of the Cracow Philharmonic Orchestra, which was necessary after a fire, was the reason for the acoustic analysis, described in this publication. The analysis concerned an evaluation of the current state of the music hearing conditions of the hall and determination of the influence of temporary arrangement of the stage during the organ reconstruction.

The basic vibroacoustic problems of the hall of the Cracow Philharmonic Orchestra have been divided into three groups:

— traffic noise, distinctly audible during the concerts,

— floor vibrations caused by the traffic,

— acoustic characteristics of the hall.

The first two problems result from the location of the hall at the street crossing of dense traffic of motor vehicles and streetcars. Their solution is connected with radical changes in construction of the building (increasing of the insulating power of walls, installation of sound foundation mat), which have been postponed to be realized later on. This publication concerns the acoustics of the concert hall of the Cracow Philharmonic Orchestra, and especially the attempts undertaken to assess it.

The hall of Cracow Philharmonic Orchestra has not been designed for musical purposes. Its shape is rectangular, which, according to opinion of numerous acousticians, is the best for applications of this kind. As it might be concluded from remarks of musicians, the main problem is poor mutual audibility both of them and of the conductor. No essential remarks have been made about conditions of music hearing in the auditorium (apart from the extremely annoying traffic noise and vibrations). These remarks inspired the undertaken investigation of acoustic characteristics of the hall. For the assessment of the characteristics the classical Beranek method has been applied (being criticized by numerous researchers) and, for the first time in home investigations, a method proposed by Ando. For the application of these methods it was necessary to perform acoustic measurements of the hall, and elaborate its digital model (Fig. 1). These problems will be presented in the following chapters.

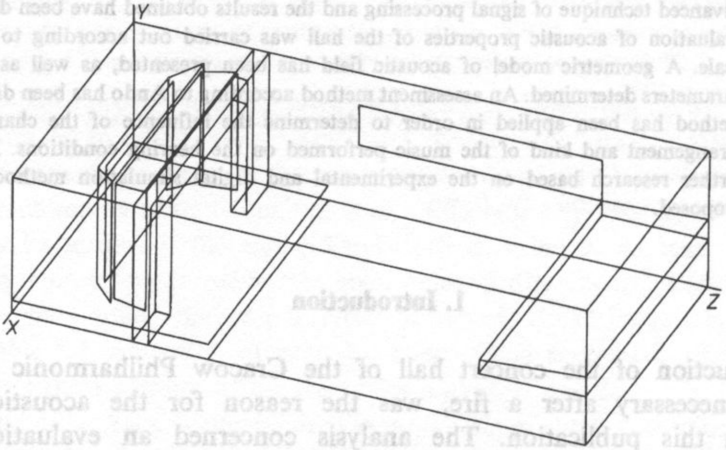


Fig. 1. Digital model of the concert hall of Cracow Philharmonic Orchestra.

2. Measurements of basic acoustic parameters

The measurements in the concert hall of Cracow Philharmonic Orchestra have been taken at points presented in Fig. 2. The applied measuring instrumentation consisted of portable microcomputer laptop Acer 1100 with signal processor card OROS AU22 type, and with professional software dB Impuls from the firm 01dB, power amplifier, and column loudspeakers (Fig. 3) [6].

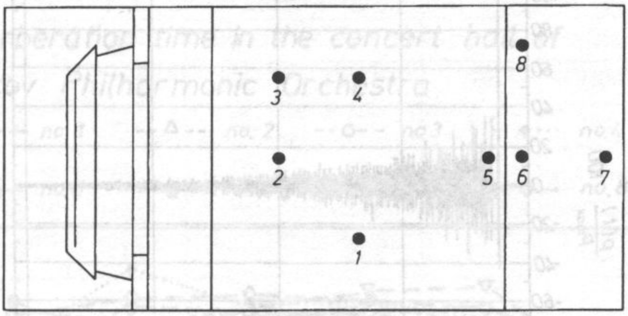


Fig. 2. Locations of measuring points (*1*–*5* orchestra, *6*–*8* balcony).

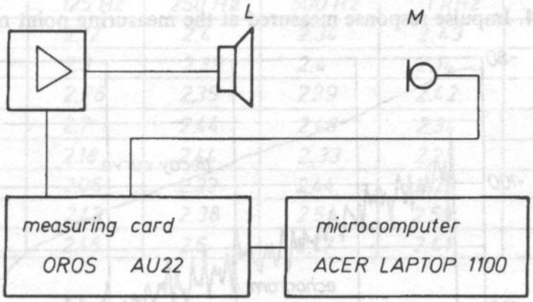


Fig. 3. Diagram of the measuring instrumentation.

The card AU22 from the firm OROS comprises signal processor TMS32OC25, two 16-bit transducers A/D, and two 16-bit transducers D/A of maximal sampling frequency 100 kHz. Storing the data in the hard disk of the microcomputer enables full elimination of magnetic recorder, while numeric computations are accelerated by the signal processor. For example, performance of spectral analysis employing FFT algorithm takes approx. 3.5 ms. Determination of acoustic parameters is realized as follows: The numerically generated white noise feeds loudspeaker *L*. The noise emitted by it is transformed into an electric signal by microphone *M*. Next, the transmittance between the two signals is determined, and after submitting it to the transformation of inverse Fourier transform the impulse response of the hall is obtained (Fig. 4). From the course of the impulse response of the hall after digital filtering a curve of acoustic pressure fading and an echograph are traced (Fig. 5), and out of them, employing the Schroeder method, the reverberation times are determined. The additional parameters determined by the dB Impuls are: early reverberation time, clarity, expressiveness, etc. The determined reverberation times for empty hall (without audience) have been shown in Fig. 6.

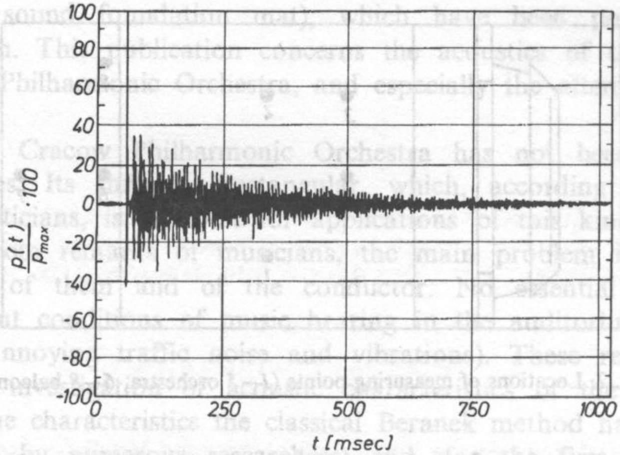


Fig. 4. Impulse response measured at the measuring point no. 6.

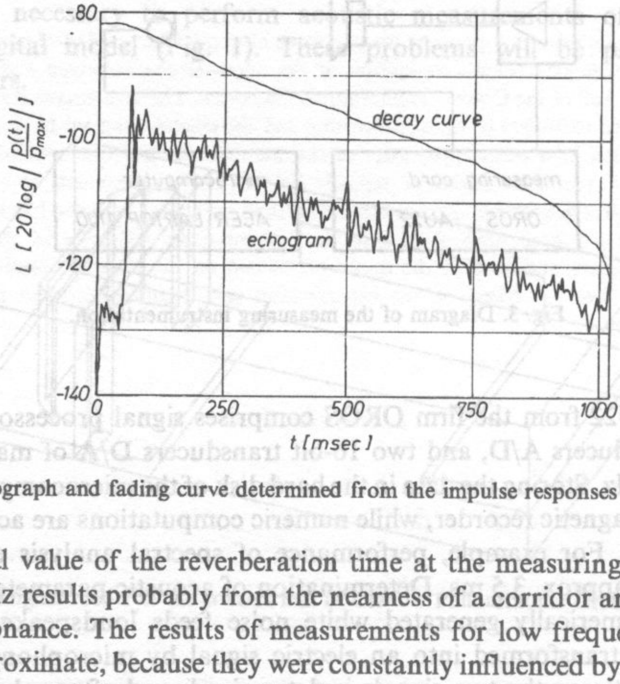
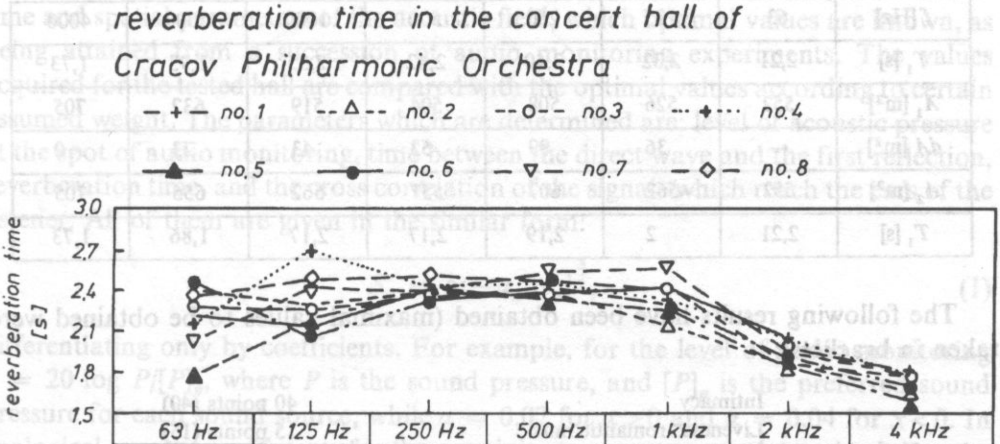


Fig. 5. Echograph and fading curve determined from the impulse responses from Fig. 4.

The maximal value of the reverberation time at the measuring point no. 4 for frequency 125 Hz results probably from the nearness of a corridor and the possibility of a rise of resonance. The results of measurements for low frequencies should be regarded as approximate, because they were constantly influenced by a low-frequency traffic noise, impossible to eliminate. For the remaining frequencies the results were repeatable. Application of this method to determination of the reverberation time in the hall with the audience seems to be troublesome because of the necessity of emitting of white noise of high level of acoustic power during the time of ten seconds. This is however a problem which concerns all presently applied methods of determination of reverberation time, and despite the attempts carried out with new measuring techniques (for instance applying a forced impulse caused by clapping hands) it has not been till now solved.



63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
2.21	2.12	2.4	2.34	2.43	2.04	1.79
2.4	2.3	2.39	2.4	2.14	1.86	1.66
2.28	2.26	2.35	2.39	2.42	1.85	1.77
2.16	2.7	2.44	2.46	2.34	2.05	1.77
1.78	2.18	2.44	2.33	2.25	1.83	1.58
2.46	2.06	2.33	2.44	2.29	1.9	1.7
2.02	2.43	2.38	2.54	2.55	1.95	1.78
2.35	2.48	2.5	2.47	2.41	1.97	1.8

Fig. 6. Reverberating times in the concert hall of Cracow Philharmonic Orchestra determined according to Fig. 5.

3. Evaluation of acoustic features of the hall according to Beranek scale

In order to assess the acoustic characteristic of the hall as the first one the BERANEK method [2] was applied. The measured reverberation times refer to an empty hall (without audience), while the scale of valuations utilizes the reverberation times for filled halls. Having not at disposal such results, the times were assessed using a statistical method. Necessary data as for absorbing coefficients of empty chairs and with people have been taken from [5]. The obtained results of measurements and computations are presented in the Table 1 where T_1, A_1 are reverberation times and acoustic absorptivity of the hall without audience, while T_2, A_2 with audience (dA — estimated increment of acoustic absorptivity).

For frequency 63 Hz suitable data as for absorption coefficients were not at disposal, because of low frequency the effect of sound absorption by listeners has been neglected. It does not influence the scale of valuations, because only the reverberation times for frequencies 125 Hz, 250 Hz, 500 Hz and 1000 Hz have been utilized.

Table 1.

f [Hz]	63	125	250	500	1000	2000	4000
T_1 [s]	2,21	2,32	2,40	2,42	2,35	1,93	1,73
A_1 [m^2]	552	526	508	504	519	632	705
dA [m^2]	---	36	99	53	43	23	0
A_2 [m^2]	552	562	607	557	562	655	705
T_1 [s]	2,21	2	2,19	2,17	2,17	1,86	1,73

The following results have been obtained (maximal values to be obtained were taken in brackets):

Intimacy	40 points (40)
Liveness: romantic music	15 points (15)
orchestral music	10 points (15)
classic music	6 points (15)
baroque music	4 points (15)
Warmth	5 points (15)
Loudness of the direct sound	8 points (10)
Loudness of the reverberant sound	0 points (6)
Diffusion	2 points (4)
Balance and blend	4 points (6)
Influence of other factors: echo	0 points
noise	−15 points
tonal distortions	0 pts.

Final valuation (maximal 100 points)

Romantic music	74 pts.	B+	Orchestral music	69 pts	B
Classic music	65 pts.	B	Baroque music	63 pts.	B

Only for romantic music the hall has been given a valuation within the range: good — very good, and for the remaining kinds within the range: satisfactory — good. These valuations do not include negative points. Taking them into consideration will result in depreciation to the hall category of satisfactory quality. This method seems however not to be presently fully adequate to qualifying, because of both the influence of subjective tastes of the evaluating person, and the difference between the direct wave and the first reflection.

4. Evaluation of acoustic features of the hall according to Ando method

The mentioned ambiguity of the evaluations according to the Beranek scale was the ground of the application of a method developed by Ando [1] to the assessment of the acoustic characteristic of the hall. The method, in comparison with the previous one, offers decidedly wider possibilities and, what is especially important, is able to an objectification of the evaluation process by operation exclusively on the numerical values, designated by a computer simulation (unlike in case of the Beranek method, there is no necessity to estimate e.g. an influence of echo).

The objectification is realized by an appointment of mutually independent, both time and spatial parameters of the acoustic field, which optimal values are known, as being attained from a succession of audio monitoring experiments. The values acquired for the tested hall are compared with the optimal values according to certain assumed weight. The parameters which are determined are: level of acoustic pressure at the spot of audio monitoring, time between the direct wave and the first reflection, reverberation time, and the cross correlation of the signals which reach the ears of the listener. All of them are given in the similar form:

$$S_n = \approx -\alpha_n |x_n|^{\frac{3}{2}}, \tag{1}$$

differentiating only by coefficients. For example, for the level of audio monitoring $x = 20 \log P/[P]_p$, where P is the sound pressure, and $[P]_p$ is the preferred sound pressure for each sound source, while $\alpha = 0.07$ for $x>0$ and $\alpha = 0.04$ for $x<0$. In analogical way the coefficients for the remaining parameters are determined. For the time difference between the direct wave and the first reflection $x = \log \Delta t/[\Delta t]_p$, for the reverberation time $x = \log T_p/[T_p]_p$, while for the function of the inter-aural cross correlation x assumes its maximal value (the index p means the preferred, optimal value). The reciprocal inter-aural correlation function, which describes the diffusion of the acoustic field in the point of audio monitoring is presented in the chapter 4.2.

The final evaluation is the sum of the component evaluations. The maximal attainable value is 0, the negative values mean deviations from the optimal conditions of audio monitoring of music.

All the parameters necessary to evaluation have been determined by means of the geometric model of acoustic field.

4.1. Geometric model of acoustic field

In order to determine the parameters used in the Ando method a digital model of acoustic field has been employed. The computer program implementing a method of image handling enables modelling of rooms of any shapes, defined by flat surfaces. To each one of these surfaces a sound attenuation coefficient is attributed as an acoustic parameter, which depends, similarly as other acoustic parameters, on frequency. The point sound sources of assignable directional characterisitcs are modelled. The results obtained for anyone of observation points inside a compartment are: passes of sound beams on the route from the sound source to the observation point (Fig. 7), levels of acoustic pressure (Fig. 8), and all the other parameters are determined by combination of the above mentioned ones. For the computations of the Ando parameters an echogram (Fig. 9) has been utilized, being a visualization of relation between the time of reaching the observation point by the wave front and its energy, as well as a sound hedgehog (Fig. 10) which in turn presents a relation between the direction of coming wave and its energy.

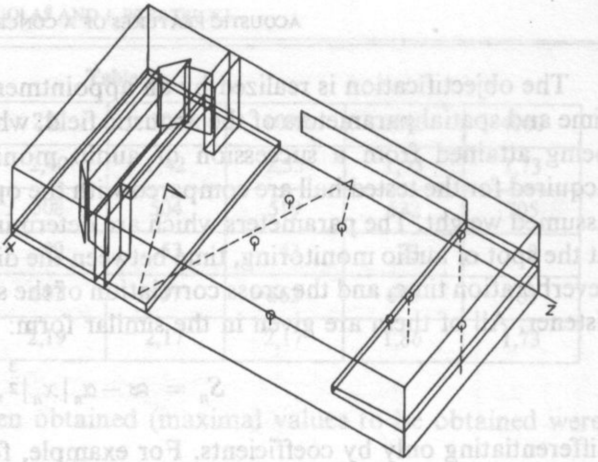


Fig. 7. Route of the sound beam.

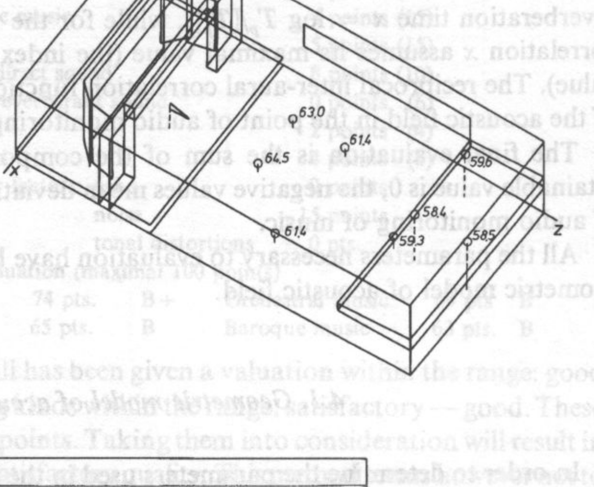


Fig. 8. Levels of acoustic pressure.

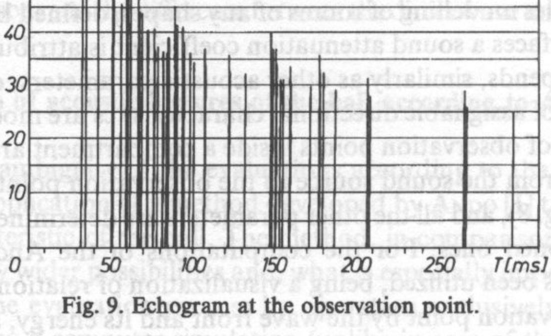


Fig. 9. Echogram at the observation point.

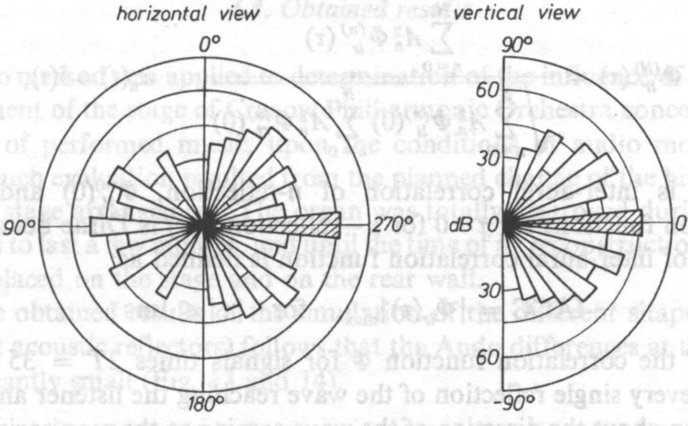


Fig. 10. Sound hedgehog at the observation point.

The model is permanently developed by both new qualitiative possibilities — as an attempt of consideration of the effects of diffraction and diffusion — as well as by quantitative ones concerning first of all the number of modelled elements and computation time.

4.2. Inter-aural cross correlation function IACC

In order to present the relations between the signals which reach the ears, it is possible to introduce a single coefficient, e.g. an inter-aural correlation between the signals $f'_l(t)$ and $f'_r(t)$, which are the acoustic pressures. The correlation becomes a significant coefficient for the determination of the degree of the field diffusion. A subjective diffusion (lack of feeling of directivity) is attained during audio monitoring in acoustic field of low correlation degree. On the other hand, well determined direction is discernable if the function has a distinct amplification for the time < 1 ms. The function depends mainly on the directions, from which the reflected waves reach the listener, and on their amplitudes. It is defined as follows:

$$\Phi_{lr}(\tau) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} f'_l(t)\,f'_r(t+\tau)\,dt, \qquad |\tau| \leqslant 1\,\text{ms} \tag{2}$$

If the listener's face is pointed at the source of sound, the standardized inter-aural correlation function is given by the equation:

$$\Phi^{(0)}_{lr}(\tau) = \frac{\Phi^{(0)}_{lr}(\tau)}{\sqrt{\Phi^{(0)}_{ll}(0)\,\Phi^{(0)}_{rr}(0)}} \tag{3}$$

where $\Phi^{(0)}_{ll}(0)$ and $\Phi^{(0)}_{rr}(0)$ are auto-correlation functions for $\tau = 0$ for every ear. If they were added to the wave of the direct reflection the standardized inter-aural correlation is expressed by:

$$\Phi_{lr}^{(N)}(\tau) = \frac{\sum_{n=0}^{N} A_n^2 \Phi_{lr}^{(n)}(\tau)}{\sqrt{\sum_{n=0}^{N} A_n^2 \Phi_{ll}^{(n)}(0) \sum_{n=0}^{N} A_n^2 \Phi_{rr}^{(n)}(0)}}, \quad w_n(t) = \delta(t), \tag{4}$$

where $\Phi_{lr}^{(n)}(\tau)$ is inter-aural correlation of n-reflection, $\Phi_{ll}^{(n)}(0)$ and $\Phi_{rr}^{(n)}(0)$ are auto-correlation functions for $\tau = 0$ for $n-$reflection, $\delta(t)$ is Dirac delta function.

The value of inter-aural correlation function is defined as:

$$\mathrm{IACC} = |\Phi_{lr}(\tau)|_{\max}, \quad \text{for} \quad |\tau| \leqslant 1\mathrm{ms} \tag{5}$$

The values of the correlation function Φ for signals times $2T = 35$ s have been measured for every single reflection of the wave reaching the listener and inserted in [1]. Information about the direction of the wave coming to the monitoring point, and about the amplitude A_n of the wave are read out from the sound hedgehog (Fig. 10). Figures 11 and 12 present the determined values of the IACC function and corresponding evaluations. Great values of IACC by the stage are visible, where the influence of the direct wave is distinct, and a gradual diminishing together with the increase of the distance and nearing the walls of the compartment.

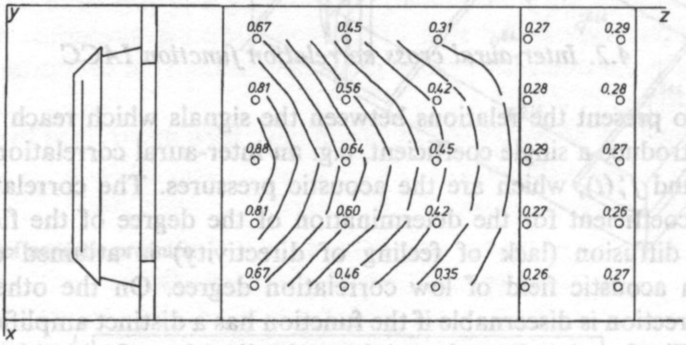


Fig. 11. Determination of IACC values.

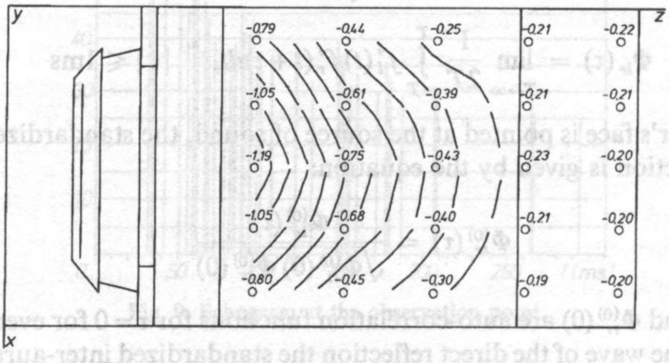


Fig. 12. Valuations according to Ando for IACC.

4.3. Obtained results

The Ando method was applied to determination of the influence of the changes in the arrangement of the stage of Cracow Philharmonic Orchestra concert hall, as well as the kind of performed music, upon the conditions of audio monitoring. The necessity of such evaluation resulted from the planned change of the hitherto existing shape of the stage arrangement. The organ was totally destroyed during the fire, its restoration is to last a few months, and until the time of its reconstruction a mockup of it has been placed on the stage and on the rear wall.

From the obtained results of the simulation of the different shapes of sceneries (being in fact acoustic reflectors) follows that the Ando differences at the auditorium are insignificantly small (Fig. 13 and 14).

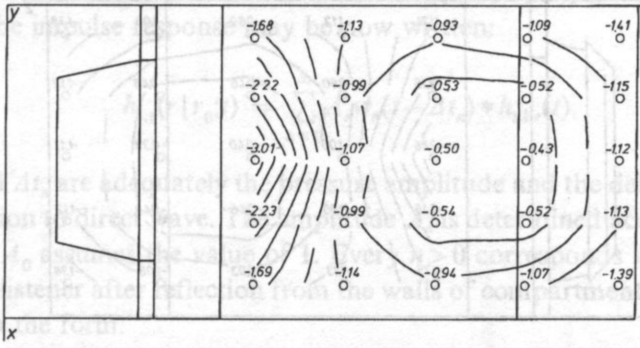


Fig. 13. Sum of valuations before modification of the hall.

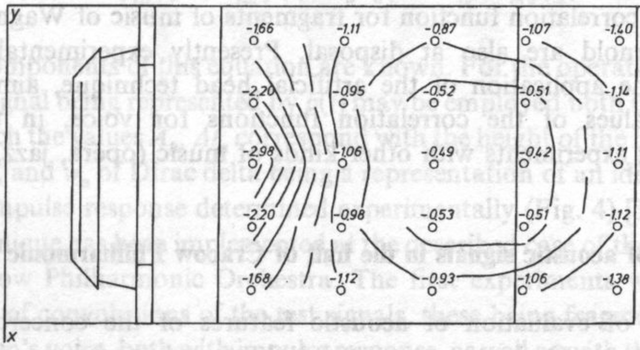


Fig. 14. Sum of valuations after modification of the hall.

For the hall of Philharmonic Orchestra the sums of evaluations of Ando parameters have been determined for different kinds of music. From the Fig. 15 and 16, which show the final evaluations adequtely to fragments of Philharmonic no. 102 of Haydn (motive C according to Ando) and Philharmonic C dur of Mozart (motive E), follows that for the last one the audio monitoring conditions are better.

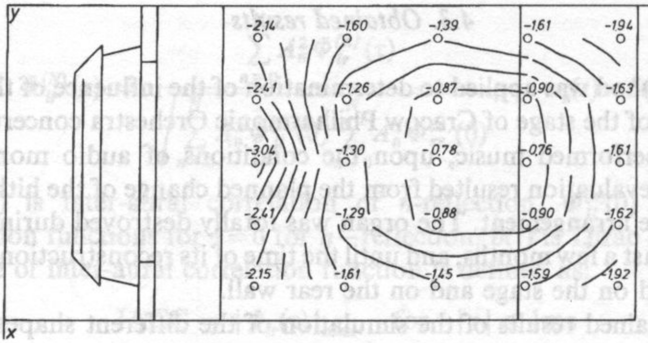


Fig. 15. Sum of valuations for Haydn music.

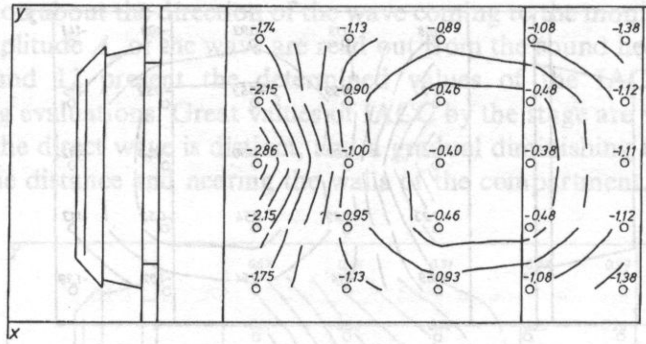


Fig. 16. Sum of valuations for Mozart music.

The values of correlation function for fragments of music of Wagner, Gibbons, and Malcolm Arnold are also at disposal. Presently experimental studies are carried out on the application of the artificial head technique, aimed to designation of the values of the correlation functions for voice, in the stage of preparation being experiments with other kinds of music (opera, jazz, rock music, etc.).

5. Simulation of acoustic signals in the hall of Cracow Philharmonic Orchestra

The methods of evaluation of acoustic features of the concert hall of the Cracow Philharmonic Orchestra presented hitherto are based on such acoustic parameters as reverberation time, inter-aural cross correlation function etc. Still the final criterion is the audio monitoring in the hall. However, exist occurrences when this monitoring is impossible, e.g. at the design stage or during considering possible changes of the shape and arrangement of halls. After all, exists a possibility of simulation of audio monitoring of the hall according to the way presented hereafter [1].

Assuming that only one source of sound exists in the stage, and that $h_l(r : r_0; t)$ and $h_r(r : r_0; t)$ are impulse responses of the pressure between the sound source located at r_0 and at the left and right ear channel of the listener (r means location of the geometric centre of the head), the acoustic pressure in the both ears, containing all the acoustic information, may be expressed by:

$$f_{lr}(t) = \int_{-\infty}^{t} p(\upsilon) h_{l,r}(t-\upsilon) d\upsilon = p(t) * h_{lr}(t), \tag{6}$$

where $p(t)$ is a signal from the source of sound, and the star means the convolution operation. The impulse response can be divided into the two components: $w_n(t)$ describing the effect of reflection from the walls of compartment and impulse responses from the free field to the ear channel $h_{nl}(t)$ or $h_{nr}(t)$, where n means a single reflection. The impulse response may be now written:

$$h_{l,r}(r \mid r_0; t) = \sum_{n=0}^{\infty} A_n w_n(t - \Delta t_n) * h_{nl,r}(t), \tag{7}$$

where A_n and Δt_n are adequately the pressure amplitude and the delay of the reflected wave in relation to direct wave. The amplitude A_n is determined according to the rule "$1/r$", while A_0 assumes the value of 1. Every $n > 0$ corresponds with a single wave reaching the listener after reflection from the walls of compartment. The equation (8) assumes then the form:

$$f_{l,r}(t) = \sum_{n=0}^{\infty} p(t) * A_n w_n(t - \Delta t_n) * h_{nl,r}(t), \tag{8}$$

All the components of this equation are known. For the operation of convolution of acoustic signal being represented by $p(t)$ may be employed both the echogram (Fig. 9) — for which the values A_n, Δt_n correspond with the height of the line, and its shift in the time axis, and w_n of Dirac delta being a representation of an ideal reflection — as well as the impulse response determined experimentally (Fig. 4) [3].

This technique has been implemented at the described case of the evaluation of the hall of Cracow Philharmonic Orchestra. The first experiments were based on the performance of convolutions of the test signals, these being fragments of symphonic music and men's voice, both with impulse response, as well as with the echograph (Fig. 9). Fig. 17 presents a test signal, which has been submitted to convolution with the echogram (Fig. 9). The result of the operation is shown in Fig. 18. Audible are these changes of the signal which are relevant to appearance of reverberation. Further experiments, which have already been planned, are however necessary, as well as the verification of the results obtained e.g. by the method of cross correlation of the simulated and real signal, recorded in the hall.

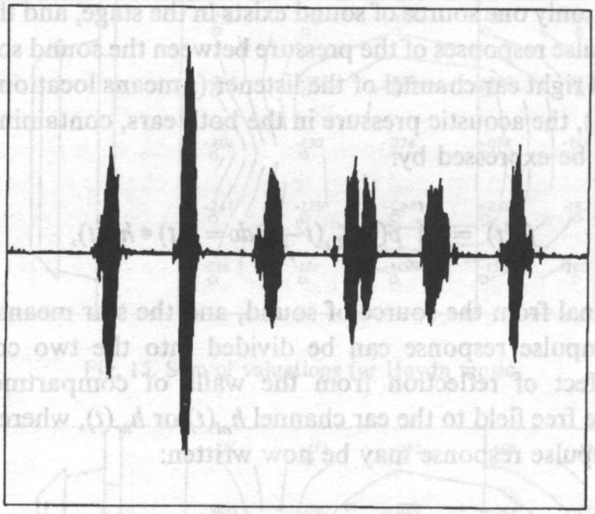


Fig. 17. Fragment of the signal from human speech.

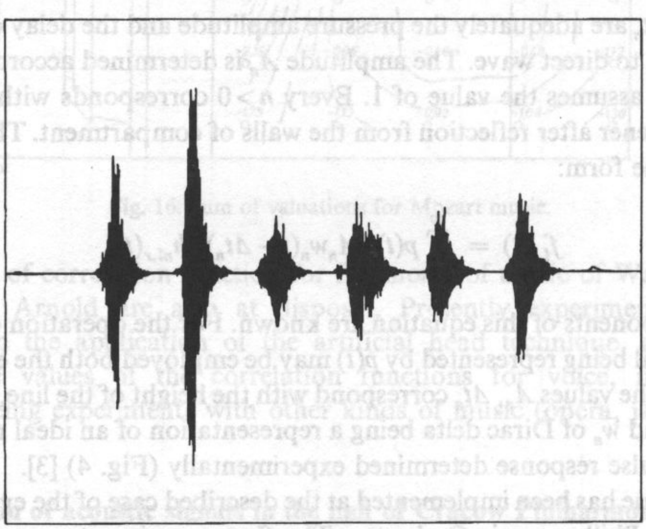


Fig. 18. The result of convolution of the signal from Fig. 17 with echogram (Fig. 9).

6. Evaluation of acoustic properties of the hall and directions of further research

The hall of the Cracow Philharmonic Orchestra has obtained the valuation within the scope of good — very good for romantic music, while for the remaining kinds satisfactory — good. After taking into account the scores for the disturbing effects, the valuation for all kinds of music lowers to satisfactory. It comes however from the

Ando method that the hall suits better to the presentation of the Mozart music than the Haydn, and the proposed changes of the stage arrangement do not cause any essential changes in the audio monitoring conditions. This method, as opposed to the Beranek method, does not enable assigning a singular valuation to the hall, and consequently, a direct comparison of different halls. The work being conducted is aimed to creation of such possibility e.g. by determination of the ratio between the zones of highest values of valuation and the entire zone of auditorium.

The results obtained hitherto demonstrated the usefulness of application of the Ando method as an essential extension of valuations according to the Beranek method. Linking the Ando method and the potentials of simulations of acoustic signals tends towards creation of a comprehensive expert system. Such system, assuring ability of modelling of acoustic field in compartments of any shape, will enable an evaluation of both current state as well as indication of applicable solutions, e.g. acoustic adaptation, etc. Being equipped with a library of absorption coefficients for different materials, directional characteristics of sources, and test acoustic signals should become a help for both acousticians and architects.

The first attempts of automatization of the process of choice and selection of arrangement of acoustic elements in a compartment have been undertaken. In the publication [4] an implementation of the method of factor analysis to choice of arrangement of sound sources has been presented, the method being able to assure a minimal level of acoustic pressure in the observation point. This method can be also applied to choice of location of musicians on the stage in order to assure the optimal hearing conditions e.g. by conductor. This subject in being developed, however not possible to a realization before modifications of the geometric model of acoustic field. The work being presently conducted are focused first of all on considering the effects of diffraction and diffusion of the sound wave. Its novelty is regarding the wave not as a sound beam; the new approach is based on determination of the degree of mutual visibility for every pair of surfaces, both between them reciprocally, as well as from direction of the sound source and the listener.

Parallel with the simulative investigations the experiments with the artificial head are carried out. Its objective is determination of the inter-aural cross correlation function for other kinds of music than the ones quoted by publications of Ando, and also to establish a basis for development of the technique of creating the virtual reality — which expands so spontaneously now — but within the domain of acoustic signals.

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