Acoustics of Russian Classical Opera Houses*

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Some acoustic problems of threater halls built in the classical style (stalls in a horseshoelike shape and several rows of balconies along the walls) have been studied. A list of such theater halls built in Russia and existing to this day is given. The main parameters of the halls, such as dimensions and number of seats, and a full bibliography dealing with research into their acoustics are presented. The results of acoustic measurements in the halls are analyzed and some recommendations are proposed which may be useful for the renovation of old halls and the acoustic design of new ones.

0 INTRODUCTION

Theater halls built in a horseshoelike shape and having some rows of balconies along the walls and a flat ceiling first appeared in Italy. We use the term "classic theater houses." Since that time these halls spread widely throughout Europe. In Russia such theater halls appeared at the end of the eighteenth century, and by the nineteenth century they existed in many cities. Nowadays, there is again much attention being paid to the construction of such halls, as well as the reconstruction of existing halls. This explains the necessity for detailed research into the acoustics of such theater halls. This study is organized in the following manner.

Section 1 gives detailed information on the existing Russian classical theater halls. The theaters are divided into two main groups—opera houses and drama theaters. There is also a limited group of small wooden theaters. Data concerning the location of the theaters, the time of their construction, the number of seats, and so on, are presented.

The results of acoustic measurements in several of the most interesting and well-known halls are given in Section 2, as well as data on reverberation time RT_{60} and some energy criteria such as clarity C_{80} and definition D_{50}. Some drawings of the halls are also presented.

An analysis of the acoustics of the classical theater halls is given in Section 3. Some general remarks on the acoustics of such halls and recommendations for their design are made.

Finally Section 4 gives an example of the acoustic design of a new classical theater hall (about 1000 seats)—the Sister Stage of the Bolshoi Theater in Moscow.

1 DATA ON THEATER HALLS

The first theater halls were built in Russia in the eighteenth century. At first they were mostly located in the palaces of the noble families, both in the capitals and in the suburbs. The first public theaters appeared later, at the end of the eighteenth and the beginning of the nineteenth centuries. In the second half of the nineteenth century construction of the theaters spread widely, not only in the capitals (St. Petersburg and Moscow) but also in other cities. The building boom lasted from 1880 until the start of the twentieth century, when the beginning of World War I brought construction to a halt. Thus the majority of the classical theater halls, including all the best known ones, were built prior to 1914. The next period of theater building covers the years of the Soviet regime. After the end of World War I the first new theater was built in 1926. About 90 new theaters were built in Russia from that time until today. Among these

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only nine theaters had halls of the classical type. It should be noted that these nine theaters were all built during a rather limited time period of 6 years, from 1956 to 1961.

Brief information about all Russian theaters up to 1977 can be found in [1], a reference republished in more limited form in 1989. This publication and others [2], [3] were used in organizing Tables 1 and 2. A list of the classical theaters existing in Russia today is presented in Table 1. The theaters are divided into three groups. The first two include opera houses (eight halls) and drama theaters (26 halls). In the third group there are three little halls located in special buildings all made of wood. In the past there were many such small buildings in the villages of Russian noble families. But wood is a material with a limited lifetime, and only a few such buildings still exist. The year of construction, the total number of seats N, and the volume of the hall V_T (without stage) are also shown. Many of the halls were renovated subsequently. These dates are not mentioned in Table 1.

An estimate of the sound quality by means of questionnaires lead to the conclusion that among the classic opera houses and drama theaters there are no halls with really poor acoustics. Nevertheless, it is possible to divide the halls into two groups (see Table 1). Group B comprises the halls with fair acoustics, group A includes those whose acoustics are characterized as good according to widespread opinion. On a 5-point scale group B corresponds to estimations from "fair" to "good" and group A from "good" to "excellent." Of course such a division into two groups is not precise because in every hall there are areas of seats with relatively better and worse acoustics. More detailed information on this subject is given in Section 2.

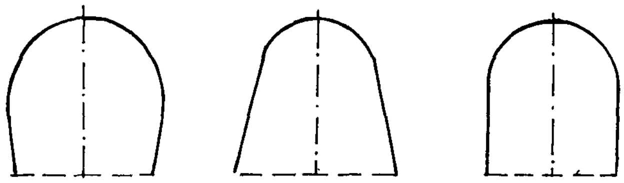
Some additional data on the geometry of the halls are presented in Table 2. It shows 1) the number of balconies (the balconies with ground floor boxes is not included); 2) the average width W; 3) the length L from the footlights to the rear wall; 4) the average height H; 5) the room volume per seat V_1; 6) the floor area per seat S_1; 7) the shape of the plan. Most halls have a horseshoelike form. But it was decided to include in the list some halls with balconies that have different shapes.

Table 1.

Number	City, Theater	Date	N	V_T (m^3)	Group
	1. Opera House				
1	Moscow, Bolshoi Theater	1825	2000	12000	A
2	St. Petersburg, Mariinsky Theater	1860	1780	9630	A
3	St. Petersburg, Maliy Opera House	1833	1263	6158	A
4	Saratov, Opera House	1865	1192	7629	A
5	Ekaterinburg, Opera House	1912	1304	5398	B
6	Upha, Opera House	1914	1055	6330	B
7	St. Petersburg, Music Hall	1912			B
8	Voronej, Opera House	1961	1113	5676	B
	2. Drama Theaters				
9	St. Petersburg, Bolshoi Drama Theater	1877	1432	7188	A
10	St. Petersburg, Aleksandrinsky Theater	1832	1385	7000	A
11	Moscow, Central Theater for Children	1820	989	5439	B
12	Moscow, Mayakovsky's Theater	1885	1232	4805	A
13	Tver, Drama Theater	1886	943	4488	B
14	Nijny Novgorod, Drama Theater	1896	1035	4243	B
15	Moscow, Maliy Theater	1824	1112	4047	B
16	Ulianovsk, Drama Theater	1787	938	3920	A
17	Moscow, MHAT (main old stage)	1885	1134	3765	A
18	Samara, Drama Theater	1888	982	3633	B
19	Rostov-on-Don, Theater for Children	1890	620	3472	B
20	Astrakhan, Drama Theater	1883	768	3050	B
21	Orenburg, Drama Theater	1856	737	2970	B
22	Omsk, Drama Theater	1904	745	2883	B
23	Irkutsk, Drama Theater	1894	830	2814	A
24	Kostroma, Drama Theater	1868	746	2536	B
25	Taganrog, Drama Theater	1883	674	2561	B
26	Ryazan, Theater for Children	1889	502	1609	B
27	Moscow, Mossovet's Theater	1956	1198	6037	B
28	Kaliningrad, Drama Theater	1960	945	4271	B
29	Ryazan, Drama Theater	1961	850	4165	B
30	Kaluga, Drama Theater	1959	783	3672	B
31	Cheboksary, Drama Theater	1961	807	3502	B
32	Petrozavodsk, Theater for Music & Drama	1956	780	3439	B
33	Ioshkar-Ola, Drama Theater	1961	792	3302	B
34	Prokopievsk, Drama Theater	1960	746	3058	B
	3. Wooden Theaters				
35	St. Petersburg, Theater on Kamenniy Island	1844	550	2700	B
36	Moscow, Theater in Ostankino Palace	1795	200	2000	B
37	Archangelskoje, Gonzago Theater	1818	280	1750	A

The shapes are illustrated in Fig. 1. Fig. 1(a) shows the most widespread horseshoelike shape, Fig. 1(b) may be called "belllike," and Fig. 1(c) has parallel lateral walls next to the stage area and a curved (semicircle or ellipse) rear wall. These shapes are also listed in the last column of Table 2. The halls are listed numerically in Tables 1 and 2 and later will be referred to by these numbers. For example, TH13 means the theater hall in the Drama Theater in Tver (see Table 1).

Due to their dimensions and geometry the opera houses can be divided into two groups. The first includes large halls with $V_T > 9000$ m^3 and $N > 1700$. There are two such halls in Russia (TH1 and TH2). They have four or five rows of balconies, $L \cong 25$ m, and $W = 28-30$ m. The second group includes the other six opera houses. They have three rows of balconies (except for TH3 with four balconies), 1000–1300 seats, and $V_T = 5600-7600$ m^3. Their average dimensions are $\overline{W} = 21.4$ m; $\overline{L} = 24.8$ m; $\overline{H} = 16.1$ m. The dimensions of the halls in the two groups differ greatly and there is no gradual transition between the groups. For example, the smallest difference in V_T values between the groups is 2000 m^3 and in capacity, 480 seats. On the other hand the values of V_1 and S_1 are very close (5.7 versus 5.3 m^3 and 0.65 versus 0.68 m^2 for groups 1 and 2, respectively.



1 2 3

Fig. 1. Shapes of floor plans.

Table 2.

Number*	Number of Balconies (with Dress Balcony)	W (m)	L (m)	H (m)	V_1 (m^3)	S_1 (m^2)	Shape of Floor Plan†
			1. Opera Houses				
1	5	25.0	30.4	19.0	6.00	0.65	(a)
2	4	24.7	28.0	17.1	5.41	0.66	(a)
3	4	21.0	24.1	16.1	4.80	0.62	(a)
4	3	22.5	26.1	16.6	6.40	0.63	(a)
5	3	20.2	22.7	16.1	4.15	0.74	(a)
6	3	21.0	25.7	16.7	6.00	0.78	(a)
7	3			No data available			(a)
8	2	22.4	25.8	14.8	5.10	0.64	(a)
			2. Drama Theaters				
9	3	18.6	27.3	15.6	5.03	0.60	(c)
10	4	20.5	23.7	18.0	5.06	0.51	(c)
11	3	24.7	15.1	20.6	5.50	0.74	(c)
12	3	19.0	20.2	15.2	3.90	0.63	(c)
13	2	20.5	26.3	13.0	4.76	0.60	(a)
14	2	16.9	27.5	12.8	4.10	0.59	(a)
15	3	17.8	19.5	12.0	3.64	0.47	(a)
16	3	21.2	21.5	11.3	4.18	0.70	(c)
17	2	16.9	22.9	12.6	3.32	0.52	(c)
18	3	17.7	21.0	14.0	3.70	0.54	(a)
19	2	16.7	18.3	14.1	5.60	0.68	(c)
20	3	16.8	20.1	11.8	3.97	0.64	(a)
21	2	18.9	20.7	10.0	4.03	0.74	(c)
22	3	13.6	18.6	13.9	3.87	0.57	(c)
23	3	16.8	19.5	10.4	3.39	0.66	(c)
24	3	12.5	16.8	11.0	3.40	0.56	(b)
25	2	14.0	17.6	11.0	3.80	0.63	(a)
26	3	7.8	15.5	9.8	3.20	0.59	(b)
27	3	26.2	27.5	14.0	5.04	0.62	(a)
28	2	20.6	25.8	13.2	4.52	0.67	(c)
29	2	17.9	21.1	11.7	4.90	0.58	(c)
30	2	18.1	21.0	11.4	4.69	0.62	(c)
31	2	17.4	24.1	12.5	4.34	0.59	(a)
32	2	18.0	21.0	11.7	4.41	0.63	(b)
33	2	18.0	21.0	11.0	4.17	0.60	(c)
34	2	18.0	21.1	12.6	4.10	0.60	(a)
			3. Wooden Theaters				
35	3	15.4	18.1	10.6	4.9	0.58	(a)
36	1	11.4	16.0	10.1	10.0	0.64	(a)
37	2	10.0	8.10	7.80	6.20	0.61	(a)

* See Table 1.
† See Fig. 1.

In the same way the drama theaters can be divided into two groups. In the first group there are large halls with $V_T > 3700$ m^3 (TH9–17, 27–29) and in the second, the other halls (TH18–36, 30–34). $N \cong 950$ seats is the border between these groups. The average dimensions for the first group are $\overline{W} = 20.1$ m; $\overline{L} = 23.2$ m; $\overline{H} = 14.0$ m, and for the second, $\overline{W} = 16.0$ m; $\overline{L} = 19.7$ m; $\overline{H} = 11.8$ m. The difference between the two groups of drama theaters is not as distinct as for the opera houses. The values of V_1 and S_1 are also very close (4.5 versus 4.0 m^3 and 0.60 versus 0.62 m^2 for groups 1 and 2, respectively).

2 ACOUSTIC MEASUREMENTS IN THEATER HALLS

The acoustics of several classical theater halls are given in this section. We selected the halls best known for their importance in the history of Russian theater hall architecture.

2.1 Opera Houses

2.1.1 Bolshoi Theater (TH1)

According to its volume, dimensions, and number of balconies TH1 is the largest classical theater hall in Russia. The plan of TH1 is shown in Fig. 2. Detailed investigations of its acoustics were made three times [4]–[6]. The main purpose of the study in [5] was to propose a form of acoustic shell for concerts of the orchestra on stage. (These proposals were never realized.) In spite of the different methods of acoustic measurements, all three investigations lead to rather similar results. The response time $RT_{60}(f)$ has a typical form and RT_{60} values decrease as the frequency f increases. In the empty hall at the middle frequencies $RT_{60} = 1.3$–1.4 s, and in the occupied hall $RT_{60} = 1.2$ s. While taking into account the hall's volume $V_T = 12\ 000$ m^3, such a reverberation is lower than the recommended optimum [7] by a value of ≈ 0.3 s. Intelligibility in the hall is characterized as good. The average RASTI values in the hall are equal to 0.63 and $D_{50} > -3$ dB. Only in the central part of the stalls is D_{50} somewhat smaller than -3 dB. The results of articulation tests also indicated good intelligibility. The tables of logograms of the Russian language were used in these tests. The average C_{80} values in the hall are close to 4 dB for sound sources on stage. When the sound source is located in the pit, C_{80} decreases, which is a typical result. It was estimated that C_{80} increases as the microphone is moved from the front rows of the stalls to the back rows.

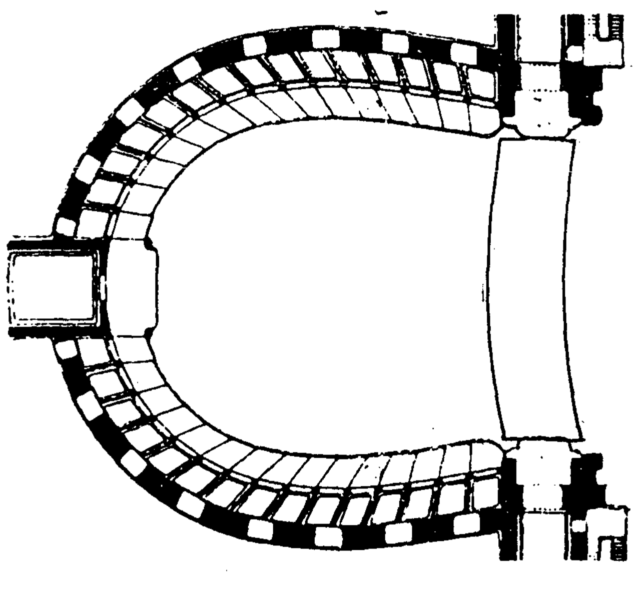


Fig. 2. Plan of TH1.

Analysis of the measured data and the results of the listening tests showed that the acoustics is good in the majority of the seating areas. Some deterioration of the sound quality was noticed 1) in the balconies near the rear walls of the boxes (lack of loudness and change of timbre), and 2) in the first rows of the stalls (lack of balance between singers and orchestra). The first effect is caused by heavy sound-absorbing curtains in the depth of the boxes and by the fact that at those seats the direct sound is partly screened by the barriers of the boxes. The second effect is due to a lack of early high-level reflections when the sound source (singer) is on stage.

The theater is a monument of Russian architecture and its interior could not be changed. Nevertheless in order to exclude the faults mentioned it was proposed [4] 1) to install chairs in the hall that absorb less of the sound energy, 2) to minimize the quantity of curtains on the balconies, and 3) to lower the floor of the pit (in the area of percussion and wind instruments).

2.1.2 Mariinsky Theater (TH2)

A detailed history of the construction of TH2 may be found in [3] (see the plan in Fig. 3). The acoustics of the hall has traditionally been characterized as good. In the empty hall at the middle frequencies $RT_{60} = 1.2$ s [8]. This leads to $RT_{60} \cong 1.0$ s in the occupied hall, and such a value is below the recommended optimum [7]. The intelligibility in TH2 is good and D_{50} is above -5 dB in all areas. (Mainly it is above -3 dB.) In the first and central rows of the stalls C_{80} is close to 2 dB and in the back rows $C_{80} = 5$–6 dB (empty hall). The values of C_{80} were measured while moving the microphone in the balconies along a vertical line from the floor up to the ceiling. The results for two such lines are given in Table 3 for an empty hall. Line 1 corresponds to the boxes that are close to the stage and line 2 to the central boxes that are farthest from the stage. Source position S-1 was 2 m from the footlights, and S-2 was 7 m from the footlights. It can be seen that in the central boxes C_{80} is larger than in the boxes that are closer to the stage. The measured impulse responses showed that there is a lack of high-level reflections in the part of the hall closest to the stage. For that reason the C_{80} values are larger in the rear of the hall. In general, analysis of the results leads to the conclusion that the acoustics of TH2 are very close to those described in Section 2.1.1 for TH1.

2.2 Drama Theaters

2.2.1 Maliy Theater (TH15)

TH15 is one of the oldest and most famous drama theaters in Russia. Its plan is shown in Fig. 4. The acoustics of TH15 was traditionally characterized as good. But in the hall there were some areas with a lack of sound quality. Acoustic investigations were undertaken twice: before [9] and after [10] the renovation of the hall. The measures RT_{60} values in the empty hall are shown in Fig. 5. Before renovation RT_{60} in the occupied hall at the middle frequencies was about 0.8 s. This value is below the recommended optimum [7]. For that reason during renovation some work was done to increase the reverberation time, dealing mostly with the use of less sound-absorbing materials for chairs and curtains. As a result RT_{60} was increased by the rather large value of 0.2 s (see Fig. 5). In the occupied hall at the middle frequencies RT_{60} = 1.0–1.1 s. These values coincide with the optimal reverberation time for drama theaters with V_T = 4000 m^3.

The energy criteria averaged in the different parts of the hall are listed in Table 4.

The value of $D_{50} > -3$ dB corresponds to good speech intelligibility. The results of articulation tests lead to the same conclusion. Nevertheless after renovation of the hall some areas remained with relatively bad acoustics, namely, 1) the central part of the stalls, and 2) the last rows in the balconies. The results of impulse measurements showed that this is caused by a lack of early high-level reflections.

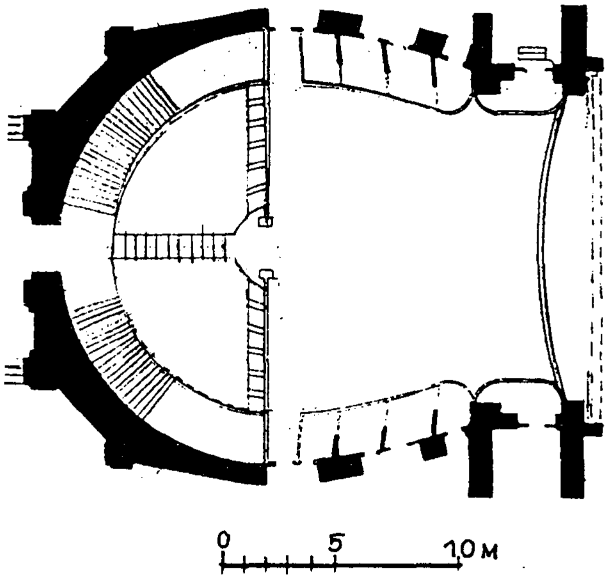


Fig. 4. Plan of TH15.

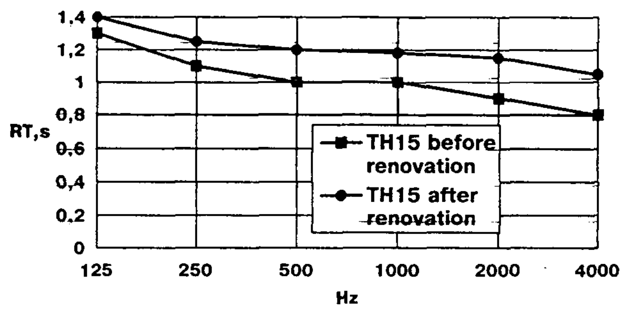


Fig. 5. RT_{60} values in TH15.

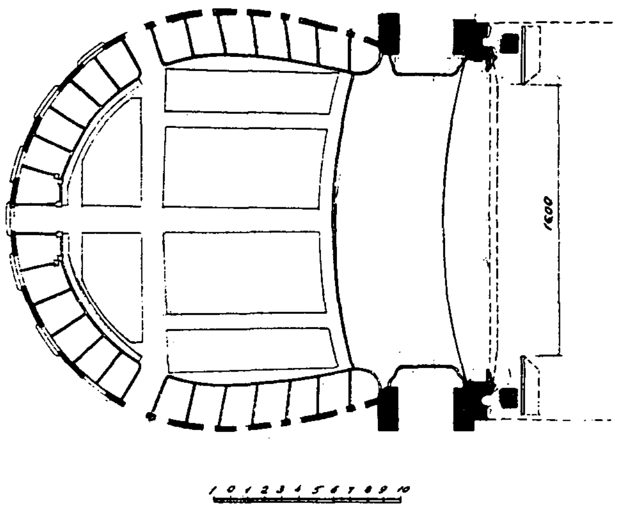


Fig. 3. Plan of TH2.

Table 4.

Seating Area	D_{50} (dB)	C_{80} (dB)
First rows of stalls	−1.4	5.4
Center of stalls	−2.5	3.8
Last rows of stalls	−0.3	9.7
Last rows of balconies	−1.9	7.0

Table 3.

Microphone Position	Vertical Line 1 through Second Box (as Counted from Footlights)		Vertical Line 2 through Box Next to Central (Tzar's) Box	
	S-1	S-2	S-1	S-2
Ground floor	3.6	3.3	8.5	7.8
Dress balcony	2.2	1.6	7.5	8.0
1st balcony	2.7	1.5	7.0	8.7
2nd balcony	3.3	1.7	5.6	6.2
Gallery	0.5	2.1	4.9	5.6

2.2.2 *MHAT (TH17)*

The interior of TH17 was finally completed after the great reconstruction of the building in 1909. There had been no changes since that time (see plan in Fig. 6). The latest renovations deal mainly with stage technology and not with the hall's interior. The RT_{60} values in the empty hall and on the stage are shown in Fig. 7 [11]. The reverberation times of the hall and the stage are close to each other, which is a positive factor. In the occupied hall at the middle frequencies RT_{60} = 1.1–1.2 s, which is close to the recommended optimum [7]. The values of EDT lay below RT_{60} at all measurement points. As an example the values of EDT measured in the center of the stalls and in the central box of the first balcony are shown in Fig. 7. The impulse responses measured with an integration time of 35 ms showed concentration of the sound reflections with a delay of 80–100 ms at the back of the stalls. But the levels of these reflections are rather low and no echo is heard in the stalls. The results of the measurements as well as the articulation tests correspond to good speech intelligibility, which is the most important criterion for a drama theater.

2.2.3 *Bolshoi Drama Theater (TH9)*

TH9 is the largest classical drama theater in Russia. The hall has four rows of balconies. Unlike the other classical theaters, the ceiling in TH9 is not flat. It has the shape of a dome with a large radius of curvature. The plan of TH9 is shown in Fig. 8, and the values of RT_{60} are given in Fig. 9. The values of RT_{60} in the empty hall and in the occupied hall are rather close to each other [12]. This is due to the installation in the hall of highly sound-absorbing chairs. The values of RT_{60} in the occupied hall ($\approx$1.1 s) correspond to the recommended optimum for drama theaters with $V_T \approx 7000$ m^3 [7].

Besides traditional (ISO/DIS3382) measurements the diffusion of the sound field was investigated by the method described in [13]. The omnidirectional sound source was located on the stage. Octave bands of noise with constant level were used as test signals. The sound pressure levels (SPL) were measured at points along four rays I–IV (see Fig. 8) with an omnidirectional microphone. The results for rays I, II, and III and for the two frequencies of 250 and 1000 Hz are shown as an example in Fig. 10. In this figure the distances are counted from points 1, 2, and 3 marked in Fig. 8. It is well known from statistics theory that at distances greater then the critical radius r_C the diffusion part of the sound field predominates and the SPL should be constant. This rule is never exactly fulfilled in real halls. It can be seen from Fig. 10 that in TH9 SPL values are decreasing by

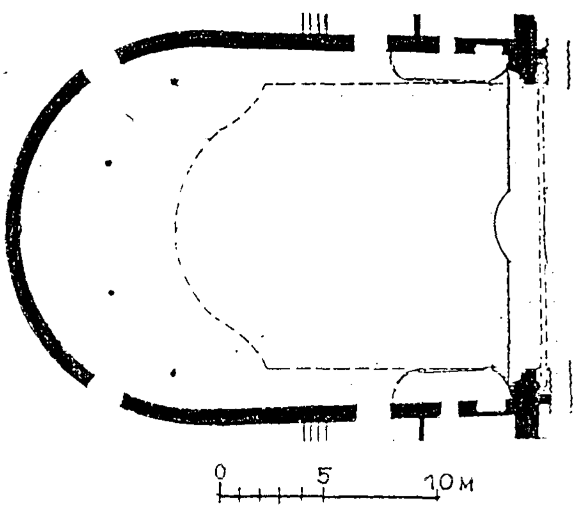


Fig. 6. Plan of TH17.

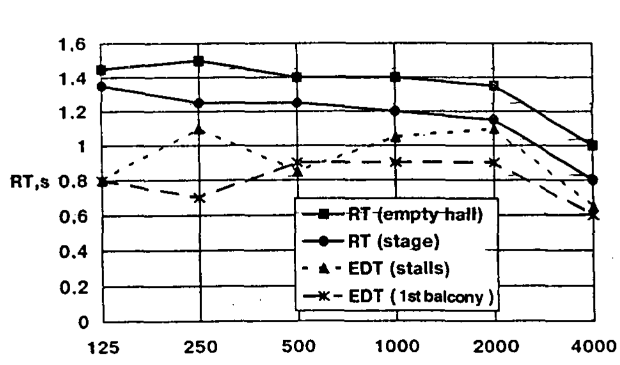


Fig. 7. RT_{60} and EDT values in TH17.

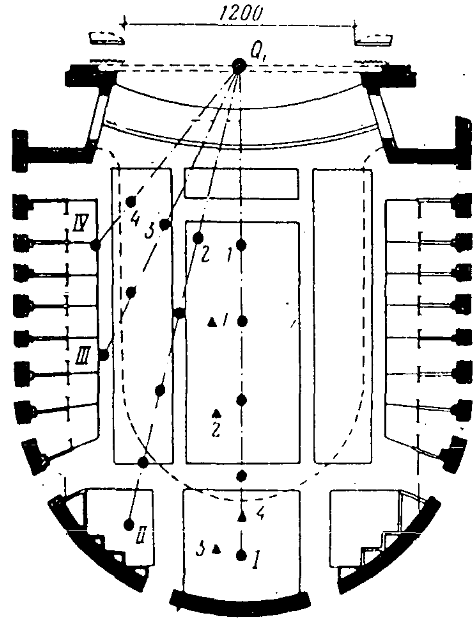


Fig. 8. Plan of TH9.

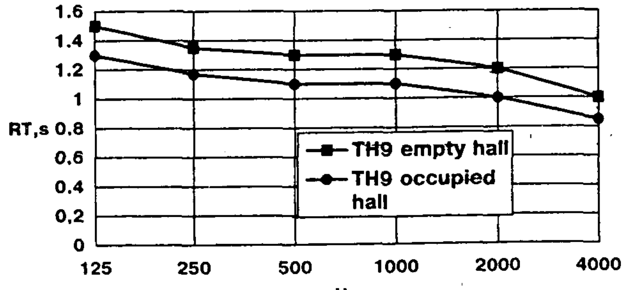


Fig. 9. RT_{60} values in TH9.

not more than 4 dB while the microphone is moving to the back of the hall. Only on the rear seats under the balconies is this decrease equal to 7 dB.

A similar method was used for estimating directional diffusion. Instead of the omni a special unidirectional microphone was used. At every point on the rays the SPL was measured while the main axis of the microphone was directed toward the sound source (L_0), to the right (L_1), to the left (L_2), upward (L_3), and toward the back (L_4). The level difference $L_0 - L_1$ is shown in Fig. 11. The results of these measurements lead to the conclusion that there exists a rather equal distribution of the sound energy from the different directions.

The impulse measurements show a good structure of the early sound reflections in the main areas of the hall. Only in the central part of the stalls a lack of early reflections was noticed at levels greater than -10 dB (relative to the direct sound). Good speech intelligibility was estimated through articulation tests. In the worst seats (the central part of the stalls and the last rows of the balconies) the intelligibility was equal to 75% and in the other seating areas it was not less than 80%.

2.3 Wooden Theaters

The form of the $RT_{60}(f)$ curve in wooden theaters differs from the results obtained in the majority of the theater halls. The values of RT_{60} measured in all three empty wooden theaters (TH35–37) are shown in Fig. 12. At low frequencies there is no raise in reverberation time, as is typical for public halls. All surfaces in TH35–37 were made of wood. Many act as wooden panels spaced apart from the rigid wall. Such constructions absorb the sound energy mainly in the low-frequency band. This is why there is no raise in reverberation time below 500 Hz.

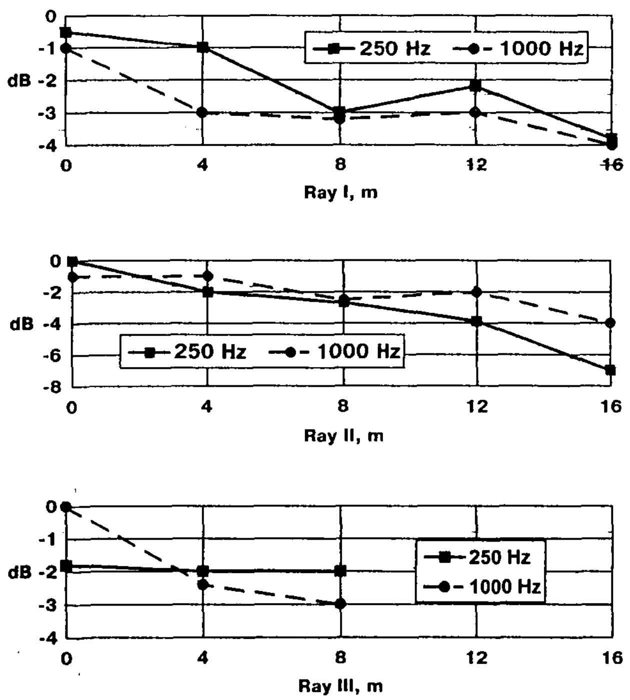


Fig. 10. SPL along rays I, II, and III (see Fig. 8) in TH9.

2.3.1 Theater on the Kamenniy Island in St. Petersburg (TH35)

This classical hall with a horseshoelike floor plan and three rows of balconies is no longer used for theater productions. There are no doors in the boxes and no chairs in the boxes and in the stalls. There is no pit and the stage is rebuilt as a low platform. Thus there is a common volume for the hall and the stage. This volume is also connected through the doorways to the corridors around the balconies. For that reason the results of RT_{60} measurements (as well as the measurements of energy criteria such as C_{80}) could not correspond to the original interior of the hall. The results of the impulse measurements lead to the conclusion that there is a good structure of the sound reflections in the boxes. The impulse responses have a proper form of a "Christmas tree" in all three balconies. But in the stalls flutter is heard and is

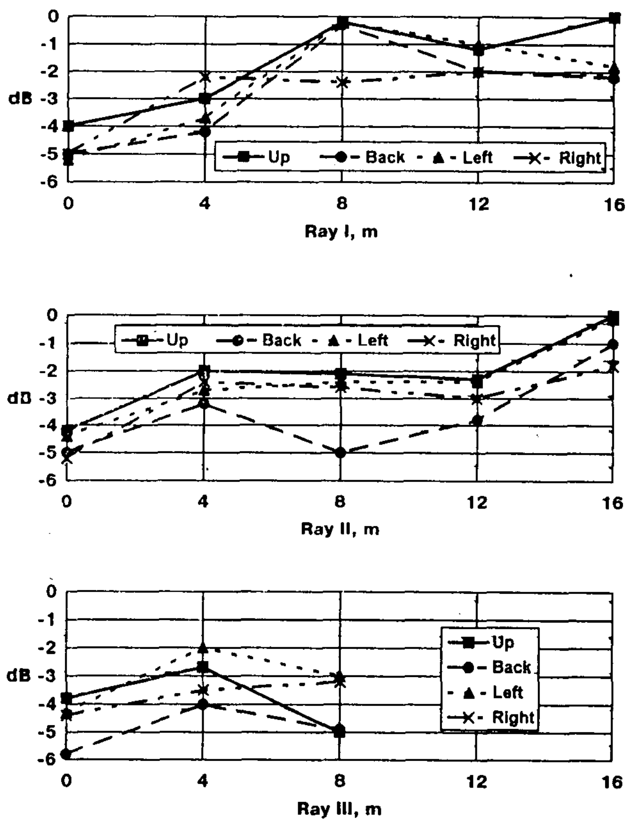


Fig. 11. Distribution of sound energy from different directions (octave band 250 Hz) in TH9.

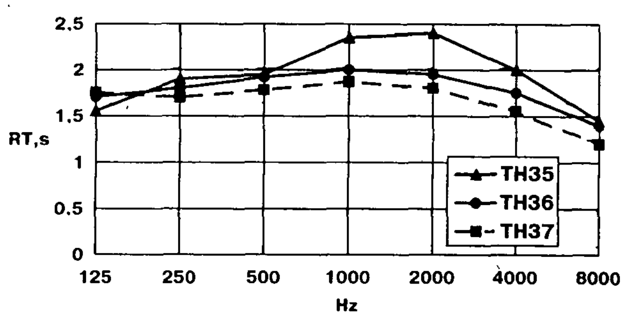


Fig. 12. RT_{60} values in three wooden theaters.

clearly seen on the measured impulse responses. It is caused by the multiple reflections between the ceiling and the floor where there are no chairs [14].

2.3.2 Theater in the Ostankino Palace in Moscow (TH36)

The small hall has a form close to an ellipse (Fig. 13). The public is seated in the stalls and in the first floor balcony, which is separated from the stalls by a high barrier. To be exact, this hall is not a classical opera theater. But the authors included TH36 in the list because of its unique interior, which had a great influence on the Russian theater architecture. Musical concerts are rarely organized in the hall, and there are problems with the sound quality, mainly for the singers. This is caused by the large reverberation time. At the middle frequencies in the empty hall RT_{60} = 1.9–2.0 s, and with the presence of 200 persons RT_{60} = 1.55–1.60 s. Such values exceed the recommended optimal values [7]. This situation is caused by the large value of V_1 = 10 m^3. On the average in the hall C_{80} = 1.7 dB and D_{50} = −3.36 dB. It was estimated that the values of C_{80} and D_{50} decrease when the sound source is moving toward the rear of the stage. Commonly the values of these criteria are increasing as the microphone is moving from the first rows in the stalls to the back wall (for a fixed source position on the stage). Some recommendations for the improvement of the sound quality during musical concerts are presented in [15].

2.3.3 Gonzago Theater in Archangelskoje (TH37)

Gonzago's theater is a part of a large palace and park architectural complex of Archangelskoje, situated near Moscow. The small hall has a horseshoelike plan and two rows of balconies with 11 boxes in each of them (see Fig. 14). The length of the hall from the footlights to the back wall is only 14 m. The benches for the audience are located in the stalls. About 280 persons may comfortably be seated both in the stalls and in the boxes. The measurements were made in the empty hall; the stage was equipped with decorations. At the middle frequencies $RT_{60} \cong 1.8$ s (see Fig. 12). Considering the sound absorption of the audience it can be shown using statistics theory that RT_{60} will be equal to 1.35 s at middle frequencies. This value coincides with the optimal reverberation time for theaters of such volume [7]. Average values of the energy criteria for the whole hall are C_{80} = 1.68 dB and D_{50} = −3.43 dB [16]. The largest values of C_{80} = 5.5 dB were measured at the rear of the stalls. A smooth decaying structure of the impulse response with a large number of early high-level reflections was assumed in most areas of the hall. Nowadays the hall is not used for opera production. Musical concerts are organized there rarely. Visitors at these concerts speak about good acoustics of the hall.

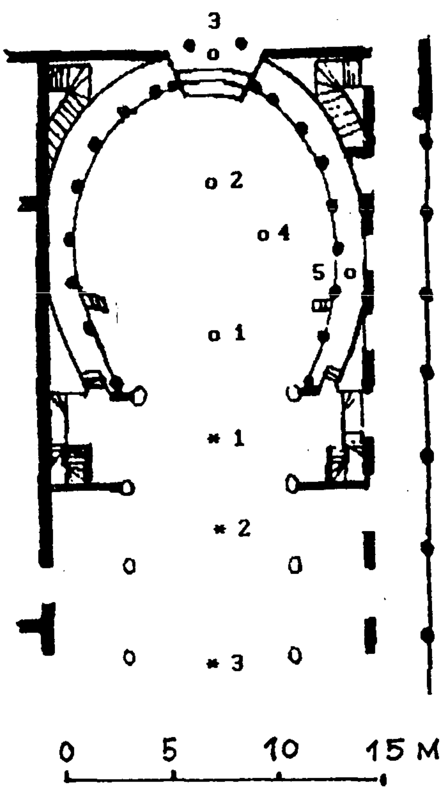


Fig. 13. Plan of TH36.

3 SOME REMARKS ON THE ACOUSTICS OF CLASSICAL THEATER HALLS

While analyzing the acoustics of the classical theaters, some common advantages should be mentioned. These theaters may have a relatively large number of seats ($N \approx$ 2000) with rather small distances between the stage and the seats. The seat-dip effect is practically excluded for the areas in the balconies. Both these factors (distance and seat-dip effect) are very important for the quality of the direct sound. Besides, the system of the balconies together with the rich decoration of their barriers and other surfaces is extremely useful for decreasing the concentration of sound caused by the curved walls as well as for high diffusion.

In classical theaters, in spite of the low reverberation time, the spatial impression (which is very important for both orchestra music and singing) is usually good. Evidently it is caused by the effect of the lateral reflections. Due to the relatively small width of the halls (see Table 2) the early lateral reflections arrive first at the seating areas, and the reflections from the high ceiling arrive later.

The acoustics of the classical theaters in general is

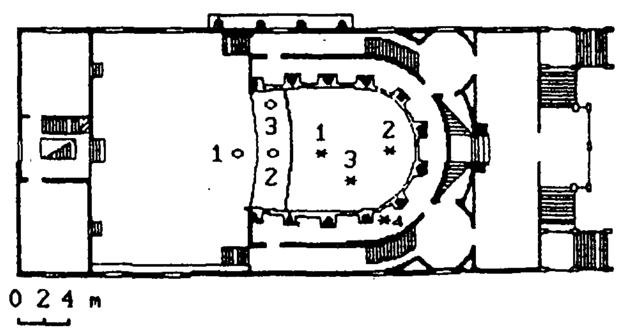


Fig. 14. Plan of TH37.

defined as good, but it could not be defined as excellent. There is usually a lack of loudness, spatial impression, and change of timbre at the seats at the end of the boxes. Rather often the lack of early high-level reflections leads to a decrease of definition in the center of the stalls. This last fault in the structure of sound reflection has the following causes: 1) The early reflections from highly decorative lateral walls have a rather low level. 2) The reflections from the ceiling arrive at the center of the stalls with too large a delay or do not appear at all. The mentioned lack of early sound reflections is the main reason why in the first rows of the stalls the orchestra prevails over the voice of the singer (located at the rear of the stage).

The other characteristic feature of the classical theaters, especially the opera houses, is the relatively low value of RT_{60}. It is caused mostly by the low V_1 value of about 5 m^3. An important role in the sound absorption in classic opera houses is played by heavy portieres, the curtains, carpets, and wooden paneling. It is but natural that during the reconstruction of the European opera houses destroyed during World War II any attempts to increase RT_{60} were mostly concerned with minimizing the amount of curtains and using less sound-absorbing chairs.

The wooden paneling is often used in classical theaters. Such constructions absorb the sound energy mostly at low frequencies. But the influence of wood on the sound quality is much more complex than just low-frequency absorption. Wooden panels placed apart from rigid surfaces are often called "sounding boards" in analogy with musical instruments, because they make the timbre of music richer.

4 ACOUSTIC DESIGN OF THE BOLSHOI THEATER'S SISTER STAGE

It should be mentioned that nowadays the tradition of building the classical theater halls is not forgotten in Russia. The authors are taking part in the acoustic design of the Sister Stage of the Bolshoi Theater in Moscow. This hall will be of the classical type with a horseshoelike floor plan, balconies, and a flat ceiling.

The authors tried to avoid the above-mentioned acoustic disadvantages of the classical theater halls while designing the new one. The design was based on the use of computer models [17]. According to the original plans the hall had $V_T = 9100$ m^3 and $N = 1050$. The corresponding computer model is shown in Fig. 15. The impulse responses were calculated for 24 positions of the receiver in all areas of the seats and for several positions of the sound source on the stage and in the pit. The values of RT_{60}, C_{80}, D_{50}, and the total energy of the impulse response E_{TOTAL} were calculated. The results were obtained in the frequency band of 125–4000 Hz. The values of RT_{60} calculated using the computer model are presented in Fig. 16 together with the results obtained from statistics theory. It can be seen that both methods lead to similar results, which coincide with the recommended optimum. Due to the modern require-

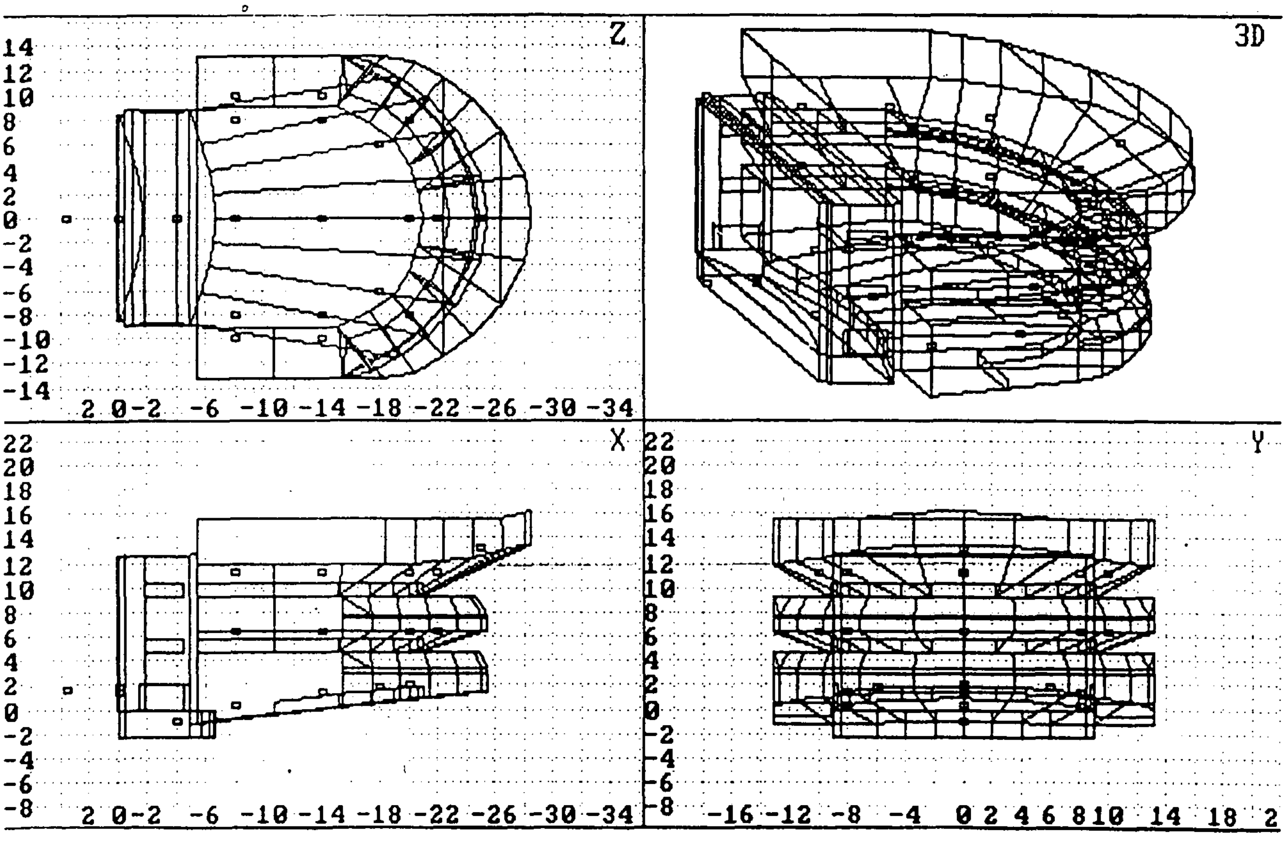


Fig. 15. View of Sister Stage of Bolshoi Theater.

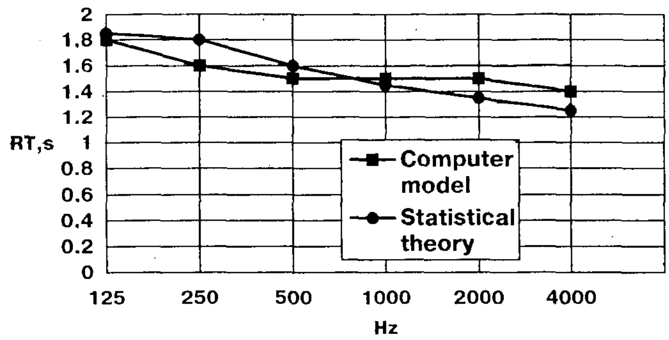


Fig. 16. Calculated RT_{60} values for Sister Stage of Bolshoi Theater.

ments of opera houses, with $V_T \approx 10\ 000\ m^3$ the reverberation time should be about 1.5 s at the middle frequencies [7].

In all 24 points the average D_{50} values in the frequency band were greater than -3 dB. This corresponds to good speech intelligibility. The Sister Stage is an opera house, so the values of C_{80} were mostly calculated for the positions of the sound source in the pit. It was estimated that in the first rows C_{80} is within the limits of -2 dB to 3 dB, and in the rear row within 5 dB and 9 dB. This result corresponds to the optimal values proposed by some specialists in room acoustics. The values of E_{TOTAL} were calculated for the average sound power of an orchestra and for the strong voice of a singer. The frequency responses $E_{TOTAL}(f)$ are rather flat. The spatial irregularities of the sound field are not large. As an example ΔL, the greatest difference between E_{TOTAL} values for several seating areas, is shown in Table 5 for the octave band of 1 kHz.

Table 5. ΔL values in decibel.

Source Position	Stalls	1st Balcony	2nd Balcony
On stage	2.0	2.5	0.8
In pit	2.8	1.4	1.3

Later the dimensions of the hall became somewhat smaller ($V_T = 7900\ m^3$, $N = 972$), generally due to architectural demands. In that period the authors consulted with W. Ahnert (ADA, Germany), M. Antek (Roll Audio, Czech Republic), and J. P. Vian (CSTB, France). The model was made according to the EPIDAURE program while cooperating with CSTB, France. It was estimated that $RT_{60} = 1.4$ (at 1 kHz) and is close to the optimum value. Besides, $D_{50} > -3$ dB at all points and C_{80} is within the limits of 2–6 dB. In all these calculations soft chairs were used and there were no special sound-absorbing materials in the interior of the hall.

There will be a lot of curved constructions and decorations behind and above the balcony. Also the form of the ceiling will be rather complex. For these reasons and also taking into account the importance of the new hall, it was decided to use a scale model as well as computer research. The model made at the scale of 1:25 is now ready and will be examined in the near future.

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Michael Lannie graduated with a Dipl. Eng. from the Moscow Institute of Telecommunications in 1972. Since that time he has been employed in the Research Institute for TV and Radio, Moscow, as head of the Acoustic Laboratory. His main job deals with acoustic design of television and radio studios. He received a Ph.D. for research on a new method for measuring room acoustics. Recently he has also worked as a consultant on the acoustic laboratory of the Moscow Research and Design Institute for Culture, Leasure, Sports, and Public Health Constructions. He is the designer of acoustic solutions in many studios and public halls built in Russia. Dr. Lannie is an officer of the AES Moscow Section and is responsible for the section's activities in room acoustics and sound reinforcement. He is the member of the expert council of the Russian Ministry of Culture (Architectural Acoustics and Sound Reinforcement Section). He is also a member of the Russian Acoustical Society and the Acoustical Society of America.

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Professor Makrinenko was the author of many papers on room acoustics. His monogram "Acoustics of Auditoriums in Public Buildings" was translated into English and published by the Acoustical Society of America. Professor Makrinenko was the most well-known scientist in room acoustics in Russia and took an active part in the acoustic design of most large halls that were built in Russia during the last 25 years. Besides his very intensive activity in acoustic design, he worked successfully in the sphere of education. For many years he was a professor at the Moscow Architectural Institute, where he developed and published a lecture course on architectural acoustics. Professor Makrinenko died on September 18, 1997 and this manuscript, presented at the AES 102nd Convention, was his last paper.