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THE NEAR AND FAR ACOUSTIC FIELD AND ITS RELATIONSHIP TO THE HALL ACOUSTICS

V. Stauskis

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1. Introduction

In any musical hall, the sounding of music is perceived by a listener differently depending on the location of the sound source. At any point of the hall, the listener is reached by the sound energy consisting of two components: the direct sound and the reflections from the hall surfaces. The relationship between the direct sound energy and the reflection energy will be varied at various points of the hall.

When considering this relationship, it is important to know the influence exerted upon it by the early and the late sound reflections as well as their intensity at various times. The structure of these reflections will always be different at various points of the hall. Consequently, the listener will perceive music differently depending on his/her location in the hall.

The aim of this paper is to determine the changes in the relationship between the direct sound and the reflection energy depending on the distance to the sound source and the geometrical and acoustic parameters of the hall.

2. Theory

The sound field of a closed premise is well-characterized by the density of energy. In a free space far away from the sound source, the sound energy diminishes along with the increase in distance and it is proportional to the energy emitted by the source. In a closed space, this rule is no longer valid. In certain cases the energy density may not be dependent upon the distance to the sound source and sometimes the density may grow as the distance increases.

At any point of a closed premise, the energy density is described by the density emitted by the sound source and the energy density consisting of the sound waves reflected from various planes. Let us assume that the sound source emits energy with a power P_A. Then the density of direct sound energy at a given point will be equal to

$$W_t = \frac{P_A \Omega \phi_t^2}{4\pi r^2 c_0} \tag{1}$$

where P_A is the acoustic power of the sound source; Ω is the source axial concentration ratio; ϕ_d is the source directivity ratio; r is the distance between the source and the given point and c_0 is the sound velocity in the air.

The direct sound energy density may be expressed in terms of the sound pressure, their relationship being expressed as

$$W_t = \frac{\bar{p}^2}{\rho_0 c_0^2} \tag{2}$$

where $\bar{p}$ is the average of the sound pressure and ρ_0 is the air density.

Upon inserting (2) into (1) we obtain direct sound pressure

$$\bar{p}_t^2 = \frac{P_A \Omega_t^2 \phi_t \rho_0 c_0}{4\pi r^2} . \tag{3}$$

When the distance to the sound source is 1 m, we will have

$$\bar{p}_t^2 = \frac{P_A \Omega \rho_0 c_0}{4\pi} . \tag{4}$$

The listener will be reached by the direct sound and then, after some time, by the first reflection. Its energy density will be equal to:

$$W_{at} = \frac{P_A \Omega \phi_{at}^2 \beta}{4\pi (r_1 + r_2)^2 c_0} \qquad (5)$$

where ϕ_{at} is the source directivity ratio between its acoustical axis and vector r_1; β is the plane reflection ratio; r_1 is the distance between the source and the reflection plane; r_2 is the distance between the reflection plane and the listener.

The energy density of the first reflection may be recalculated into the square of the sound pressure by the following formula:

$$\overline{p}_1^2 = \frac{P_A \Omega \rho_0 c_0}{4\pi} \sum_{i=1}^{n} \frac{\phi_i^2 \overline{\beta}_i}{(r_{1i} + r_{2i})^2}. \qquad (6)$$

There will always be a varied time interval between the direct sound and the first reflection. The first reflection will be followed by the second, the third etc. Their density will constantly increase. This depends on the frequency and the geometrical characteristics of the premise, i.e. [1]

$$\frac{dN_r}{dt} \approx 4\pi c_0 \frac{(c_0 f)^2}{V}. \qquad (7)$$

After each reflection, the sound energy decreases by $(1-\alpha)$, therefore after the time t the reflection intensity will be proportional to $(1-\alpha)^{\overline{n}t}/(c_0 t)^2$, where n is the number of reflections. The average decrease in the sound energy per time unit due to reflection will be equal to

$$E(t) \approx e^{nt \ln(1-\alpha)}. \qquad (8)$$

The sound will be reflected from the hall surfaces n times per second, i.e.

$$\overline{n} = \frac{c_0 S}{4V} \qquad (9)$$

where S is the area of all hall surfaces; and V is the volume of the hall.

Then the formula (8) may be rewritten taking into account geometrical parameters of the hall, i.e.

$$E_{at}(t) = E_0 e^{\frac{c_0 S t}{4V} \ln(1-\alpha)}. \qquad (10)$$

This formula describes the muffling of the sound energy after the emission of the sound impulse, which have energy E_0.

Apart from the direct sound and early reflections, the diffusional sound field and its share in the reflection structure are also important. In various halls this field appears at various time moments t. The energy density of the diffusional field must be equal at all points of the hall and it is expressed as

$$W_{df} = \frac{4 P_A \overline{\beta}^2}{c_0 S(1-\overline{\beta})}. \qquad (11)$$

The average square of the sound pressure of the diffusional sound field is expressed as

$$\overline{p}_{df}^2 = \frac{4 P_A \overline{\beta}^2 \rho_0 c_0}{S(1-\overline{\beta})}. \qquad (12)$$

When the distance to the sound source is equal to $r = r_n$, then the direct sound energy will be equal to the all sound reflection energy $W_t(r_n) = W_{df}(\infty)$ i.e.

$$\frac{P_A \Omega_t \phi_t^2}{4\pi r^2 c_0} = \frac{4 P_A \overline{\beta}^2}{c_0 S(1-\overline{\beta})}. \qquad (13)$$

The sound pressure values must also be equal:

$$\frac{P_A \Omega \phi_t^2 \rho_0 c_0}{4\pi r^2} = \frac{4 P_A \overline{\beta}^2 \rho_0 c_0}{S(1-\overline{\beta})} \left(\frac{r_n}{r}\right)^2. \qquad (14)$$

If the sound field is excited by an impulse, then

$$\frac{\overline{p}_t^2}{\overline{p}_{df}^2} = \frac{\int_0^\infty p_t^2(t)dt}{\int_0^\infty p_{df}^2(t)dt} = \left(\frac{r_n}{r}\right)^2. \qquad (15)$$

V. Reichardt [2] proposes to compute the echoing radius from the formula

$$r_n = \sqrt{\frac{A}{50}}. \qquad (16)$$

N. Zarkov [3] proposes to compute the echoing radius from the formula

$$r_n = \sqrt{\frac{R}{16\pi}\sqrt{Q}} \qquad (17)$$

where $R = \frac{\overline{\alpha} S}{1-\overline{\alpha}}$; Q is the source directivity ratio.

In the above formulas, the overall sound energy is only divided into the direct sound energy and the diffusional sound energy. However, no diffusional sound ever starts immediately after the direct sound. There is always a time interval between the direct sound and the diffusional sound, filled by the early sound reflections. In this time interval, the reflection structure is always discrete and no diffusional sound field will ever appear. The time interval of the early sound reflections may be very different and it depends on the premise size and the frequencies. The smaller the premise, the sooner will early sound reflections start, followed by the diffusional sound field. Therefore, when one analyses the variations of the echoing radius in relation to the distance and frequencies, it is expedient to single out the area of the early sound reflections, which may be expressed by the formula:

$$\bar{p}_t^2 = \bar{p}_{at}^2 + \bar{p}_{df}^2\left(\frac{r_n}{r}\right)^2 \tag{18}$$

where $\bar{p}_t$ is the direct sound pressure; $\bar{p}_{at}$ is the early sound pressure reflection and $\bar{p}_{df}$ is the diffusional sound pressure field.

Upon inserting (3), (6) and (12) into (18), we will obtain the expressions of the sound pressure

$$\frac{P_A \Omega \phi_t^2 \rho_0 c_0}{4\pi r^2} = = \frac{P_A \Omega \rho_0 c_0}{4\pi}\sum_{i=1}^{n}\frac{\phi_i^2 \bar{\beta}_i}{\left(r_{1i}+r_{2i}\right)^2} + \frac{4P_A\bar{\beta}^2\rho_0 c_0}{S\left(1-\bar{\beta}\right)} . \tag{19}$$

Upon the impulse excitation of the sound field and the acceptance of the energy ratio, we will have

$$\frac{\bar{p}_t^2}{\bar{p}_{df}^2} = 10\lg\frac{\int_0^{t_1} p_t^2(t)dt}{\int_{t_1}^{t_2} p_{at}^2(t)dt + \int_{t_2}^{\infty} p_{df}^2(t)dt} = \left(\frac{r_n}{r_n^2}\right)^2 . \tag{20}$$

Then the echoing radius may be expressed by the following formula:

$$r_n = 10\lg\sqrt{\frac{\int_0^{t_1} p_t^2(t)dt}{\int_{t_1}^{t_2} p_{at}^2(t)dt + \int_{t_2}^{\infty} p_{dt}^2(t)dt}} \tag{21}$$

It is accepted in the architectural acoustics that the direct sound takes a time interval equal to 5 ms, i.e. t_1 = 5 ms. The time interval from t_1 to t_2 , as it has been mentioned above, is variable and may only be found experimentally.

3. Conditions of the experiment

Three halls were chosen for the experiment: St. John's Church, the Archcathedral, and the Small Hall of the Philharmonic Society in Vilnius. The first two are very long and high, their sound absorption coefficients are small and the reverberation time is long.

The Small Hall of the Philharmonic Society is small, but its sound absorption coefficients are also small and the reverberation time is long. Such hall selection, when the difference in volume is great, allows to evaluate the influence of volume on the echoing radius. The investigations in the Small Hall were conducted in two modes: the hall completely empty, without chairs, and with 120 upholstered chairs. Thus, the hall volume was constant in both cases, while the overall sound absorption and the reverberation times were different. Such selection enabled to measure the influence of the sound absorption on the echoing radius.

The main characteristics of these halls are presented in Table 1.

4. The results of the experiment

In Fig. 1 the relationships between the direct sound energy and the reflected sound energy along

Table 1

Hall	Length, m	Width, m	Height, m	Volume, cbm	T_{125}, s	T_{500}, s	α_{125}	α_{500}
1. St. John's Church	61	25	20,6	27000	15,2	6,9	0,03	0,06
2. Archcathedral	57	20	19,8	22500	7,3	6,0	0,06	0,08
3. Small Hall of the Phil. Society	13,6	10,7	7	1018	6,3	5,5	0,055	0,08

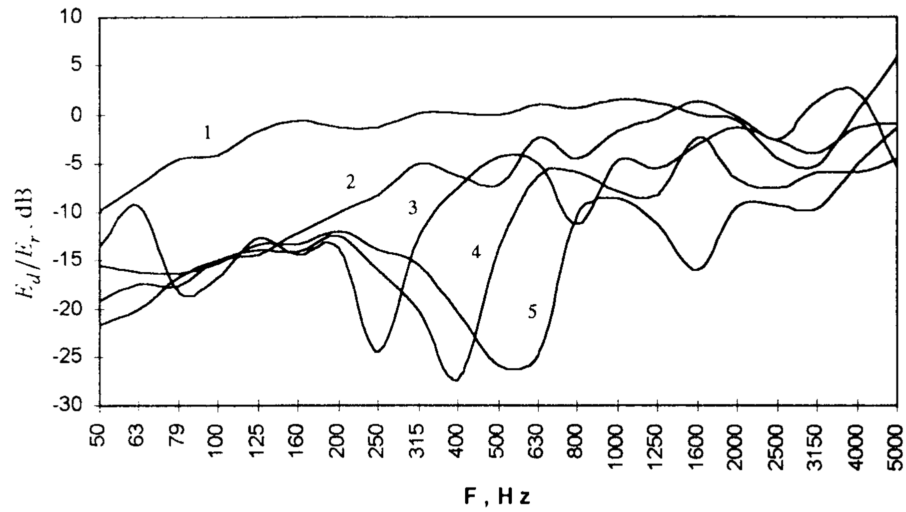

Fig. 1. The relationship between the direct sound energy and the reflected sound energy in St. John's Church. Measurements along the hall. Distance between the sound source and the microphone:
1 - 1 m; 2 - 2 m;
3 - 5 m; 4 - 7.5 m;
5 - 10 m

St John's Church hall are presented. The measurement points are 1; 2.5; 5; 7.5 and 10 metres away from the sound source. The areas both close to the source and sufficiently far away from it are embraced by such measurement.

The results of the investigation show that the ratio of the above energies is only equal to zero when the microphone is at the distance of 1 m from the sound source and, furthermore, solely in the frequency range of 160-2000 Hz. When the distance to the microphone is 2.5 m, under low frequencies the ratio is equal to -10 - 15 dB and is close to zero only under 1600 Hz. As the distance to the microphone increases, under low frequencies up to 200 Hz this ratio remains more or less constant, while in the range of 250-800 Hz it reaches as much as -25 - 28 dB. A sudden decrease in the ratio is observed and it moves towards high frequencies to such extent to which the distance to the sound source is increased.

Based on the computations of the formulas (16) and (17), the energies should be equal when the distance from the source is 3.1 m and more. However, experiments show a different situation. As the distance to the sound source increases, decisive role is played by the sound reflections whose number is increasing.

In Fig. 2, the results of the investigation with the measurement points placed across the hall are presented.

The energy ratio is undoubtedly influenced by the distance to the sound source. However, investigations show that decisive role is assumed by the hall planes from which early sound reflections reach the point under investigation, which is confirmed also by the formulas (19, 20). Therefore interesting re-

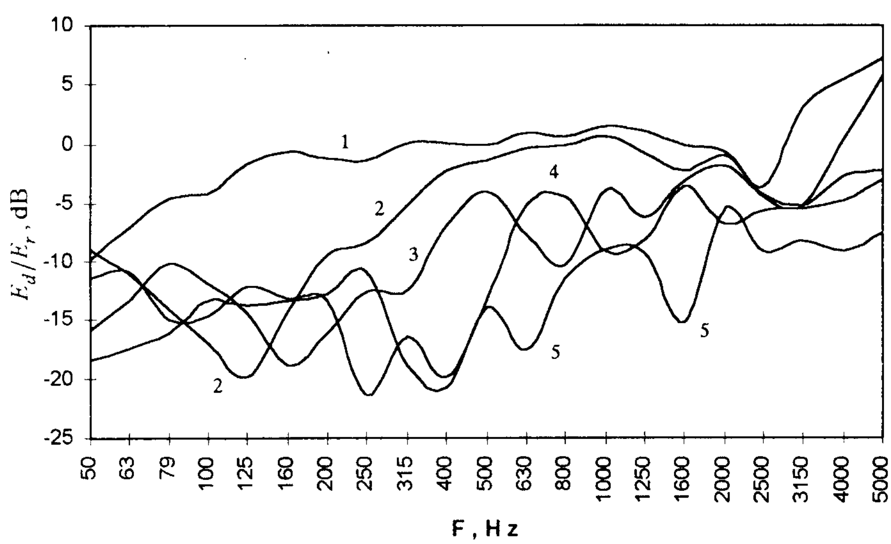

Fig. 2. The relationship between the direct sound energy and the reflected sound energy in St. John's Church. Measurements across the hall. Distance between the sound source and the microphone:
1 - 1 m; 2 - 1 m;
3 - 6 m; 4 - 8.5 m;
5 - 11 m

sults are obtained when both microphones are located at the interval of 1 m from the sound source. The sound source is placed exactly in the middle of the hall, while the microphones are positioned symmetrically with respect to the source. Consequently, the ratios between the direct sound energy and the reflected sound energy must be identical in both cases. However, it is not so. Curves 1 and 2 in Figure 2 show an obvious 20 dB difference between the ratios under low frequencies, when the ratios should be equal. The energy ratios become almost equal solely at 500 Hz. As the distance to the source increases, the energy ratio decreases, however, in a different manner than in the case of longitudinal placement.

Such energy ratios are determined by the early reflections and their energy. This is clearly shown in the case when the measurement points are located on both sides of the source at a 1 m distance. Then one or some early reflections are sufficient and it is these reflections and not the direct sound that determine the energy distribution at this point.

St. John's Church is very high and wide. Therefore the first reflections, which are very important for the subjective evaluation of the sounding of music, will reach the listener quite late. This will determine the relationship between the direct and the reflected sound energy. We must know how this relationship will be affected by a small premise, for example, the Small Hall of Vilnius Philharmonic Society.

In Fig. 3, the changes in energy ratios taking place along with the change in the distance to the source and in frequency are represented.

There we have a different situation than in St. John's Church. The energy ratio at the point which is only 1 m away from the source reaches about - 10 dB, while in St. John's Church this ratio is equal to 0 almost throughout the spectrum. Under 250 Hz, a marked reduction of the energy ratio is observed (to -17 dB). When the microphone is at the point 2, which is located 1.4 m away from the source, we have a completely different energy ratio range under low frequencies. Sudden fall of the ratio value takes place under 63 Hz, not under 250 Hz, and reaches -25 dB. When the microphone is being brought away up to 3.5 m from the source (point 3), the energy ratio at low frequencies is smaller than when the microphone is located 1 m away from the source. When the microphone is over 6 m away from the source, the energy ratio throughout the frequency range is equal to -15 - 20 dB. These results show that, in a small hall, the sound reflection structure and the reflection energy, not the distance to the sound source, have crucial importance in the distribution of sound energy. Furthermore, the energy ratio is influenced by various resonances of the hall as well as recurring echo.

In this hall, all surfaces are made of materials that reflect sound well, therefore its absorption coefficients are very low and similar to those of St. John's Church. In order to determine the impact of the general hall absorption upon the energy ratio, inves-

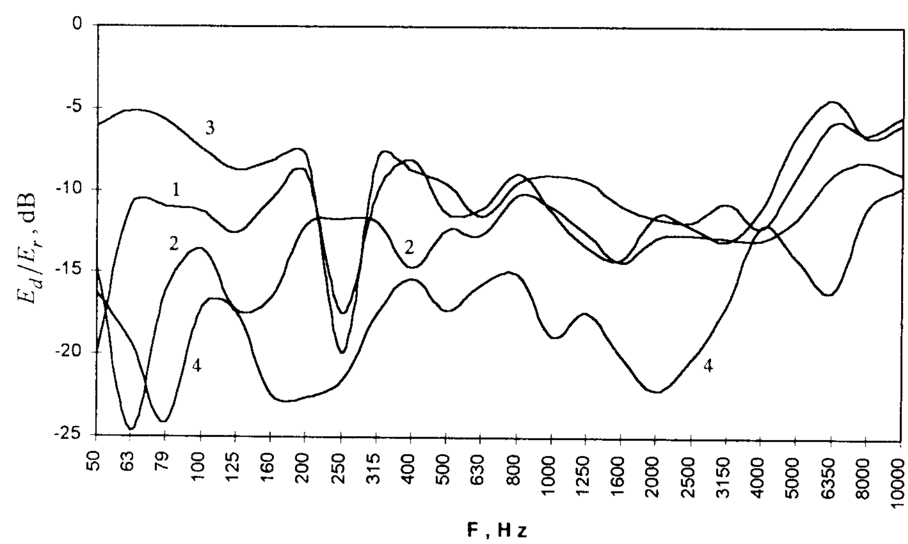

Fig. 3. The relationship between the direct sound energy and the reflected sound energy in the Small Hall of the Philharmonic society. The hall is completely empty:
1 - 1 m; 2 - 1,4 m;
3 - 3,6 m; 4 - 6 m

tigations were conducted in this hall with 120 upholstered chairs. The results of the experiment are presented in Fig. 4.

We see that the increase in the sound absorption, when microphone positioning is identical (near the sound source), markedly reduces the impact of strong reflections upon the energy ratio. This is shown by the curves 1 and 2 in Fig. 4 when compared with the curves 1 and 2 in Fig. 3. If the sound energy ratio measured near the microphone in an empty hall is around -10 dB throughout the spectrum with a resonance frequency under 250 Hz, then, after the absorption increase, this ratio is as small as -5 dB, while resonance frequencies disappear. As the distance from the source to the microphone increases, the energy ratio is reduced.

By summarizing the findings of the investigation one may determine the hall volume and the hall sound absorption dependence of the ratio between the direct sound energy and the reflected sound energy. The hall volume dependence is shown in Fig. 5.

The halls selected for the investigation were quite different in volume (Table 1). The sound absorption coefficients of all halls were very small - about 0.05. This allowed to determine the influence exerted on the energy ratio by the hall volume alone.

Fig. 5 shows that the results obtained in the halls of St. John's Church and Archcathedral, whose volumes differed by 4,500 cbm, are almost identical. The results obtained in the Small Hall of the Philharmonic Society with the volume as small as 1,018 cbm are quite distinctive. The ratio between the direct sound energy and the reflected sound energy throughout the frequency range is around -10 dB, whereas in both churches this ratio is around 0 under medium and high frequencies. It seems that it may be therefore concluded that volume is essential for the direct and reflected sound ratio. However, the author is of the opinion that it is not the premise

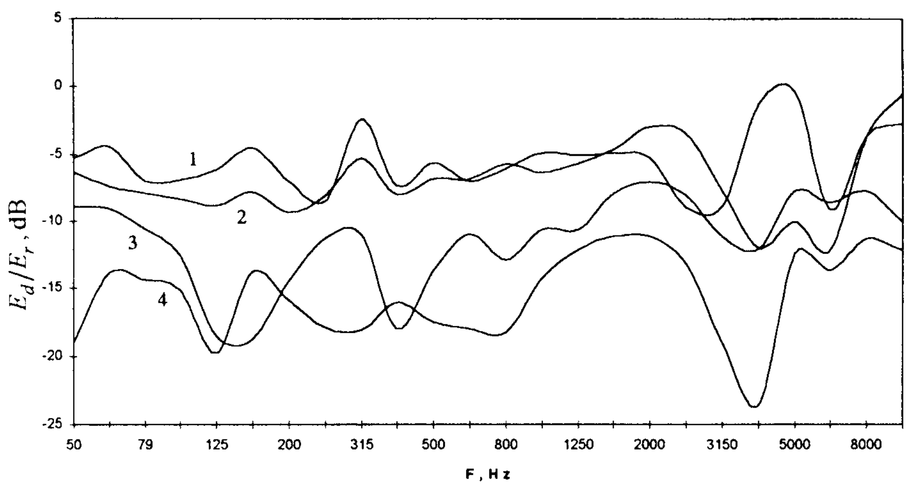

Fig. 4. The relationship between the direct sound energy and the reflected sound energy in the Small Hall of the Philharmonic Society with 120 upholstered restored chairs. Distance between the sound source and the microphone:
1 - 1 m; 2 - 1.4 m;
3 - 3.6 m; 4 - 6 m

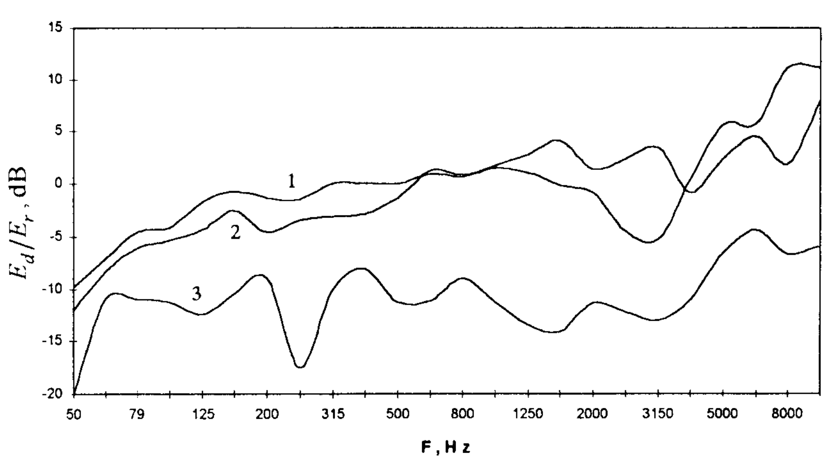

Fig. 5. The hall volume dependence on the direct and reflected sound energy ratio. Microphones positioned at the distance of 1 m from the sound source.
1 - St. John's Church;
2 - Archcathedral;
3 - Small Hall of the Philharmonic Society

volume that determines the results.

In both churches, the distance from the sound source to the lateral walls is about 10 m and to the nearest column - 5-6 m. Therefore the early reflections from these planes will arrive considerably later than in the Small Hall. Fig. 6 depicts the sound energy distribution during the first 200 ms in St. John's Church and in the Small Hall.

This figure indicates that direct sound only arrives in the first 100 ms in St. John's Church, whereas in the Small Hall strong reflections arrive from the ceiling and the front/lateral walls after 40 ms and these reflections are much more energetic than the direct sound. As investigations show, the reflection structure in both halls is greatly varied with time. It is precisely these reflections that determine the ratio between the direct sound energy and the reflected sound energy.

Fig. 7 shows the relationship between the energy ratio and the change in the hall sound absorption. Two cases have been selected: a completely empty hall and the hall with 120 upholstered restored chairs.

The graph demonstrates that the energy ratio is dependent on the sound absorption. The higher the overall sound absorption, the smaller the ratio. The sound absorption change in both cases is shown in Fig. 8.

It is seen from the graph that under low frequencies (below 160 Hz) the overall sound absorption is almost independent of the filling of the hall, whereas the ratio between the direct sound energy and the reflected sound energy under the same frequencies comes to about -4 - 5 dB (Fig. 7). Similar ratio remains when frequency is increased, though the overall sound absorption grows and its difference reaches -10 - 20 dB (Fig. 8).

Figure 9 depicts the changes in the acoustical centre of gravity which characterizes the energy distribution by frequency.

The graph shows that in the empty hall of the Philharmonic Society all sound energy is concentrated under low and medium frequencies. The acoustical centre of gravity is very large and reaches 350-400 ms. The hall is overloaded from an energetic point of view. When the hall sound absorption is increased, a considerable centre reduction is observed (to 100-150 ms). It is interesting to note that the acoustical centre of gravity in the Archcathedral is very small under low frequencies and considerably smaller than that in St. John's Church, throughout the frequency range. These findings show that, in a hall with a high echoing ability, the relationship between the direct sound energy and the reflected sound energy is strongly dependent on the early sound reflections which frequently are much more energetic than the direct sound.

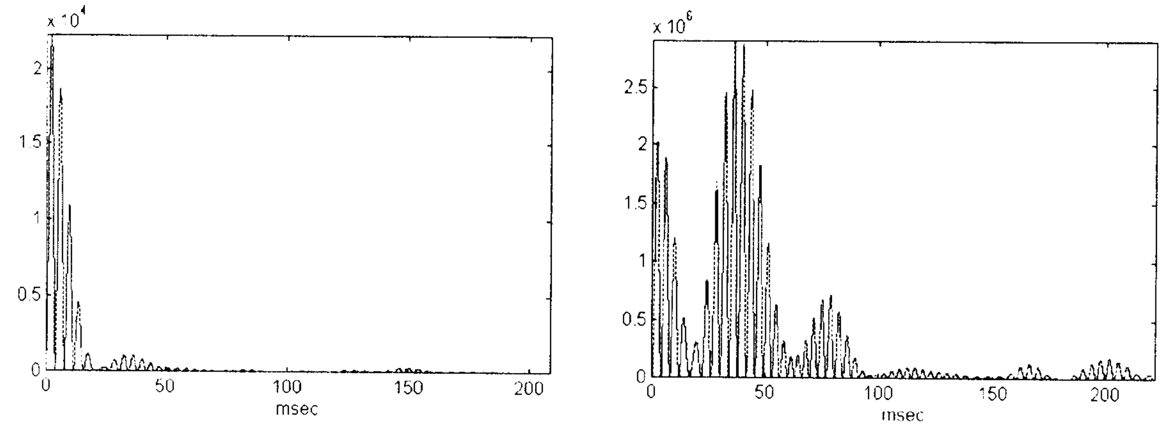

Fig. 6. The distribution of the early sound energy during the first 200 ms in St. John's Church (left graph) and in the Small Hall of the Philharmonic Society (right graph). Microphone positioned at the distance of 1 m from the sound source. Frequency 125 Hz 1/3 octave

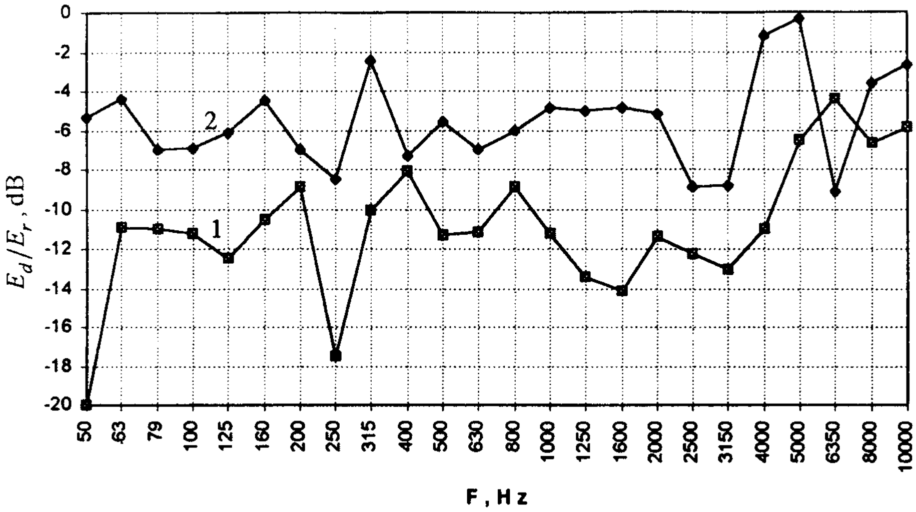

Fig. 7. The relationship between the direct and reflected sound energy and the change in the overall hall sound absorption. Microphone positioned at the distance of 1 m from the sound source. 1 - hall completely empty; 2 - hall with 120 upholstered restored chairs.

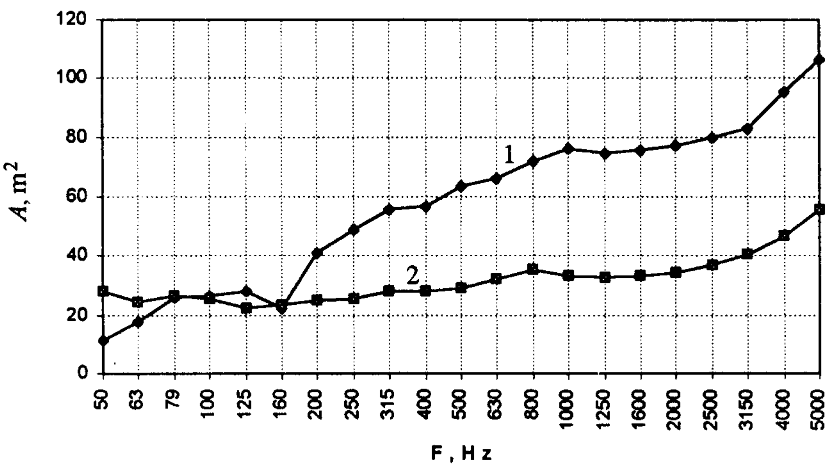

Fig. 8. The change in the overall sound absorption in the Small Hall of the Philharmonic Society. 1 - hall completely empty; 2 - hall with 120 upholstered restored chairs

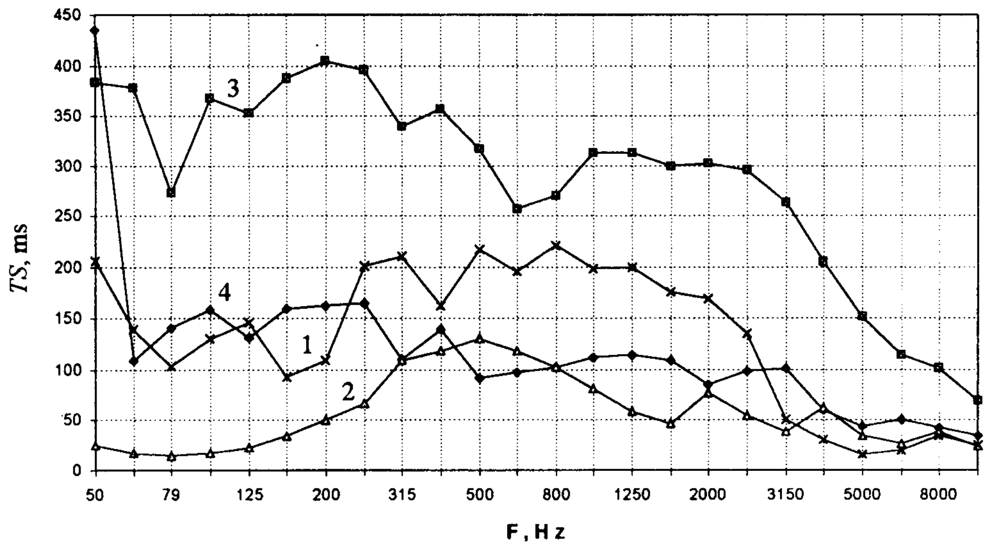

Fig. 9. The dependence of the acoustical centre of gravity on the volume and the overall sound absorption of the hall. 1 - St. John's Church; 2 - Archcathedral; 3 - the Small Hall of the Philharmonic Society, completely empty; 4 - the same with 120 upholstered restored chairs

Conclusions

1. In the case of impulse excitation of the acoustical field, the ratio between the direct sound energy and the reflected sound energy computed from the formulas (16) [1] and (17) [2] is at complete variance with the results of the experiment. In both formulas, the energy ratio is described solely by the hall sound absorption coefficient and the overall hall absorption. The insufficiency of these parameters is obvious.

2. The results of the investigation show that the energy ratio is influenced by the hall volume and the overall hall sound absorption. However, these factors are not crucial ones.

3. The ratio between the direct sound energy and the reflected sound energy is determined by the early intense sound reflections from the planes, by the materials of the planes, and by the distance between the planes and the sound source.

4. When the hall is high and wide, the musicians and soloists will always feel an excess of the direct sound energy in the area around the sound source. They will always experience a shortage of early sound reflections, without which no good perception of music nor a balance between individual instruments is possible.

5. A listener positioned close to the performer (front rows) will have a quite different perception of the sounding of music than the listener who is far from the performer (middle and back rows).

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ARTIMASIS IR TOLIMASIS GARSO LAUKAS IR JO RYŠYS SU SALĖS AKUSTIKA

V. Stauskis

Santrauka

Teoriškai ir eksperimentiškai nagrinėjamas tiesioginio ir atsispindėjusio garso energijos santykis ir jo priklausomybė nuo salės geometrinių ir akustinių parametrų. Teoriškai nagrinėjama tiesioginio ir difūzinio garso lauko energijų priklausomybė nuo patalpos akustinių ir geometrinių parametrų. V. Reichardt ir N. Zarkov pateiktose formulėse siūlo aidumo radiusą įvertinti tik panaudojant patalpos garso absorbcijos plotą, arba tik garso absorbcijos koeficientą. Apskaičiavę pagal šias formules, gauname, kad aidumo radiusas yra 3,1 m nuo garso šaltinio. Tačiau eksperimentas to nepatvirtina. Šio darbo autorius siūlo formulę, kuri nustatant energijos santykį įvertintų ankstyvuosius garso atspindžius.

Eksperimentas atliktas trijose salėse, kurių garso absorbcijos koeficientai yra labai maži, o reverberacijos laikai labai dideli. Salių tūris buvo 27000, 22500 ir 1018 m³. Mažoje salėje tyrimai atlikti esant skirtingai garso absorbcijai. Tai leido įvertinti, kaip kinta aidumo radiusas keičiantis salių tūriui ir mažos salės garso absorbcijai.

Tyrimais nustatyta, kad salėje, kurios tūris yra 27000 m³, tiesioginio ir atsispindėjusio garso energijų santykis lygus nuliui tik esant mikrofonui 1 m nuo garso šaltinio ir tik dažnių diapazone 160-2000 Hz. Kai atstumas iki garso šaltinio yra 2,5 m ir daugiau, esant žemoms dažnių energijoms santykis siekia - 10-15 dB. Kai salės tūris yra mažas ir siekia 1018 m³, netgi esant mikrofonui 1 m atstumu nuo šaltinio energijos santykis visame dažnių diapazone lygus -10 dB. Padidėjus salės garso absorbcijai, energijų santykis turi mažesnes reikšmes. Tyrimai rodo, kad energijos santykis priklauso nuo dažnio, nuo salės tūrio ir garso absorbcijos. Tačiau tai nėra lemiantys veiksniai. Tyrimais nustatyta, kad šį santykį apsprendžia ne tik atstumas iki garso šaltinio, bet ir ankstyvųjų garso atspindžių struktūra ir plokštumos, esančios arti garso šaltinio. Didelėse salėse arti garso šaltinio tiesioginio garso energija aukštų dažnių diapazone yra didesnė negu atspindžių energija. Tirtoje mažoje salėje šis dėsningumas jau negalioja. Čia energijos santykį lemia tik garso atspindžiai, o ypač ankstyvi, ir jų intensyvumas įvairiais laiko intervalais. Klausytojas, esantis skirtingame atstume nuo šaltinio, skirtingai suvoks ir muzikos skambėjimą.

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