

THE INFLUENCE OF A CROSS-SHAPED RESONANCE CEILING ON THE HALL ACOUSTICS

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The results of investigations of the influence of a suspended ceiling with cross-shaped slits on the hall reverberation time, sound absorption coefficients, sound absorption of the entire hall, acoustic centre of gravity and musical sound clarity index C_{80} are presented.

The investigations were conducted in a scaled physical model of the hall $M 1 : 25$. The selection of the scale and materials of the model is substantiated. The main characteristics of the spark sound source and the analogue-code transducer are quoted.

The investigations revealed that 100 cm wide slits between the suspended ceiling planes located 100 cm from the rigid surface of the ceiling reduce the reverberation time by 1.14 s at resonant frequencies of 200 Hz and 250 Hz. An increase of the height of the suspended ceiling up to 400 cm is of importance only at low frequencies.

The sound absorption coefficients show a maximum increase at the resonant frequencies of 200 Hz and 250 Hz, the increase being proportional to the decrease in the height of the suspended ceiling. When the height equals 400 cm, the absorption coefficients tend to decrease rather than increase throughout the whole frequency range except for the resonant frequencies.

The overall sound absorption of the hall is increased to 60 m^2 only at the resonant frequencies and at the ceiling height of 100 cm. At the height of 400 cm, the absorption is reduced by $60 - 100 \text{ m}^2$ throughout the frequency range, though the reverberation time is also reduced.

The resonant suspended ceiling affects the acoustic centre of gravity and the music sound clarity index.

The changes in all the above-mentioned acoustic indicators are determined solely by the cross-shaped slits between the ceiling planes. No additional sound-absorbing materials were used.

1. Introduction

For the optimization of the reverberation time in a hall, a certain quantity of sound-absorbing materials with appropriate acoustic characteristics must be used. The reduction of the reverberation time is most often necessary only at low frequencies because at medium and high frequencies the sound is well absorbed by the audience and the air. There exist acoustic materials that are characterized by an easy sound absorption at low frequencies, however, at the same time they absorb sound also at medium and high frequencies which is often undesirable.

A resonant suspended ceiling with cross-shaped slits formed by the space between the ceiling planes may constitute a sound-absorbing structure. The slits may be quite wide, reaching one metre or more, while the suspended ceiling itself may be located at

various distances from the rigid surface. Such a ceiling structure both absorbs the sound energy and reflects sound waves of various length from the planes. This is useful for the formation of the hall reflection structure. Furthermore, slits between planes may be found also in real halls. Therefore the knowledge of how such resonant ceilings absorb sound energy is very important.

The resonant suspended ceiling was examined theoretically earlier [1, 2, 3]. The aim of the present paper is to determine the influence of the resonant suspended ceiling on the acoustic indicators of the hall by means of studies conducted with a physical model of the hall.

2. The peculiarities of modelling of the hall

To the factors influencing the hall acoustics belong the width and form of the slits of the suspended ceiling, the distance between the ceiling and the rigid surface, the absorption of the hall walls and the absorbing material that may be placed above the plane of the suspended ceiling. There are thus many variables. It is absolutely clear that there exists no possibility for determining the acoustic effect of such variables in a real hall. The best results are therefore expected from the investigation of acoustic processes in the physical model of a hall.

If the model is similar to the original by its geometrical parameters and is executed on a linear scale, n_l , then, upon meeting the corresponding initial and boundary conditions, one may expect a similarity of the acoustic processes in the air volume of the model and the original hall. From the condition $n_l = n_L$ it follows that the similarity will occur in the model at frequencies $f_m = f_{or} n^{-1}$.

2.1. Scale and materials of the model

A recording studio hall of a symphony orchestra was chosen for the investigation. Its dimensions are $34 \times 22 \times 12.7$ m. The model scale of 1 : 25 was selected for such big a hall. Consequently, the frequencies of both the model and the original must meet the condition $f_m = f_{or} n^{-1}$, i.e. model frequencies must be 25 times higher than those of the original. When investigating the real hall acoustics, the frequency range of 100–4000 Hz was used. If the scale of 1 : 25 is used, the frequency range must be expanded to 2500–100000 Hz, occupying a large ultrasound area.

There exist difficulties in the area of boundary conditions. In the cases when the planes in the original hall are made of isotrophic materials, in which energy losses are incurred due to internal friction, these materials may be characterized by the Young and shift modules. The boundary conditions mean that the model structures must be executed to the scale and complex modules of both the original and the model and must be equal at certain frequencies. Consequently, at certain frequencies the loss coefficients must be equal for the model and the original. In practice, such requirements may be fulfilled only in a few materials, e.g., in concrete, and solely for the frequency range in that the loss coefficients are not frequency-dependent. It is impossible to make a model of such materials; therefore materials used for the model are different from those of the original.

While the surfaces of the original are characterised by the complex impedance Z_{or} , which does not depend on the sound wave incidence angle, the boundary conditions for the internal planes of the model must satisfy the condition that the impedances of the original and the model are equal at frequencies of f_{or} and f_m respectively, i.e.

$$Z_m(f_{or} \cdot n_L^{-1}) = Z_{or}(f_{or}). \quad (1)$$

In practice, the reverberational sound absorption coefficients are chosen for the model's materials in such a way that they equal approximately the original's absorption coefficients at corresponding frequencies $f_m = f_{or} \cdot n_L^{-1}$. However, these are not exact boundary conditions.

In the model, all wall and floor planes are made of a fabric-based laminate. Its absorption coefficient at 10 Hz is 0.15 [4]. The suspended ceiling is made of plywood 6 mm thick, lacquered three times along the entire contour. Its absorption coefficients were close to those of the fabric-based laminate. The orchestra dais was closed with a 5 mm thick flannel, the absorption coefficient of which being about 0.5–0.6.

2.2. Sound absorption in air

Difficulties arise when, conducting investigations in a model, one must estimate the sound absorption in air because the frequency range embraces an ultrasound area in that the sound absorption is very large. The sound wave that is transmitted in the model over a fixed distance loses part of its intensity. This may be characterized by the multiplier e^{-mx} , where m is the attenuation index. It consists of two components m_1 and m_2 . The first one describes the density and the heat conductivity of the air. It is proportional to the frequency square and depends on the temperature of the air. The second component characterizes the molecular absorption in air. It reaches its maximum when $\omega = 1/\tau$, where τ is the process relaxation time, i.e. the time per which the pressure is reduced e times. The relative humidity of the air has a considerable influence on this component; when it increases, the index m is also increased and the sound absorption is determined by the molecular absorption. WINKLER [5] has established that sound absorption increases with the increase in frequency, while the absorption maximum moves towards greater relative humidity. The condition of similarity of absorption in the air of both the model and the original will be satisfied when, under the corresponding frequencies, $m_m = m_{or} \cdot n_L^{-1}$. The sound absorption in air may be reduced by making the model hermetic and filling it with a gas of lower attenuation index, e.g. nitrogen. Then there would be no molecular absorption up to 100 kHz – it is clear that such conditions are hardly feasible.

All the results obtained from the examinations made within this work are relative ones.

3. Methods of investigation

A special flow chart was used for recording the acoustic signals in the model. It consists of a sound source, a microphone, a microphone amplifier, an analogue-code transducer and a computer signal-analyzing program.

A spark impulse was used as sound source. It was formed by a spark generator with preset technical parameters specially produced by us. Its main acoustic characteristics include the impulse duration, power, spectrum and form. The duration of the impulse may be regulated from 0.36 ms to 0.14 ms. The power and the spectrum maximum of the impulse may also be altered. Under the maximum power, the spectrum maximum is at 16 kHz, while at minimum power the maximum is reached at 31 kHz. At the maximum impulse power, the sound energy radiated is eight times greater than that radiated at minimum power. A maximum impulse power was chosen for the investigation because the maximum radiated sound energy is concentrated on lower frequencies. In this case, the radiation of high frequencies is worse; therefore insufficient dynamic range is obtained when determining certain acoustic indices. The spark impulse results in a spheric directivity diagram. The impulses emitted by the generator are stable, the automatic and remote control over them being possible.

A 1/4" microphone was used for the investigations. Its sensitivity up to 100 kHz is sufficient and its frequency characteristics are flat in the frequency range 0.1–70 kHz. In order to improve the directivity diagram at high frequencies, the microphone was erected vertically using a hole in the floor.

The analogue-code transducer was constructed according to preset characteristics. Its purpose is to convert analogue signals for their further processing into a digital form. The nominal level of the incoming signal is ± 1 V. The resolution of the transducer is 12 bits; the time of conversion is $2\mu\text{s}$ and the time of quantization is $5\mu\text{s}$. The quantization frequency is 200 kHz.

For the purpose of analysis of the investigation results, the lower frequency limit of 50 Hz was chosen instead of 100 Hz. In the model's scale of 1 : 25 this would be 1250 Hz instead of 2500 Hz. The aim is to determine how resonators absorb sound energy at very low frequencies because the range of low frequencies is very important and the most interesting physical processes usually take place in it. The upper limit of the frequency range was chosen as 2000 Hz, or 50 kHz in the model. This has been done for two reasons: at the quantization frequency of 200 kHz and the upper limit of the frequency range of 50 kHz, the Nyquist frequency ratio is equal to 4.0, and more exact results are obtained when this frequency ratio is higher; too low a dynamic range is obtained when approximating the attenuation of the sound field at frequencies exceeding 2000 Hz. In my opinion, however, such upper range limit is quite acceptable because just at the low and medium frequencies the resonant ceiling will have the greatest impact on the hall acoustics.

The main acoustic indices of the model were analyzed by means of a specialized computer program developed by our own efforts.

The sound-absorbing material flannel was spread in the floor area occupied by the orchestra players. The area is 119 m^2 . It was possible to locate the microphones at three points: close to the sound source, far from it and above the suspended ceiling. The experiment was planned in such a way that it would be possible to determine the dependence of the main acoustic indices on the form and width of the slits of the suspended ceiling, on the distance between the ceiling and the rigid surface, and on the absorption in the hall and by the suspended ceiling.

In this paper we will present the results of the investigation of the effects of the resonant ceiling from the rigid surface on the acoustic indices when the slit width is constant.

4. Results of investigations

A resonant suspended ceiling with the cross-shaped slits between the planes was chosen for the investigation. The section of the hall and its plan are schematically represented in Figs. 1 and 2.

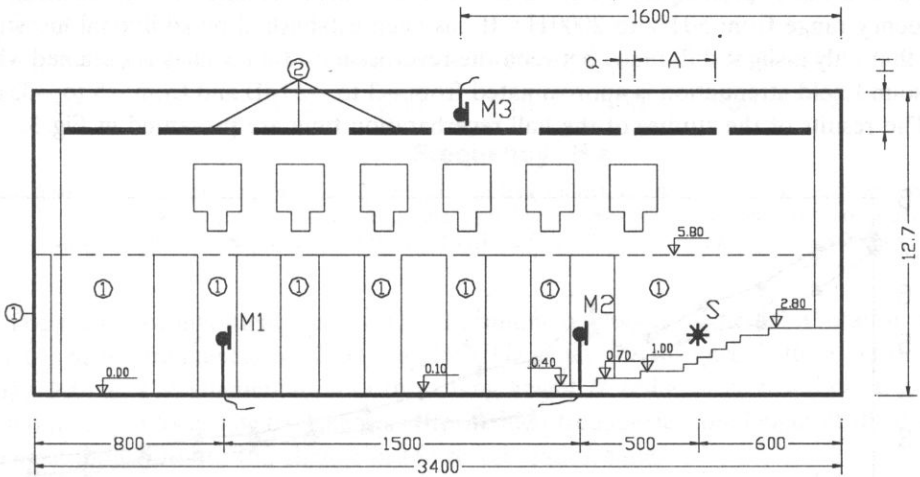


Fig. 1. The longitudinal section of the hall with the resonant suspended ceiling. S – sound source; M1, M2, M3 – positions of the microphones; 1, 2 – possible points of location of the sound-absorbing materials.

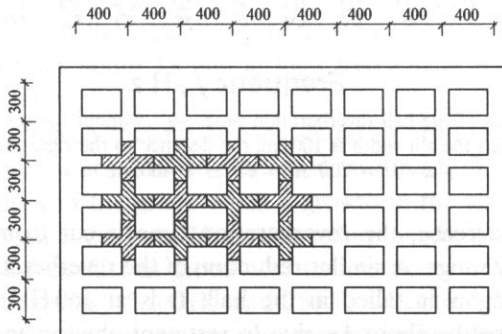


Fig. 2. Plan of the resonant suspended ceiling with cross-shaped slits between the planes.

By examining the influence of such a ceiling on the hall acoustics, we will establish its reverberation time, the index of purity of the music sound, and the acoustic centre of gravity. On the basis of the reverberational sound-field attenuation curves, the sound

absorption coefficients and the overall sound absorption will be computed in the case of a hall with no suspended ceiling and in that with the suspended ceiling.

When computing the values of the reverberation time from the sound-field attenuation curves, there arose the question about the point from which the evaluation of the attenuation should be started. In the computation of the standard reverberation time, the sound-field attenuation is approximated by evaluating the level from -5 dB to -35 dB. In our case, however, a too narrow dynamic range is obtained at high frequencies. It may be expanded by increasing the power of the impulse. It is still not sufficient because the resolution of the 12-bit transducer is too low. For this reason the attenuation of the sound-field was approximated from -3 to -33 dB. Reliable results were obtained in the frequency range from 50 Hz to 2000 Hz. It has been established by additional investigation that only a slight difference between the reverberation time values is obtained when the sound-field attenuation is approximated from -3 to -33 dB and from -5 to -35 dB.

The results of the studies of the hall reverberation time are presented in Fig. 3.

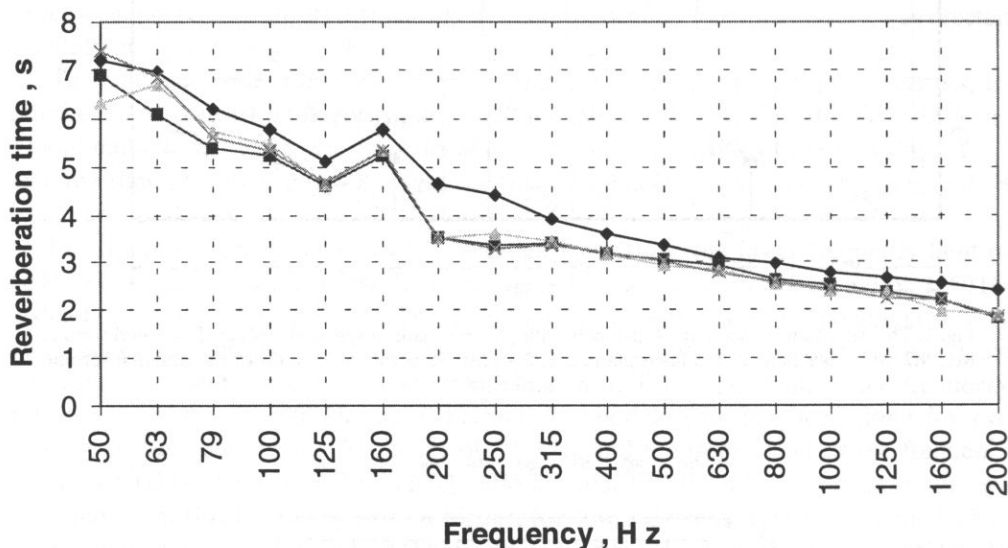


Fig. 3. Frequency characteristics of the hall reverberation time. —◆— without the resonant suspended ceiling; —■— with the ceiling when the slit width is 100 cm, the distance to the rigid surface $H = 100$ cm; —▲— $H = 200$ cm; —×— $H = 400$ cm.

As the frequencies increase, the reverberation time is cut from 7 s to 2.5 s evenly throughout the frequency range. A similar reduction of the reverberation time is observed when the resonant ceiling is installed in the hall. It is at 160 Hz only that this index increases, in all study cases by about 1 s, due to resonant phenomena.

It is very inconvenient to analyze the reverberation time changes in the hall with the resonant ceiling from such a graph. Therefore all investigation results presented below will be relative ones, taking as zero line the results for the hall with no suspended ceiling.

The relative changes in the reverberation time for the hall with a suspended ceiling are shown in Fig. 4.

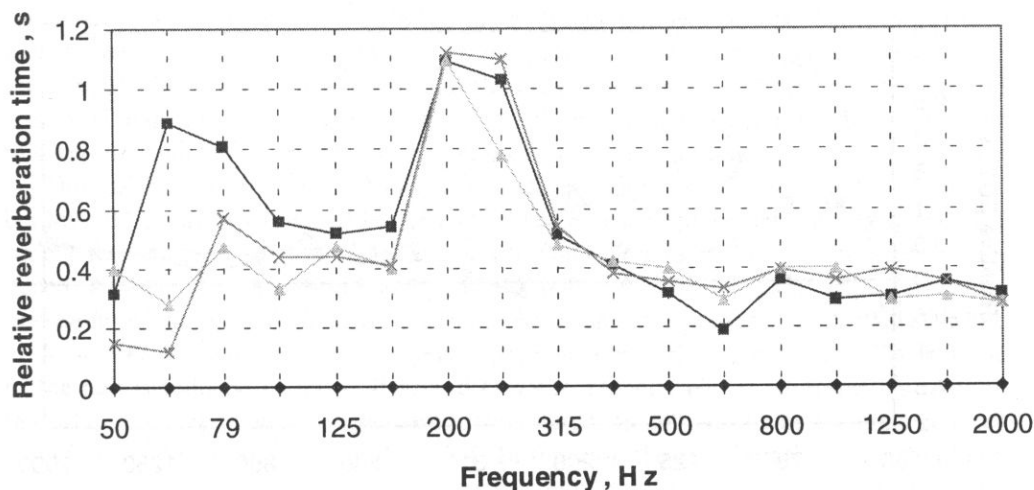


Fig. 4. The relative dependence of the hall reverberation time on the distance from the resonant suspended ceiling to the rigid ceiling surface. Slit width 100 cm. Zero line corresponds to the case when no suspended ceiling is installed. —■— distance to the rigid surface $H = 100$ cm; —▲— 200 cm; —×— 400 cm.

The results of investigations reveal a maximum reduction of the reverberation time by 1.14 s at the frequencies of 200 Hz and 250 Hz, when the distance to the rigid surface equals 100 cm. The augmentation of the ceiling height H reduces the reverberation time by about 0.2 – 0.5 s at low frequencies only. At high frequencies, the height of the ceiling is almost immaterial to the change in the reverberation time.

The early reverberation time is very important for the evaluation of the hall acoustics. It is connected with the early sound reflections and the subjective evaluation of music. The results of the studies are presented in Fig. 5.

In this case, a considerable reduction of the reverberation time of 3 s is obtained when the distance between the suspended ceiling and the rigid surface is 400 cm. When the height of the ceiling is smaller, this reduction has no pronounced resonant character. At low frequencies it equals about 1 s and at high frequencies – about 0.5 s and is almost independent of the ceiling height.

The sound absorption coefficients and the sound absorption area were calculated from the reverberation time values. The results are shown in Fig. 6.

The negative values of the graph mean a growth in the absorption coefficient, while the positive ones mean a decline. When the ceiling height is small and equals 100 cm, the relative absorption coefficient grows over the frequency range reaching its maximum at the resonant frequencies of 200 Hz and 250 Hz. As the ceiling height increases, the character of the change in the relative absorption coefficient remains the same. When the ceiling height is 400 cm, however, the coefficient does not show an increase at low and high frequencies as expected but, on the contrary, it is smaller. Thus, the absorption coefficient decreases along with the reduction of the reverberation time.

At the resonant frequencies of 200 Hz and 250 Hz, the reverberation time is shorter by about 1 s. Consequently, the absorption coefficients should be high at these frequencies.

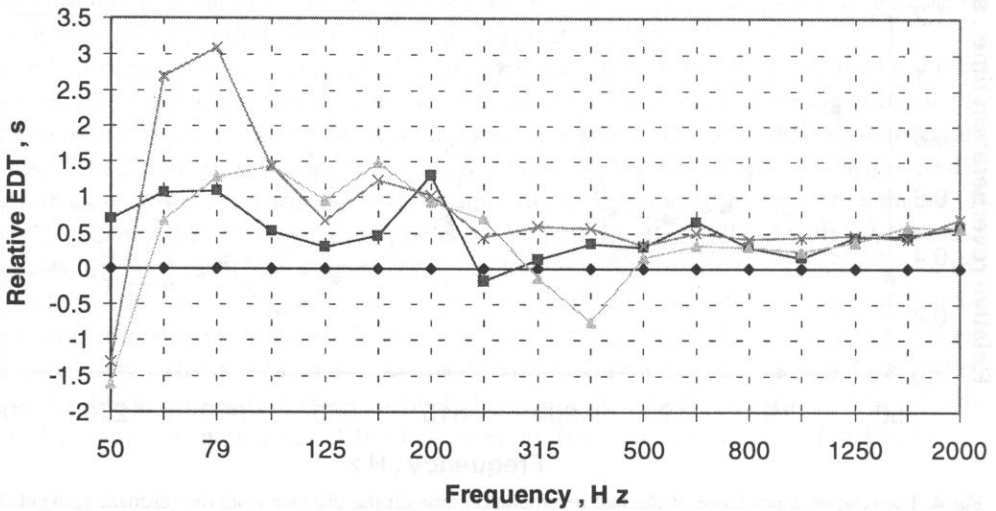


Fig. 5. The relative dependence of the early reverberation time EDT on the distance from the resonant suspended ceiling to the rigid ceiling surface. Slit width 100 cm. The zero line corresponds to the case when no suspended ceiling is installed. —■— distance to the rigid surface $H = 100$ cm; —▲— 200 cm; —×— 400 cm.

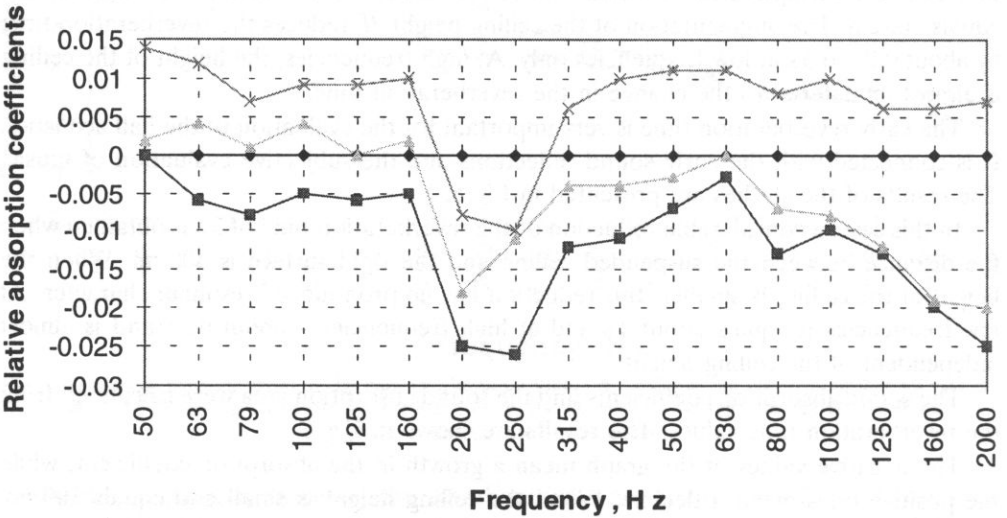


Fig. 6. The relative dependence of the sound absorption coefficients on the distance from the resonant suspended ceiling to the rigid ceiling surface. Slit width 100 cm. The zero line corresponds to the case when no suspended ceiling is installed. —■— distance to the rigid surface $H = 100$ cm; —▲— 200 cm; —×— 400 cm.

The relative values of the coefficient, however, are small. When no suspended ceiling is installed in the hall, its volume is about 9000 m^3 and the surface area is 2910 m^2 . The presence of the suspended ceiling reduces the hall volume and the surface area. These

values are again assessed by calculating the above-mentioned indices. Thus, the surface area is assessed twice, whereas the sound energy is only absorbed by the resonant ceiling the area of which is equal to 748 m^2 and the area of the slits is 288 m^2 only. The overall area of all hall surfaces, i.e. from 2400 m^2 to 2790 m^2 , is assessed in the calculations. For this reason small values of the absorption coefficients are obtained.

The lowering of the sound absorption coefficient along with shortening of the reverberation time may be explained by the fact that when the distance between the suspended ceiling and the rigid surface H increases, the hall volume and the surface area are reduced. However, an interesting change in the reverberation time is of importance too. For example, in the hall without a suspended ceiling it equals 5.77 s at 100 Hz , while at $H = 100, 200$ and 400 cm it equals $5.20, 5.44$ and 5.33 s , respectively. The volume of the hall is reduced to $8273, 7500$ and 6080 m^3 , respectively. It is interesting to note that when the ceiling height is increased from 100 cm to 200 cm , the hall volume reduces from 8273 m^3 to 7500 m^3 , i.e. by about 9% . In this case the reverberation time should be shorter but only for the hall volume reduction. However, it is longer by 0.24 s , while the absorption coefficient is reduced from 0.089 to 0.08 . Such an interesting change in the reverberation time is most probably determined by the sound energy which reaches the listeners from the volume between the suspended ceiling and the rigid surface.

Such a regularity is also observed at other frequencies.

We will assess the change in the overall sound absorption on the basis of the sound absorption coefficients. The results are presented in Fig. 7.

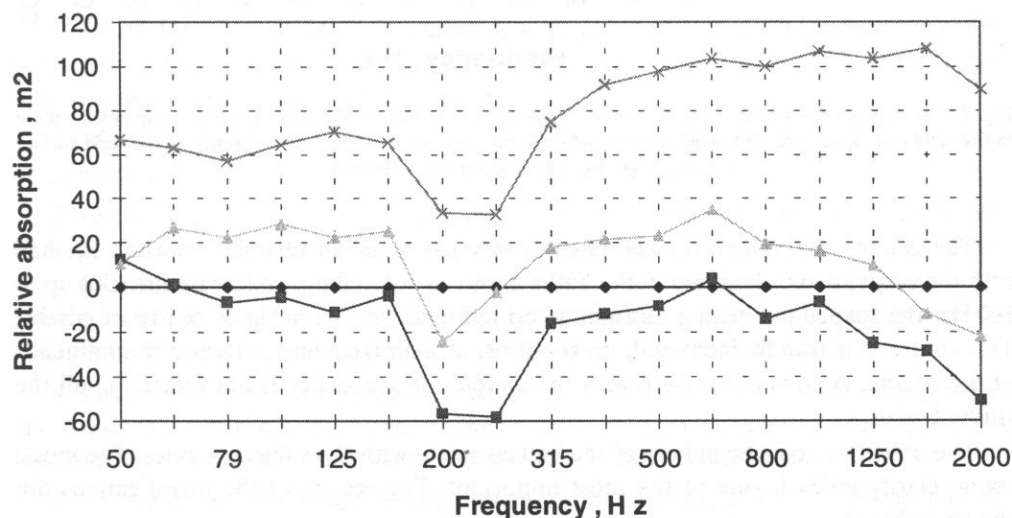


Fig. 7. The relative dependence of the sound absorption on the distance from the resonant suspended ceiling to the rigid ceiling surface. Slit width 100 cm . The zero line corresponds to the case when no suspended ceiling is installed. —■— distance to the rigid surface $H = 100\text{ cm}$; —▲— 200 cm ; —×— 400 cm .

When the height of the ceiling $H = 100\text{ cm}$, the resonant ceiling increases the sound absorption at 200 Hz and 250 Hz up to 60 m^2 . At low frequencies, the absorption remains almost unchanged, though changes in the reverberation time are marked. As the height

of the ceiling increases, absorption throughout the frequency range becomes smaller in proportion to the increase in H . Here the situation is analogous to the case of the sound absorption coefficients. After the increase in the ceiling height from 200 to 400 cm, the reverberation time is reduced from 5.44 s to 5.33 s, while the absorption area becomes smaller instead becoming larger – from 215 m² to 179 m². This reduction equals 60 m² at low frequencies and as much as 100 m² at high frequencies.

The change in the height of the resonant suspended ceiling also influences the change in the acoustic centre of gravity. The results of the investigations are presented in Fig. 8.

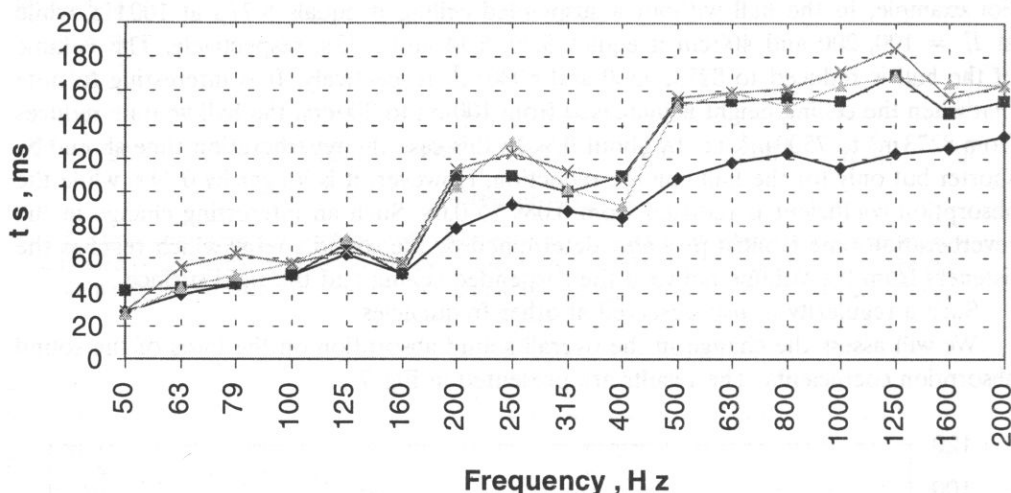


Fig. 8. The dependence of the acoustic centre of gravity on the distance from the resonant suspended ceiling to the rigid ceiling surface. Slit width 100 cm; —♦— without resonant ceiling; —■— distance to the rigid surface $H = 100$ cm; —▲— 200 cm; —×— 400 cm.

The change in the acoustic centre of gravity has a similar character both in the hall with the suspended ceiling and in the hall without such a ceiling. At low frequencies up to 160 Hz, the suspended ceiling has almost no influence on the acoustic centre of gravity. This centre is markedly increased, up to 40 ms, at high frequencies due to the influence of the ceiling. A constant growth with the increase in frequency is unexpected in all the studied cases.

The objective acoustic indices of the hall correlate with the subjective ones. The music sound clarity index is one of the most important. The results of the investigations are shown in Fig. 9.

Here the low frequency range may be divided into two parts: up to 160 Hz and above 200 Hz. At the lower frequencies, this index is now increased, now reduced by the suspended ceiling, while its absolute values vary from -7 to -14 dB. This shows that the energy of the late reflections is predominant in this range. Beginning from 200 Hz, the clarity index is increased by the suspended ceiling by 2–3 dB and this increase depends only slightly on the change in the ceiling height.

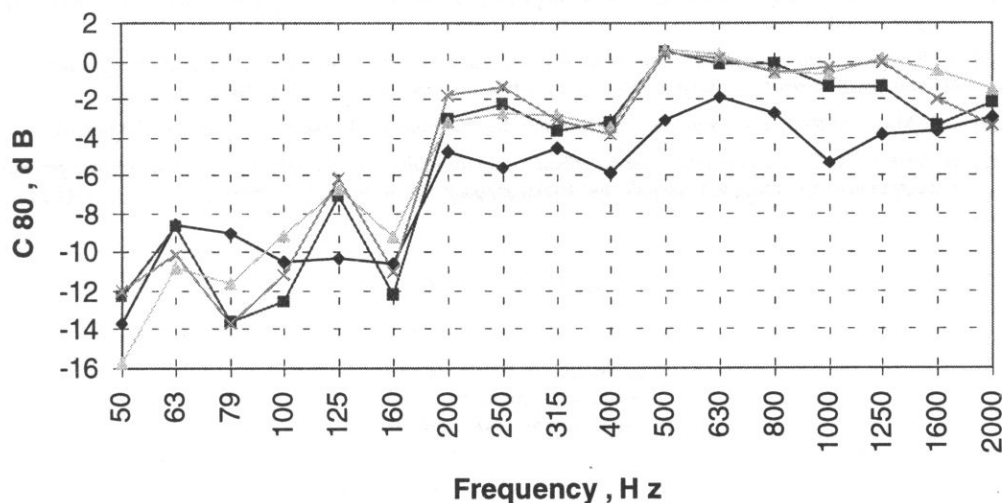


Fig. 9. The dependence of the musical sounds clarity index on the distance from the resonant suspended ceiling to the rigid ceiling surface. Slit width 100 cm. —♦— without resonant ceiling; —■— distance to the rigid surface $H = 100$ cm; —▲— 200 cm; —×— 400 cm.

5. Conclusions

1. At 200 Hz and 250 Hz, the reverberation time is reduced by the suspended ceiling with cross-shaped slits by about 1.14 s. The influence of the slits on the reverberation time is insignificant at high frequencies.
2. When the height of the ceiling equals 400 cm, the early reverberation time is cut by as much as 3 s at 79 Hz and by about 0.5 s at high frequencies.
3. As the height of the suspended ceiling increases, the sound absorption coefficients undergo the greatest rise at the resonance frequencies of 200 Hz and 250 Hz. When $H = 400$ cm, the absorption coefficient does not increase in the frequency range up to 160 Hz and from 315 Hz, as expected, but becomes smaller. This is determined by the changes in the reverberation time, the hall volume and the surface area.
4. Sound absorption is not augmented along with the increase in the ceiling height and the decrease in the hall volume; on the contrary, its area becomes smaller throughout the frequency range in proportion to the increase in the ceiling height.
5. The resonant suspended ceiling influences the acoustic centre of gravity and the music sound clarity index.

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