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AIR VOLUME RESONANCES AND THEIR INFLUENCE ON HALL ACOUSTICS

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The influence of resonances in a small rectangular music-hall on its reverberation characteristics was investigated. The length, width and height of the hall are $13.6 \times 10.7 \times 7$ m, respectively. The sound absorption coefficients of all the hall surfaces are very small and equal to $0.03 - 0.05$ through the whole frequency range.

It has been established experimentally that the attenuation of the sound field in the empty hall is close to an exponential one. When 120 and 170 semi-upholstered chairs are placed in the hall, the sound field is characterized by early and steep attenuation which is determined by an additional sound absorption and by the late and slow attenuation determined by the repetitive echoes and resonances between the rows of chairs. The late character of attenuation starts from about $700 - 800$ ms and depends on the distance between the microphone and the source.

When the number of semi-upholstered chairs arranged in rows is increased from 120 to 170, the reverberation time up to 160 Hz, approximated by the attenuation from 0 to -30 dB, is not reduced, as one would expect, but grows from $5 - 6$ s to $9 - 10$ s and is even longer than the reverberation time of the empty hall. The late reverberation time of approximately -25 to -30 dB at 160 Hz has a pronounced resonant character and equals 12 s. On increasing the number of chairs to 170, the reverberation time peaks at 100 Hz achieves as much as 20 s. The late reverberation time shows that there exist resonances in the hall, evoked by a repetitive echo. After eliminating the echo, the resonances disappear.

1. Introduction

Halls small in area and volume are usually designed for the performance of and listening to chamber music. Existing small halls are renovated and adapted for musical purposes. The layout of such renovated old halls is usually rectangular, while their volume is small. The floor plane is horizontal and upholstered or semi-upholstered chairs are arranged on it. The surfaces of such halls are made of materials that reflect the sound energy well. The average sound absorption coefficient of the hall planes is usually small.

Rectangular halls with parallel walls, well reflecting sound, are risky from the acoustic point of view. Repetitive echoes of low repetitive frequency as well as air volume resonances may occur in such halls. Both the echoes and the resonances may also be influenced by chairs, especially those arranged on the horizontal plane. It is therefore necessary to investigate the influence of such negative phenomena on the hall acoustics.

The purpose of this paper is to study the influence of different quantities of semi-upholstered chairs arranged in rows and the tapestries hung on all the walls of the hall on the acoustics of a small hall.

2. Methods

The experiment was carried out in a hall 13.6 m long, 10.7 m wide and 7.0 m high. The volume of the hall was a small one of 1018 m^3. The parquet floor was horizontal and without a stage. All the wall and ceiling planes were plastered, therefore their sound absorption coefficients were very small. The front, back and lateral walls of the hall were even. There were two beams, 60 cm high and 60 cm wide, all of them extending along the width of the hall. The hall has one window of 2 m^2. The layout and the longitudinal section of the hall are shown in Fig. 1.

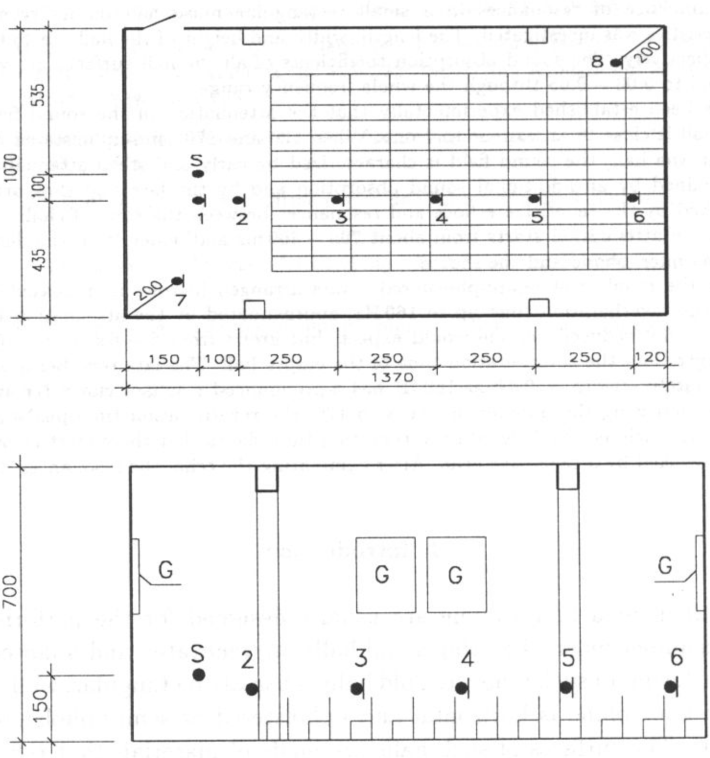

Fig. 1. The layout and section of the hall under investigation with the allocation of study points.

A 9 calibre sound pistol was used as sound source. In all cases, the sound source was situated on the longitudinal axis of the hall at a height of 1.5 m and a distance of 1.5 m from the front of the hall. It was stiffly fixed to a microphone stand.

The investigations were conducted at eight points in the hall. The selected longitudinal axis of the measurements was 1 m aside from the sound source axis. The microphones were placed at a height of 1.2 m.

The sound signal was transmitted from the microphone to the microphone amplifier, from the latter to a 2-channel, 16-bit analog-digital converter, and then to the computer memory. The acoustic analysis of signals was performed with the aid of a specially prepared program.

The main acoustic features were measured for five different cases of the hall settings: 1) empty hall; 2) hall with 120 semi-upholstered chairs; 3) hall with 170 semi-upholstered chairs; 4) hall with 170 semi-upholstered chairs and tapestries on the four walls; and 5) hall with 120 semi-upholstered chairs and 60 people.

The chair backs were upholstered with soft fabric. The edges of the chair backs were made of hard wood, while their external sides were covered with plywood covered with thin fabric. The chairs were arranged in the middle of the hall. The tapestries, whose overall area was about 11 m^2, were hung at a height of 3.3 m from the floor. The height of the tapestries was about 1.3 m. The width of the tapestries arranged on the lateral walls varied from 2.4 m to 2.8 m, while the width of those hung on the back and the front wall was 1.6 m.

In this paper the results of the investigations are represented by the measurements carried out at point 3. The distance from the point No. 3 to the sound source was 3.6 m and the distance to the right wall was 4.3 m.

3. Results

The time-dependence of the decay of the sound field energy in different hall settings is presented in Fig. 2.

When the hall is empty, the sound field decays along an exponential curve. The field decay on the logarithmic scale is almost a straight line. When there are 120 semi-upholstered chairs in the hall, the sound field attenuation has a different character. Here one may observe two markedly distinct regions: an early and a late one. The early decay is determined by the additional attenuation caused by the chair absorption, while the late decay is determined in our opinion by the resonant sound field caused by the repetitive echoes between the parallel walls and the chairs arranged in rows. The resonances occur between the rows of chairs, and the repetitive echo maintains the sounding of the excited resonances due to which the entire decay rate of the sound field is decreased considerably. When the number of chairs is increased to 170, the early sound field decay is identical to that observed in the hall with 120 chairs. Further, however, the sound field decays even slower than in the latter case. After the tapestries are hung on all the four walls of the hall, the repetitive echoes and the resonances disappear. This is evidenced by Fig. 2 which shows that both the early and the late sound

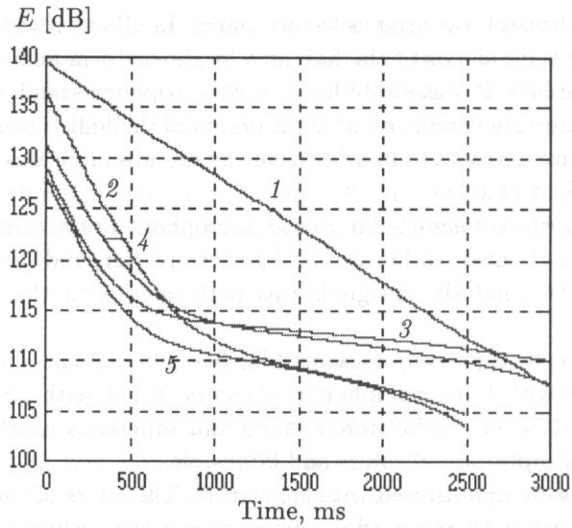

Fig. 2. Time-dependence of the sound field for different hall settings: *1* – empty hall; *2* – hall with 120 semi-upholstered chairs; *3* – hall with 170 semi-upholstered chairs; *4* – hall with 170 semi-upholstered chairs and tapestries on the walls; *5* – hall with 120 semi-upholstered chairs and 60 people.

field decay regions become steeper. This cannot be explained only by the slight increase in absorption caused by the tapestries. The change of the slopes of decay curves, occurring at around 700 – 800 ms, is clearly seen. The position of this change depends on the distance between the microphone and the sound source.

The occurrence of the resonances should be confirmed or denied by the frequency characteristics of the early and the late reverberation time. The results of the analysis in the early reverberation time are presented in Fig. 3.

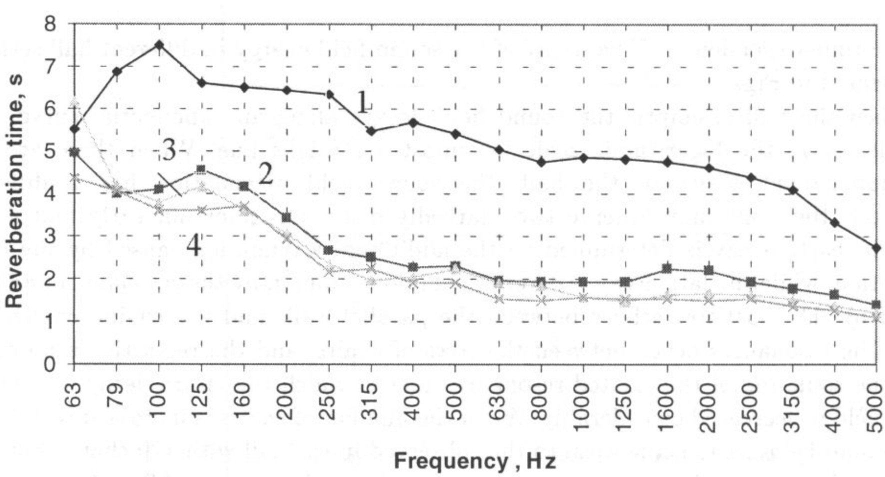

Fig. 3. Early reverberation time vs. frequency for different hall settings: *1* – empty hall; *2* – hall with 120 semi-upholstered chairs; *3* – hall with 170 semi-upholstered chairs; *4* – hall with 170 semi-upholstered chairs and tapestries.

In this case, as expected, the resonances are not observed. Filling of the hall with chairs greatly reduces the reverberation time almost equally throughout the whole frequency range. The increase in the number of chairs and additional tapestries on the walls have hardly any effect on the reverberation time.

Results of the analysis of the late reverberation time, approximated from −25 to −30 dB, are shown in Fig. 4.

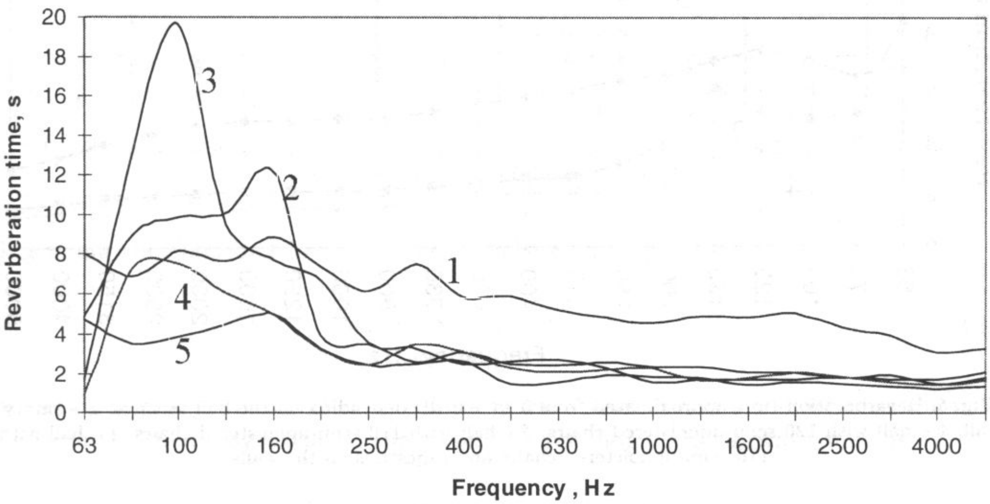

Fig. 4. Late reverberation time, approximated from −25 to −30 dB, depending on the hall settings: *1* – empty hall; *2* – hall with 120 semi-upholstered chairs; *3* – hall with 170 semi-upholstered chairs; *4* – hall with 170 semi-upholstered chairs and tapestries on the walls; *5* – hall with 120 semi-upholstered chairs and 60 people.

One can see that, after the increase in the number of chairs arranged in rows, the late reverberation time is also prolonged, but only at the resonant frequency. When there are 120 chairs, at the resonant frequency of 160 Hz, the late reverberation time is equal to 12 s. As the number of chairs is increased to 170, the reverberation time is prolonged still further and at 100 Hz it equals as much as 20 s. From this one may conclude that the resonance is evoked in the low-frequency range by the rows of chairs. The resonance is supported by the repetitive echoes after the elimination of which the resonance disappears. This is confirmed by the fact that both the repetitive echoes and the resonances almost disappear after the tapestries are hung, while the reverberation time equals about 4 s only. When there are 120 chairs and 60 people in the hall, the resonance is retained at low frequencies, but its character is different as compared with the resonance in the hall without listeners.

The time decay of the sound field of the filtered signal differs greatly from that of the non-filtered signal. At the resonant frequencies, the fast and slow parts of the decay curve can no longer be so clearly distinguished. Thus, in this case, the single reverberation time may by defined in the region 0 to −30 dB. The region chosen differs from the standard one of −5 to −35 dB because in the latter case the obtained dynamic range was too low.

Figure 5 depicts the frequency characteristics of the reverberation time approximated from 0 to −30 dB.

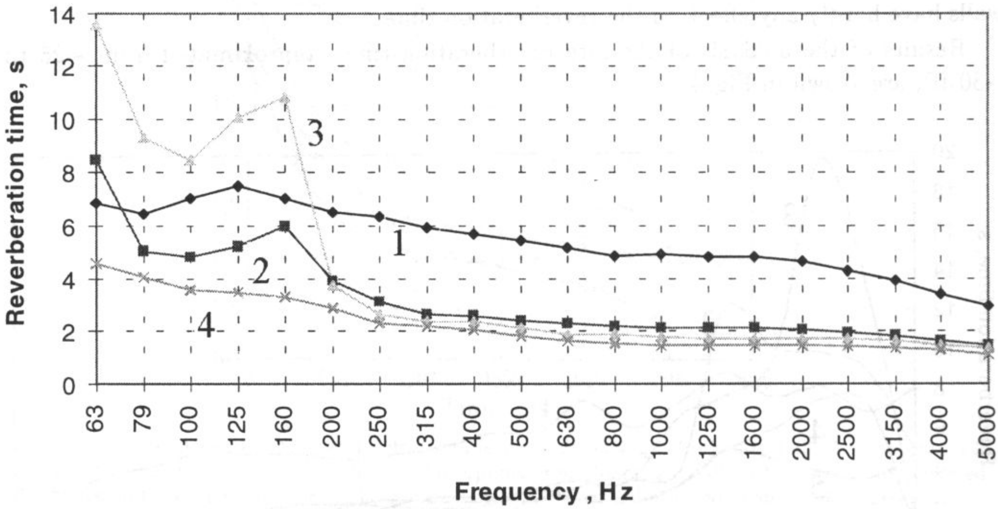

Fig. 5. Reverberation time approximated from 0 to −30 dB depending on the hall settings: *1* – empty hall; *2* – hall with 120 semi-upholstered chairs; *3* – hall with 170 semi-upholstered chairs; *4* – hall with 170 semi-upholstered chairs and tapestries on the walls.

When the hall is empty, the reverberation time appears to be only slightly different from the early reverberation time (EDT). With 120 chairs in the hall, the reverberation time is considerably longer than EDT for the same number of chairs. When the number of chairs is increased from 120 to 170, the reverberation time in the range up to 160 Hz becomes much longer, exceeding that of the empty hall. It is well known that the larger the number of chairs introduced the greater the sound absorption. This implies that the reverberation time should be decreased. The experiment, however, shows a contrary result: the time is increased. Such phenomenon may be explained by the repetitive echoes which evoke resonances between the chair rows. Therefore the sound field decay curve has two, though not significantly different, decay regions: an early and a late one. Upon eliminating the repetitive echo, the resonances must disappear. This is confirmed by curve 4. After the tapestries are hung on the walls of the hall with 170 chairs, the reverberation time is reduced to 4 – 8 s in the low-frequency range, i.e. up to 160 Hz.

The appearance of the resonance may be explained by the periodical allocation of the chairs along one coordinate and the existence of repeating echoes with respect to this coordinate. In this case, the chairs may be considered to be an infinite one-dimensional periodical structure. The geometry for the analysis of such a problem is shown in Fig. 6.

The space above the chairs is assumed to be free; this is valid when the period of the resonance, obtained in such a periodical structure, is considerably shorter than the time of sound transition between the chairs and the ceiling (we will see after the calculations that this is just the case). The acoustic field above the chairs, using notations shown in

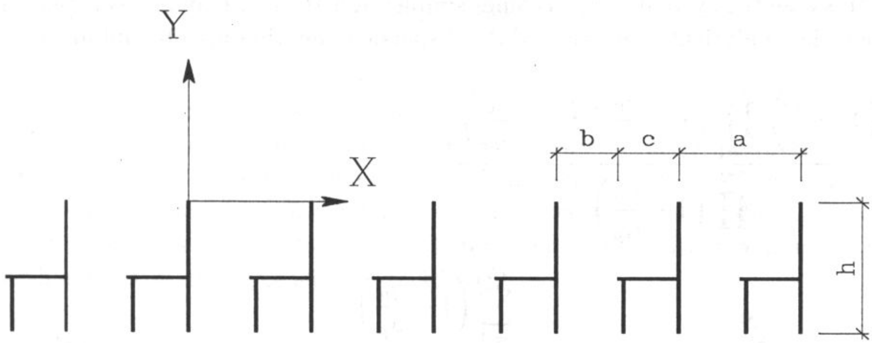

Fig. 6. The periodical infinite structure of the chairs. The height of the chair back is assumed to be equal to half of the chair height.

Fig. 6, may be described by means of the Floke waves [1]:

$$\psi_1 = \sum_{n=-\infty}^{\infty} B_n e^{i\beta_n x} e^{-\gamma_n y}, \tag{3.1}$$

where $\beta_n = \beta_0 + (2\pi n/a)$; $\gamma_n^2 = \beta_n^2 - k^2$, k is wave number and $y > 0$, whereas the field between the chairs, by means of the waves of a non-homogeneous waveguide, is

$$\psi_2 = \sum_{m=0}^{\infty} A_m ch\alpha_m (y+h) \cos k_m x\,, \tag{3.2}$$

where k_m is obtained from the equation

$$h \operatorname{tg} k_m b + \frac{h}{2} \operatorname{tg} k_m c = 0 \qquad \text{and} \qquad \alpha_m = k_m - k^2.$$

These solutions are related to the chair height level where the functions and their normal derivatives must be equal. At these boundary conditions, an infinite system of equations is obtained:

$$\sum_{n=-\infty}^{\infty} B_n \beta_n \frac{1}{\gamma_n - \alpha_p} = \frac{\varepsilon a \alpha_p A_p}{j[1-(-1)^p e^{j\beta_0 a}]} e^{-\alpha_p h}, \tag{3.3}$$

$$\sum_{n=-\infty}^{\infty} B_n \beta_n \frac{1}{\gamma_n + \alpha_p} = \frac{\varepsilon a \alpha_p A_p}{j[-1(-1)^p e^{j\beta_0 a}]} e^{-\alpha_p h}, \tag{3.4}$$

where $p = 0, 1, 2, ...$, $\varepsilon = 1$ or $1/2$, when $p = 0$, or $p \neq 0$ respectively.

Since the terms of this equation are of a special form, the system determinant may be expressed by means of an infinite product.

When solving these equations, one must first find the dispersion equation for γ_0. For this purpose, we shall accept a number of approximations:

Only the terms with $p = 0$ are left, thus $a_0 = i \times k$. This approximation will be suitable solely for wavelengths exceeding a and $h > a/p$.

In this case the system (3.1) becomes simpler and $B_n \times b_n$ may be expressed through A_0; then the analytical expression of the dispersion equation may be obtained:

$$\frac{\left(1-\frac{\alpha}{\gamma_0}\right)\prod_{m=1}^{N}\left(1-\frac{\alpha_0}{\gamma_m}\right)\left(1-\frac{\alpha_0}{\gamma_m}\right)}{\prod_{p=1}^{2N}\left(1-\frac{\alpha_0}{\alpha_p}\right)}$$

$$\times\sum_{n=-N}^{N}\frac{\sum_{p=1}^{2N}\left(1-\frac{\gamma_n}{\alpha_p}\right)}{\left(1-\frac{\gamma_n}{\gamma_0}\right)\left(1-\frac{\alpha_0}{\gamma_n}\right)\prod_{m=1}^{N}\left(1-\frac{\gamma_n}{\gamma_m}\right)\left(1-\frac{\gamma_n}{\gamma_m}\right)} = -e^{2ikh}. \qquad (3.5)$$

Furthermore, in the case of such approximations, only the terms with $n = 0$ must remain. Finally, the dispersion equation is as follows:

$$\frac{ika}{\pi}\ln 2 - i2\mathrm{arctg}\frac{k}{\gamma_0} - \frac{\gamma_0 a}{\pi}\ln 2 = 2ikh + i\pi. \qquad (3.6)$$

It can be seen from this equation that β_0 (obtained from γ_0) has resonances, but in the case of the above approximations, only the frequency of the first resonance is correctly determined. Figure 7 shows the dependence of the resonance frequency f_{rez}, e.g. when $\beta_0 \to \infty$, on the distance between the chairs.

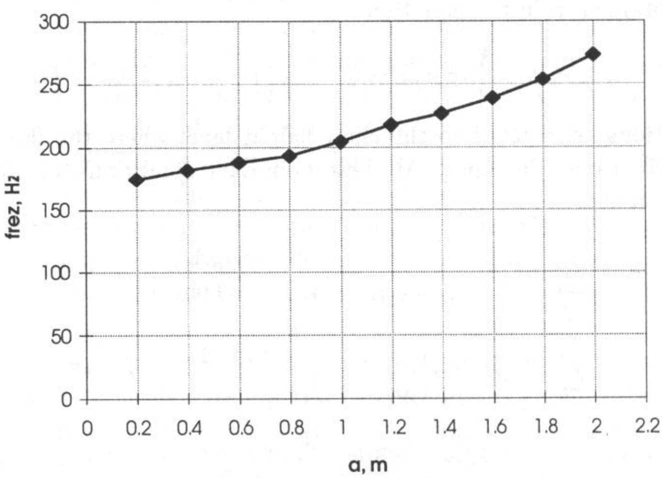

Fig. 7. Dependence of the resonance frequency on the distance between the chairs.

One can see from Fig. 7 that the arrangement of the chairs in the rows may cause a resonance in the low frequency region provided there is an echo. Eliminating the echo leads to the disappearance of the resonance.

4. Conclusions

1. In a small rectangular hall with semi-upholstered chairs arranged in rows, the sound field decay is characterized by pronounced early and late regions. The late decay is determined by the repetitive echoes and the resonances between the chair rows. The resonant frequency obtained from theoretical calculations is close to the measured one.

2. When the hall contains 170 chairs and tapestries on all the four walls, the repetitive echoes and resonances are practically eliminated. The reverberation time undergoes a considerable decrease at frequencies up to 160 Hz.

References

[1] R. Mitra, S.W. Lee, *Analytical techniques in the theory of guided waves*, The Macmillan Company, N.Y., London 1971.