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THE SOUND ABSORPTION OF AN ISOLATED RESONATOR WITH A CROSS-SHAPED SLIT AND ITS DEPENDENCE ON THE NUMBER OF RESONATORS

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Introduction

At present, Helmholz type resonators are used in acoustical applications. They represent a thin slab several millimetres thick with slits or holes small in diameter. The separation between them is not large. A sound-absorbing material is always placed behind the slab. Such structure absorbs medium- and high-frequency sounds well, while absorption of low-frequency sounds is weak. The sound absorption qualities of this structure are mainly determined by the sound-absorbing material.

Absorption of low-frequency sound is the urgent problem of architectural acoustics. Membrane structures with a large air gap behind the slab and with sound-absorbing material are used for such absorption.

A resonance structure consisting of cross-shaped slits formed by four planes may represent a prospective sound-absorbing structure. These planes may be thick and rigid slabs with an air gap behind them.

The purpose of this paper is to theoretically and experimentally examine the sound absorption qualities of such structure as well as their dependence on frequency and quantity of resonators.

2. Theory

First of all let us consider the sound absorption qualities of an isolated cross-shaped resonator and resonator-quantity dependence of absorption. The calculation diagrams for such resonators are shown in Fig. 1.

The isolated acoustical resonator with a cross-shaped slit has been theoretically examined in [1]. The main calculation formulas will be presented and the influence of the number of resonators will be theoretically assessed in this paper.

The sound absorption of such resonator will be computed from the formula

$$A = 4\rho_0 c_0 \frac{\operatorname{Re} Z}{|Z + Z_r|^2} S_r \tag{1}$$

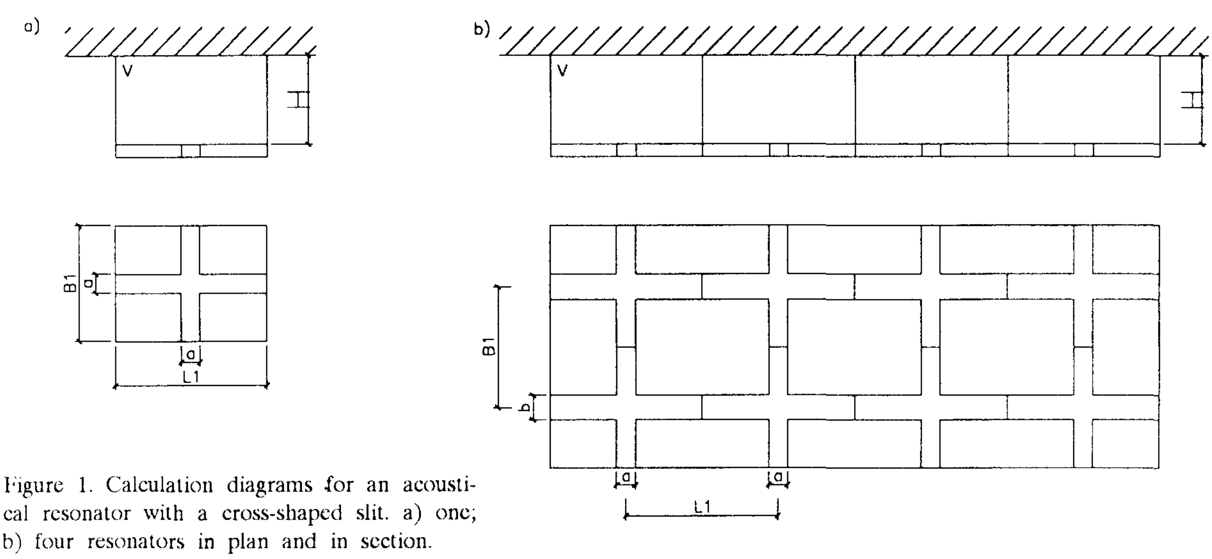

Figure 1. Calculation diagrams for an acoustical resonator with a cross-shaped slit. a) one; b) four resonators in plan and in section.

where ρ_0 is the air density; c_0 is the speed velocity in the air; S_r is the area of the resonator; Z_r is the resonator radiation impedance; and Z is the slit impedance.

For the resonator sound absorption to be calculated, we must calculate its radiation impedance Z_r and Z its slit impedance.

The radiation impedance of the resonator will be calculated from the formula [2].

$$Z_r = \rho_0 c_0 \frac{k^2 S_r^2}{4\pi^2} \frac{\langle v \rangle^2}{v_0^2} \int_0^{2\pi} d\varphi \int_0^{\frac{\pi}{2}+j\infty} |D(\gamma,\varphi)|^2 \sin\varphi d\varphi \quad (2)$$

where k is the wave number; S_r is the resonator area; $\langle v \rangle$ is the average speed of air particle fluctuation throughout the resonator area; v_0 is the speed of a moving point for which the radiation impedance must be found; and D is the radiation directivity chart for the resonator.

For the calculation of the real part of the resonator ReZ and the imaginary part of the resonator ImZ, they must be singled out. Then

$$\operatorname{Re} Z_r = \rho_0 c_0 \frac{k^2 S_r^2}{4\pi^2} \int_0^{2\pi} d\varphi \times$$

$$\times \int_0^{\frac{\pi}{2}} \frac{\sin^2(kB_1 \sin\gamma\cos\varphi)}{k^2 B_1^2 \sin^2\gamma\cos^2\varphi} \cdot \frac{\sin^2\left(\frac{a}{2}\sin\gamma\sin\varphi\right)}{k^2\frac{a^2}{2}\sin^2\gamma\sin^2\varphi} \sin\gamma d, \quad (3)$$

$$\operatorname{Im} Z = \frac{\rho_0 c_0}{j} \frac{k^2 S_r^2}{4\pi^2} \int_0^{2\pi} d\varphi \times$$

$$\times \int_{\frac{\pi}{2}-j\infty}^{\frac{\pi}{2}+j\infty} \frac{\sin^2(kB_1 \sin\gamma\cos\varphi)}{k^2 B_1^2 \sin^2\gamma\cos^2\varphi} \cdot \frac{\sin^2\left(k\frac{a}{2}\sin\gamma\sin\varphi\right)}{k^2\frac{a^2}{2}\sin^2\gamma\sin^2\varphi} \sin\gamma d\gamma \,. \quad (4)$$

Let us make a substitution: $u = \frac{\pi}{2} - j\gamma$, $du = -jd\gamma$. The lower integration limit is equal to zero and the upper limit is equal to $-\infty$. Then $\cos jx = \cosh x$ and the imaginary part of the impedance will be expressed

$$\operatorname{Im} Z = \frac{\rho_0 c_0}{j} \frac{k^2 S_r^2}{4\pi^2} \int_0^{2\pi} d\varphi \times$$

$$\times \int_0^{-\infty} \frac{\sin^2(kB_1 \cos\varphi\cosh u)}{k^2 B_1^2 \cos^2\varphi\cosh^2 u} \cdot \frac{\sin^2\left(k\frac{a}{2}\sin\varphi\cosh u\right)}{k^2\frac{a^2}{2}\sin^2\varphi\cosh^2 u} \cosh u(-jdu), \quad (5)$$

and

$$\operatorname{Im} Z = \rho_0 c_0 \frac{k^2 S_r^2}{4\pi^2} \int_0^{2\pi} d\varphi \times$$

$$\times \int_0^{\infty} \frac{\sin^2\left(k\frac{B_1}{2}\cos\varphi\cosh u\right)}{k^2\frac{B_1^2}{2}\cos^2\varphi\cosh^2 u} \cdot \frac{\sin^2\left(k\frac{a}{2}\sin\varphi\cosh u\right)}{k^2\frac{a^2}{2}\sin^2\varphi\cosh^2 u} \cosh u du \,. \quad (6)$$

The radiation directivity chart for the cross-shaped slit will be expressed as follows:

$$D = \frac{(D_1 S_1 + D_2 S_2 - D_{12} S_{12})}{S_a} \quad (7)$$

where D_1 and D_2 are the directivity charts for two rectangular slits perpendicular to each other; S_1 and S_2 are the slit areas; and D_{12} are the directivity chart for the overlapping part and S_{12} its area, respectively.

The radiation directivity chart for the rectangular slit D_1 is calculated from the formula

$$D_1 = \frac{\sin\left(k\frac{B_1}{2}\sin\gamma\cos\varphi\right)}{k\frac{B_1}{2}\sin\gamma\cos\varphi} \cdot \frac{\sin\left(k\frac{a}{2}\sin\gamma\sin\varphi\right)}{k\frac{a}{2}\sin\gamma\sin\varphi} \,. \quad (8)$$

The radiation directivity chart for the rectangular slit D is calculated from the formula

$$D_2 = \frac{\sin\left(k\frac{B_1}{2}\sin\gamma\sin\varphi\right)}{k\frac{B_1}{2}\sin\gamma\sin\varphi} \cdot \frac{\sin\left(k\frac{a}{2}\sin\gamma\cos\varphi\right)}{k\frac{a}{2}\sin\gamma\cos\varphi} \,. \quad (9)$$

The radiation directivity chart for the overlapping part of two perpendicular slits is calculated from the formula:

$$D_{12} = \frac{\sin\left(k\frac{a}{2}\sin\gamma\cos\varphi\right)}{k\frac{a}{2}\sin\gamma\cos\varphi} \cdot \frac{\sin\left(k\frac{a}{2}\sin\gamma\sin\varphi\right)}{k\frac{a}{2}\sin\gamma\sin\varphi} \,. \quad (10)$$

The impedance of the slit itself consists of four parts and is expressed as follows:

$$Z = Z_{m0} + Z_{ma} + Z_{mi} + Z_v \quad (11)$$

where Z_{m0} is the impedance of the slit itself; Z_{ma} is the impedance of the added air mass outside the slit; and Z_{mi} is the impedance of the added air mass inside the slit; Z_v is volume impedance.

The impedance of the slit itself is equal to:

$$Z_{m0} = \frac{\rho_0 t}{2a}\sqrt{\frac{8\eta}{\rho_0}\omega} + j\omega\rho_0 t\left(1 + \frac{1}{2a}\right)\sqrt{\frac{8\eta}{\rho_0\omega}} \,. \quad (12)$$

The impedance of the added air mass outside the slit is equal to:

$$Z_{mi}=\frac{\rho_0\Delta t_i}{2a}\sqrt{\frac{8\eta}{\rho_0}\omega}+j\omega\rho_0\frac{\Delta t_i}{2a}\sqrt{\frac{8\eta}{\rho_0\omega}}\quad (13)$$

The impedance of the added air mass inside the slit is equal to:

$$Z_{ma}=Z_r+\frac{\rho_0\Delta t_a}{2a}\sqrt{\frac{8\eta}{\rho_0}\omega}+j\omega\rho_0\frac{\Delta t_a}{2a}\sqrt{\frac{8\eta}{\rho_0\omega}}\quad (14)$$

where Z_r is radiation impedance.

Upon inserting (12), (13) and (14) into (11), we receive the impedance of the slit itself:

$$Z=\sqrt{8\eta\rho_0\omega}\left[\frac{u}{4S_r}\left(t+\frac{u}{\pi}\right)+\beta_1 u\right]+$$
$$+j\left[\omega\rho_0 t+\sqrt{8\eta\rho_0\omega}\left(t+\frac{u}{\pi}\right)\frac{u}{4S_r}\right]+Z_v\quad (15)$$

where η is the air viscosity; u is the slit perimeter; ω is the angular frequency; and Z_v is the air volume impedance obtained from the formula:

$$Z_v=\rho_0 c_0\frac{Z_1\coth k_0H+\rho_0c_0}{\rho_0c_0\coth k_0H+Z_1}\cdot\frac{S_1H}{V}\quad (16)$$

where Z_1 is the ceiling impedance; and k_0 is the wave number.

For the role of the resonator number in the radiation directivity charts to be assessed, introduction of additional members is necessary. Such additional member for the rectangular slit directivity chart is expressed in the following way:

$$D_{1N}(\gamma,\varphi)=$$
$$=D_1\frac{\sin\left[Nk\frac{L_1}{2}\sin\gamma\sin\varphi\right]}{N\sin\left[\frac{L_1}{2}\sin\gamma\sin\varphi\right]}\cdot\frac{\sin\left[M\frac{B_1}{2}\sin\gamma\cos\varphi\right]}{M\sin\left[k\frac{B_1}{2}\sin\gamma\cos\varphi\right]}\quad (17)$$

The additional member for the directivity chart is equal to:

$$D_{2N}(\gamma,\varphi)=$$
$$=D_2\frac{\sin\left[Nk\frac{L_1}{2}\sin\gamma\cos\varphi\right]}{N\sin\left[k\frac{L_1}{2}\sin\gamma\cos\varphi\right]}\cdot\frac{\sin\left[Mk\frac{B_1}{2}\sin\gamma\sin\varphi\right]}{M\sin\left[k\frac{B_1}{2}\sin\gamma\sin\varphi\right]}\quad (18)$$

The additional member for the directivity chart of the overlapping part is equal to:

$$D_{12N}(\gamma,\varphi)=$$
$$=D_{12}\frac{\sin\left[Nk\frac{L_1}{2}\sin\gamma\sin\varphi\right]}{N\sin\left[k\frac{L_1}{2}\sin\gamma\sin\varphi\right]}\cdot\frac{\sin\left[Mk\frac{B_1}{2}\sin\gamma\cos\varphi\right]}{M\sin\left[k\frac{B_1}{2}\sin\gamma\cos\varphi\right]}\quad (19)$$

where M and N are the number of slabs along the X and Y axes.

The formulas show that when the number of resonators is increased, the sound absorption is determined by the radiation directivity charts and the slit impedances which are added up.

3. Calculation results

In the calculations, the slab thickness is taken as 2 cm. The resonator dimensions are taken as 2.4×1.8 m and its depth H, i.e. the distance to the rigid surface is accepted as 50 cm. The sound absorption coefficients of the rigid surface of the ceiling are assumed to be minimal: from 0.02 to 0.04 throughout the frequency range. The width of the resonator slit is taken as 30 cm in all cases. 100 points are taken for the calculation of each curve. The angle of incidence is normal.

Figure 2 shows the dependence of the sound absorption area on the number of resonators.

The calculations show that the sound absorption is strongly dependent on the quantity of resonators. When there is only one resonator, its absorption is low and reaches 8 sq.m. at 40 Hz. As the frequency increases, there is a uniform decrease in the absorption reaching minimal values (curve 1). In the case of two resonators (curve 2), the absorption rises to 27 sq.m., reaching its maximum at 110 Hz. The absorption decreases along with the decrease and increase in frequency and resonance phenomena occur at high frequencies. When the number of resonators is increased to 4, 6 and 8, the sound absorption is obviously resonant with the frequency equal to 110 Hz approximately. The result is interesting because, along with the increase in the number of resonators, the frequency area with high sound absorption values is expanded. For instance, when the number of resonators is equal to 8, the absorption maximum is only reached at 130 Hz and approaches

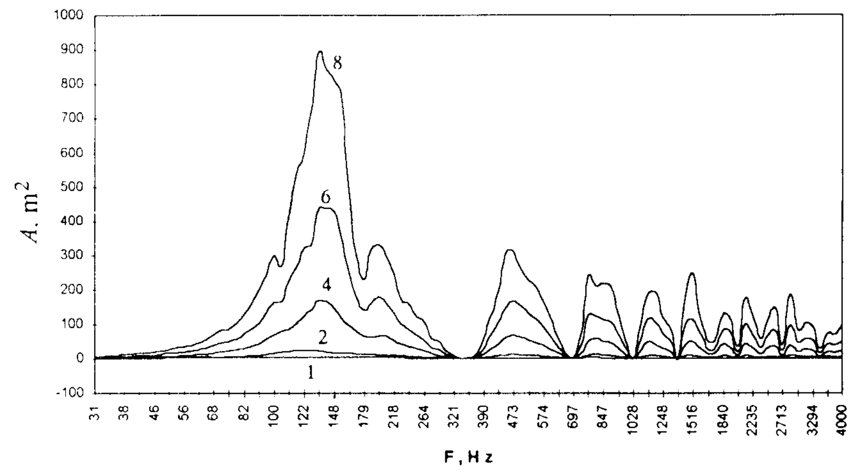

Fig. 2. The dependence of the sound absorption area of the resonators with cross-shaped slits on the number of resonators. Slit width is 50 cm and slit height is 50 cm. 1, 2, 4, 6 and 8 - 1, 2, 4, 6 and 8 resonators respectivelly

900 sq.m.; it decreases sharply when frequencies change. The absorption of 100 sq.m. occupies a frequency range of about 80 to 300 Hz, which is wider than in the case of fewer resonators.

The changes in the real parts of the slit impedance with the increase in the resonator number are shown in Fig. 3.

The real parts of the slit impedance undergo marked changes with the increase in the number of resonators. When there is only one resonator, the real parts of the impedance uniformly increase at the frequency from 31 Hz to 120 Hz, whereas at medium and high frequencies they remain almost unchanged. In the case of two resonators, the real parts of the impedance undergo spasmodic changes: they increase on frequencies up to 40 Hz, remain unchanged in the interval up to 120 Hz, and increase in leaps again up to 200 Hz. There is little change after 200 Hz. When the number of resonators is increased to 4,6 and 8, the real parts of the impedance remain almost unchanged in the frequency range up to 150 Hz. There is a sudden leap upwards with the increase in frequency. When the number of resonators is increased at low frequencies, the absolute values of the real parts grow smaller and are little-dependent on frequency.

In Fig. 4, the frequency-dependence of the imaginary parts of the slit impedance is demonstrated.

In this case, regularity is only observed with a small number of resonators. When there is 1 or 2 resonators, there is a very litle change in the imaginary parts of the impedance at low frequencies (about 300 Hz). When the number of resonators is increased from 4 to 8, the imaginary parts do not depend on this number and change little with the increase in frequency.

4. Results of the experiment

The experiment was carried out in natural conditions. The resonator with a cross-shaped slit was

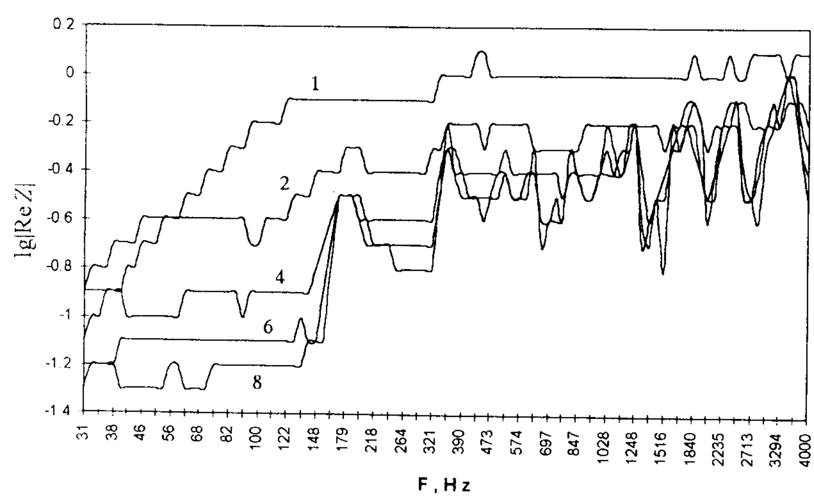

Fig. 3. The dependence of the real parts of the cross-shaped resonators on the number of resonators. 1, 2, 4, 6 and 8 - 1, 2, 4, 6 and 8 resonators respectively

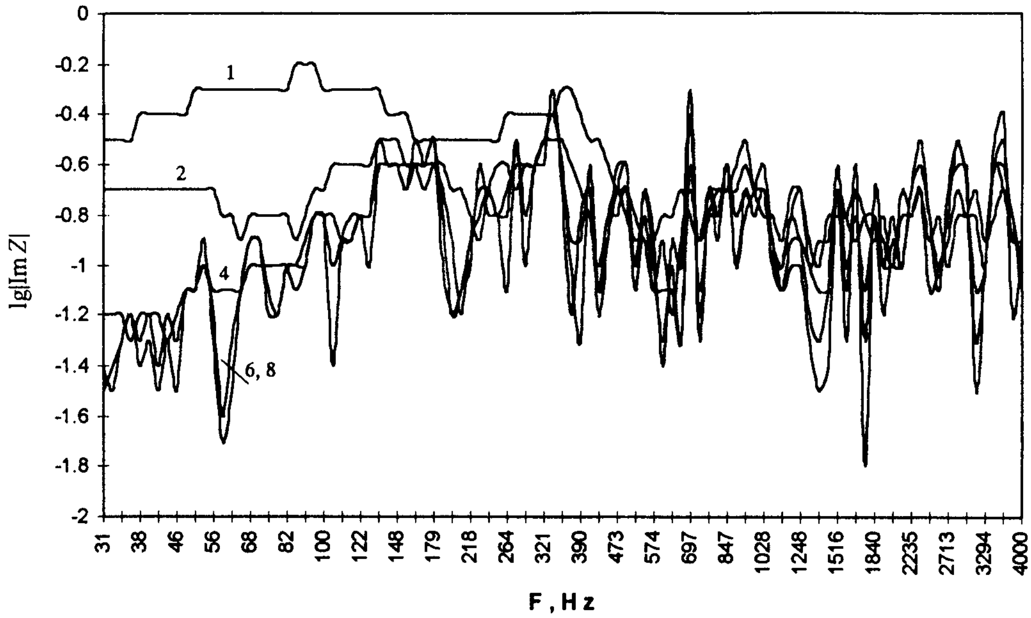

Fig. 4. The dependence of the imaginary parts of the cross-shaped resonator on the number of resonators. 1, 2, 4, 6 and 8 - 1, 2, 4, 6 and 8 resonators, respectively

mounted in the open air. The resonator was made of wood chipboard 18 mm thick. The measurements were taken in the area with no obstacles within the 20 m. distance from the resonator. This was necessary for the elimination of the negative influence of the sound waves' reflection from the obstacles. A windless day was chosen for the experiment. The resonator was put directly on the ground which was covered with thick grass, therefore the intensity of reflections from the ground was very low.

A 9-caliber sound gun was used as sound source, i.e. the source was fully spherical. The sound source was located 1.3 m. above the ground and 4 m. from the resonator. Wood chipboard used for the resonator reflects sounds of all frequencies well, i.e. the sound absorption coefficients are very small and are equal to 0.02-0.04 throughout the frequency range. Adhesive tape was used for filling the gaps between the slabs. Such conditions of the experiment enabled to assess the sound absorption qualities of the resonator itself. The diagram of the resonator under investigation is represented in Fig. 5.

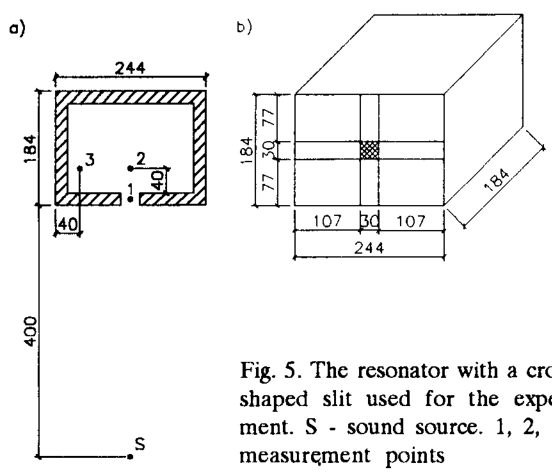

Fig. 5. The resonator with a cross-shaped slit used for the experiment. S - sound source. 1, 2, 3 - measurement points

Figure 6 presents the frequency-dependence of the sound absorption of the resonator at various points of measurement.

The measurements show that such resonator absorbs sound well at low frequencies, while absorption is also dependent on the point of measurement. In all cases, the maximum sound absorption is obtained at 100 Hz and is equal to 6 sq.m. when measured at points 1 and 2. When the measurement was taken at point 3, the absorption was considerably smaller and was equal to 4 sq.m. It is interesting to note that the maximum absorption is obtained when the measurement point 1 is located in the slit itself. These results are similar to the calculation results, with the only difference that the maximum is reached at various frequencies.

Figure 7 shows the frequency-dependence of the sound absorption coefficients.

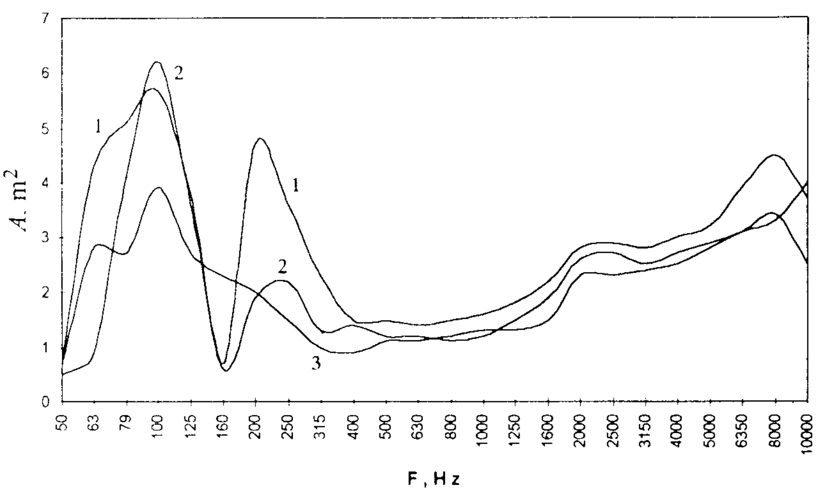

Fig. 6. The frequency-dependence of the sound absorption of the isolated resonator with a cross-shaped slit at 0 - 30 dB. 1, 2, 3 - measurement points

The sound absorption coefficient and the sound absorption have the same character. This is expected because the sound absorption coefficient is calculated on the basis of the reverberation time values, taking into account the areas of all surfaces. The maximum absorption coefficients are obtained at 100 Hz. They are equal to 0.17-0.27 and depend on the point of measurement. When the measurement point is located in the middle of the resonator slit, a considerable increase both in the absorption and the absorption coefficient is observed. Such increase is determined by the reverberation time.

Figure 8 shows the frequency-dependence of the reverberation time taking into account the muffling of the sound field at 0 - 30 dB.

At point 3, the reverberation time peaks on 400 Hz, reaching as much as 1.2 sec. At other points, this indicator is lower and is equal to 0.8-1.0 sec. at 630-800 Hz. This shows that the sound field inside the resonator is quite uneven and varies with the point of measurement. In spite of very small volume of the resonator (7.8 sq.m. only), the reverberation time is very long. It comes up with the reverberation time of a medium-size hall, though the hall volume is 100 and more times larger than the volume of the resonator.

The muffling of the sound field in time and by level is always varied, which is determined by the distribution of the early sound reflections over time. Figure 9 shows the change in the reverberation time, when the muffling of the sound field is approximated on the level from 0 to -10 dB.

The results of the examination show that the absolute values of the early reverberation time are close to the reverberation time approximated on the level from 0 to -10 dB. The values of this indicator at various points vary from 1 sec. to 1.35 sec. and are strongly dependent on frequency: the early re-

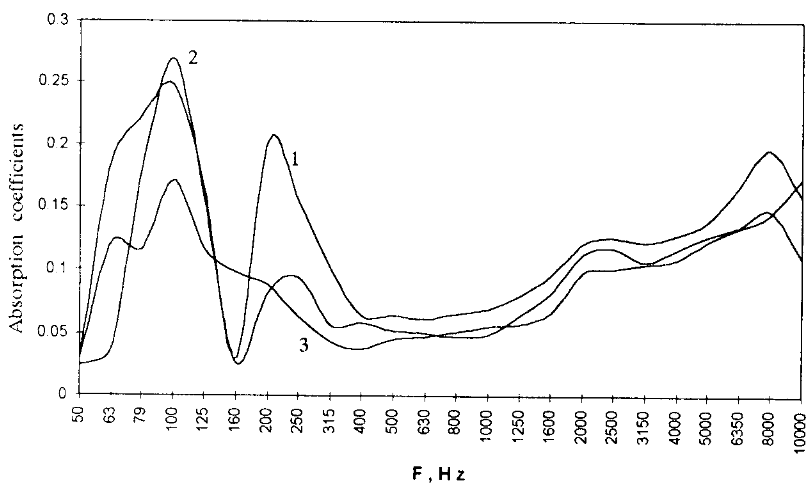

Fig. 7. The frequency-dependence of the sound absorption coefficient of an isolated resonator with a cross-shaped slit at 0 - 30 dB. 1, 2 and 3 - measurement points

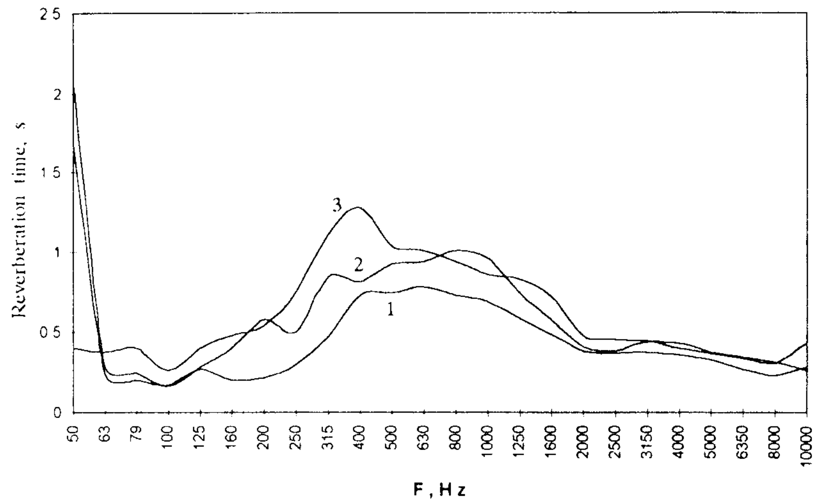

Fig. 8. The frequency-dependence of the reverberation time of an isolated resonator with a cross-shaped slit at 0-30 dB. 1, 2, 3 - measurement points

verberation time is very short at low and medium frequencies up to 250 Hz. Depending on the point of measurement, this time peaks at 400, 630 and 800 Hz and then rapidly decreases along with the increase in frequency. We see that the values of this indicator change every 0.2 sec. along with the change in frequency, which is very much.

The early reverberation time correlates with the acoustical centre of gravity well. Figure 10 shows the frequency-dependence of the acoustical centre of gravity at various points of measurement.

The results of the examination show that the acoustical centre of gravity, when measured in the slit of the resonator (point 1), is little-dependent on frequency and varies over the interval of 10-20 ms. When the points of measurement are inside the resonator (points 2 and 3), the acoustical centre of gravity has its marked maximums at 800 Hz and 400 Hz. This shows that the sound energy is concentrated in the medium-frequency range.

The distribution of the sound energy is well-characterized by the relationship between the direct sound energy and the reflection energy /3/. The results of examinations are presented in Fig. 11.

When determining the energy relationship, the direct sound energy was taken as lasting 5 ms. When the measuring microphone is in the slit (point 1), the reflection energy prevails in the frequency range up to 400 Hz. In the frequency range of 400-10000 Hz, however, an inverse phenomenon is observed: the direct sound and some early reflections are more energetic. When the point of measurement is inside the resonator (point 2), we have a balance between the direct sound energy and the reflected sound energy almost throughout the frequency range. Similar result is obtained in the case when the point of measurement (point 3) is inside the resonator, near its edge (curve 3). These results are demonstrative of the fact that the formation of acoustical indicators is greatly influenced by the direct sound.

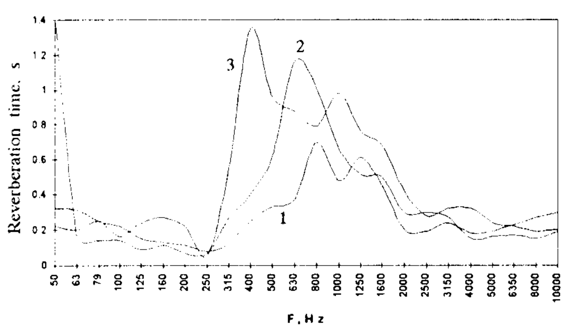

Fig. 9. The frequency-dependence of the reverberation time of a resonator with a cross-shaped slit at 0 -10 dB. 1, 2, 3 - measurement points.

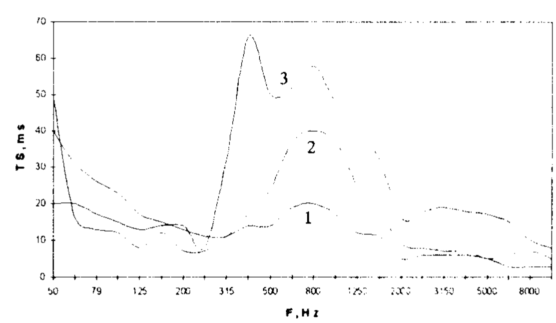

Fig. 10. The frequency-dependence of the acoustical centre of gravity of the resonator with a cross-shaped slit. 1, 2, 3 - measurement points

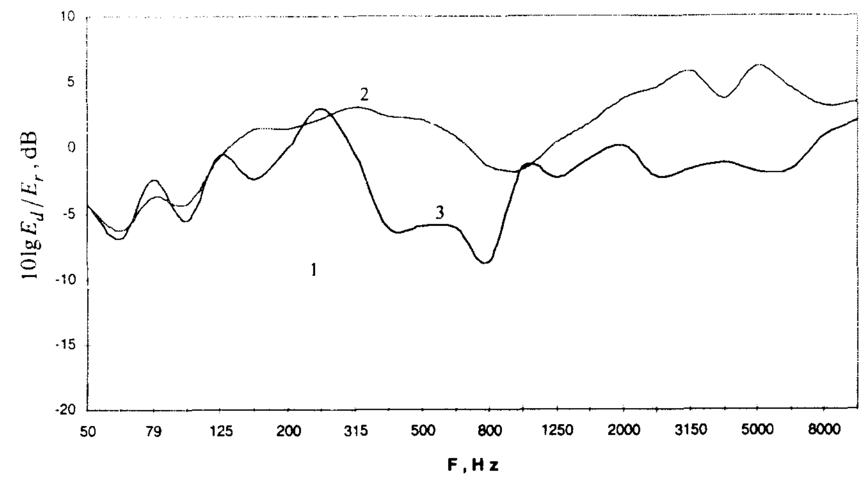

Fig. 11. The frequency-dependence of the sound energy relationship in the resonator with a cross-shaped slit. 1, 2, 3 - measurement points

Conclusions

1. The calculations show that the sound absorption of the resonator with a cross-shaped slit is strongly dependent on the number of resonators. As the number of resonators is increased, the sound absorption maximum is almost independent on frequency, whereas the absorption area is enlarged.
2. The real part of the slit impedance is dependent on the number of resonators at low frequencies only.
3. The imaginary part of the slit impedance is little-dependent on the number of resonators and on frequency.
4. The results of the experiment show that the maximum sound absorption of one resonator is obtained at 100 Hz and reaches 4-6 sq.m. depending on the point of measurement. The findings are similar to the results of calculation, with the only difference in frequency at which the maximum is achieved.
5. The sound absorption coefficients have their maximum of 0.17-0.27 at 100 Hz and vary from one point of measurement to another.
6. The reverberation time of the resonator peaks in the frequency range of 400-800 Hz, reaching as much as 0.8-1.2 sec.
7. The acoustical centre of gravity is concentrated in the frequency range of 400-800 Hz. The direct sound is of considerable importance in the energy distribution.

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VIENETINIO AKUSTINIO REZONATORIAUS SU KRYŽIAUS FORMOS PLYŠIU ABSORBCIJA IR JOS PRIKLAUSOMYBĖ NUO REZONATORIŲ KIEKIO

V. Stauskis

Santrauka

Teoriškai nagrinėjama vienetinio, didelių matmenų akustinio rezonatoriaus su kryžiaus formos plyšiu garso absorbcijos, plyšio impedanso realių ir menamų dalių priklausomybė nuo rezonatorių kiekio. Skaičiavimais nustatyta, kad garso absorbcija priklauso nuo rezonatorių kiekio. Vienas rezonatorius, kurio plotas 4,3 m², o plyšio plotis 50 cm esant 125 Hz absorbuoja apie 5 m² garso energijos. Kai rezonatorių skaičius padidėja iki 2, absorbcija siekia 27 m². Didėjant rezonatorių skaičiui iki 4,6 ir 8, garso absorbcijos plotas atitinkamai padidėja iki 180, 400 ir 900 m². Didėjant rezonatorių skaičiui, platėja dažnių sritis, kurioje garso absorbcija turi dideles reikšmes.

Plyšio impedanso realios dalys, didėjant rezonatorių skaičiui mažėja ir jos auga didėjant dažniui. Tai ypač ryšku esant žemiems dažniams. Plyšio impedanso menamos dalys, didėjant rezonatorių skaičiui, mažai priklauso nuo dažnio ir esant žemiems dažniams jos mažėja, didėjant rezonatorių skaičiui.

Eksperimentiniai tokio rezonatoriaus tyrimai rodo, kad maksimali jo absorbcija esant 100 Hz siekia 4-6 m^2, ir tai priklauso nuo matavimo taško. Toks rezonatorius, kurio tūris yra tik 7,8 m^3, turi didelį reverberacijos laiką. Matuojant pagal lygį 0 - 30 dB, jo maksimalios reikšmės dažnių diapazone 400 - 800 Hz siekia 0,8 - 1,2 s. Ankstyvas reverberacijos laikas siekia 1 - 1,4 sekundes ir turi ryškų maksimumą esant vidutiniams dažniams. Šis rodiklis taip pat priklauso nuo matavimo taško.

Akustinio svorio centro reikšmės siekia maksimumo esant vidutiniams dažniams. Jo reikšmės šiame diapazone yra žymiai didesnės negu esant žemiems ir aukštiems dažniams. Šis rodiklis gerai koreliuoja su ankstyvuoju reverberacijos laiku.

Garso absorbcijos koeficiento kitimo charakteris yra toks pat, kaip ir garso absorbcijos. Jo maksimalias reikšmes gauname esant 100 Hz, jos siekia 0,17 - 0,27 ir priklauso taip pat nuo matavimo taško. Tai rodo, kad vienetinis rezonatorius su kryžiaus formos plyšiu gerai absorbuoja garso energiją esant žemiems dažniams ir kad garso laukas rezonatoriuje yra netolygus.

Toks rezonatorius ne tik gerai absorbuoja garso energiją, bet ir didelę jos dalį grąžina atgal į aplinką. Toks akustinis reiškinys gali padėti koreguojant jau pastatytos salės akustiką, tam visai nenaudojant garsą absorbuojančių medžiagų.

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