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Nekateri analitični prijemi v sobni akustiki

Some Analytical Aspects of Room Acoustic

Ferdinand Deželak

Pri izbiri novih strojev in naprav je treba posvetiti pozornost tudi njihovemu hrupu. Nekateri izdelovalci terjajo dobro zvočno absorpcijo v prostorih, kjer bo njihova hrupna oprema nameščena. To zahtevo utemeljujejo z zmanjšanjem odmevnosti in s tem tudi celotnega hrupa. V ta namen zahtevajo dovolj majhne vrednosti odmevnega časa, oziroma zadosten padec ravni zvočnega tlaka z oddaljenostjo, kar je mogoče doseči z ustreznimi zvočno absorpcijskimi materiali v prostoru. Vendar pa sama uporaba zvočno absorpcijskih materialov ne zagotavlja zadostnega zmanjšanja hrupa, še zlasti ne v bližini hrupnega vira, ker je tako mogoče vplivati samo na odmevni del zvočnega polja.

V tem članku so opisane nekatere analitične raziskave o uspešnosti tovrstnih posegov.

(Ključne besede: akustika prostorov, absorberji, zmanjševanje hrupa, tlaki zvočni)

When choosing new machinery, equipment and installations, consideration must be given to the noise disturbance that it could produce. Some manufacturers of noisy equipment demand good sound absorption characteristics in workshops when installing such machinery. This requirement is set in order to reduce the reverberant portion of the total sound pressure level and thus to prevent high overall noise levels. A low reverberation time or a sufficient drop in the sound pressure level with distance is required, and this can be achieved by properly setting up absorbing material within a room. However, noise reduction by sound absorption alone will seldom prove completely satisfactory, especially close to a noise source, since only the reverberant portion can be reduced by placing absorbing materials on the surfaces of the room.

In this paper analytical investigations are given of some conditions under which the treatment of workshops is still practical.

(Keywords: room-acoustic, absorbers, noise reduction, sound pressure)

0 UVOD

Z zmanjšanjem odmevnosti običajno ni mogoče doseči večjega znižanja ravni hrupa na delovnih mestih. Takšen poseg je namreč primeren le v odmevnih prostorih, izpostavljena oseba pa mora biti hkrati v izrazito odmevnem delu zvočnega polja. Zato je pomembno ugotoviti delež zvočnega tlaka, ki ga lahko pripišemo neposrednemu oziroma odmevnemu polju. V točkah z izrazitim odmevnim poljem imamo lahko običajno hrupni vir kot točkovni vir. Pričujoča raziskava temelji na natančnejši analizi dobro znane enačbe:

0 INTRODUCTION

The reduction of the reverberant field is limited - as far as protecting personnel is concerned - to cases where the noise reduction desired is not great. Furthermore, the room must be reverberant and the exposed person must be in the reverberant field. Thus, it is often advantageous to be able to ascertain what portion of the sound pressure is attributable to the direct field and what portion is due to the reverberant field. At points where the reverberant field is considerable, the noise source can usually be regarded as a point source. This investigation is based on further analysis of the well-known equation:

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \quad (1)$$

kjer pomenijo:
raven zvočnega tlaka L_p v dB glede na 2×10^{-5} Pa, raven zvočne moči L_w v dB glede na 10^{-12} W, faktor usmerjenosti Q, oddaljenost od vira do preiskovane točke r v m, sobno konstanto R v m^2.

with symbols as follows:
sound pressure level (SPL) L_p in dB re 2×10^{-5} Pa, sound power level, L_w in dB re 10^{-12} Watt, directivity factor Q, distance from source to point of interest r in m, room constant R in m^2

Prvi člen v oklepaju pomeni prispevek neposrednega, drugi pa odmevnega zvočnega polja. Pričujoča analiza omogoča preprosto oceno pomembnosti teh dveh prispevkov.

The first term in the brackets indicates the contribution of the direct field and the second term is that of the reverberant field. The analysis presented provides a simple means of estimating the relative importance of these standard reverberant field and direct field levels.

1 SPREMEMBE PRI UPORABI ABSORBERJEV V SOBI

1 CHANGES DUE TO ROOM TREATMENT BY ABSORBERS

Akustične lastnosti zaprtih industrijskih prostorov večinoma podajamo s sobno konstanto ali z njenimi izpeljankami. V prostoru s sobno konstanto R_1 in odmevnim časom T_1 lahko raven zvočnega tlaka L_{p1} na oddaljenosti r popišemo z enačbo:

In most industrial environments, the acoustic characteristics can be defined in terms of a room constant. Consider the radiation of sound energy from a noise source within an enclosed space with room constant R_1 and reverberation time T_1. At distance r, its sound pressure level L_{p1} is given by:

$$L_{p1} = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R_1}\right) \qquad (2).$$

Sobno konstanto največkrat določimo iz izmerjenega odmevnega časa in znanih geometričnih lastnosti prostora:

It is common practice to determine the room constant by measuring the reverberation time and geometrical properties of the room:

$$R_1 = \frac{S}{\frac{T_1 S}{0{,}163V} - 1} \qquad (3),$$

kjer S in V označujeta površino (m^2) oziroma prostornino (m^3) prostora.

where S and V respectively denote the area (m^2) and volume (m^3) of the room.

Predpostavimo, da želimo v določeni točki prostora znižati raven zvočnega tlaka na vrednost L_{p2} z uporabo zvočno absorpcijskih materialov. Zato je treba povečati vrednost sobne konstante na R_2, kar ustreza znižanju odmevnega časa s T_1 na T_2. Po takšnem posegu velja enačba:

Assume that we want to reduce sound pressure level to L_{p2} at this point by using additional sound absorption materials. The room constant must consequently increase to R_2, which corresponds to a reduction of reverberation time from T_1 to T_2. After this treatment we have the equation:

$$L_{p2} = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R_2}\right) \qquad (4)$$

in

and

$$R_2 = \frac{S}{\frac{T_2 S}{0{,}163V} - 1} \qquad (5).$$

Če odštejemo enačbo (4) od (2), dobimo znižanje ravni zvočnega tlaka L na tej točki kot posledico takšne poprave:

Upon subtracting (4) from (2), we obtain the decrease in sound pressure level L at this point because of the treatment:

$$L_{p1} - L_{p2} = \Delta L = 10\log\frac{R_2\left(QR_1 + 16\pi r^2\right)}{R_1\left(QR_2 + 16\pi r^2\right)} \qquad (6).$$

Ta enačba omogoča oceno zmanjšenja hrupa pri povečanju sobne konstante z vrednosti R_1 na R_2. Odmevni čas lahko med popravo natančno merimo, kar omogoča preskus zahtevanega znižanja ΔL na dani točki. Z antilogaritmiranjem in preureditvijo enačbe (6) dobimo:

This equation enables one to estimate the noise reduction when the room constant increases from R_1 to R_2. Since the reverberation time during acoustical treatment of the room can be accurately measured, this procedure can be used to verify the moment / time when a supposed reduction ΔL at a given point is achieved. Taking the antilogarithm of (6), this relationship can be solved to yield:

$$R_2 = \frac{16\pi r^2 R_1 10^{\frac{\Delta L}{10}}}{16\pi r^2 + QR_1 - QR_1 10^{\frac{\Delta L}{10}}} \qquad (7).$$

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Po primerjavi (5) in (7) lahko izrazimo maksimalno vrednost odmevnega časa, ki še omogoča zahtevano zmanjšanje hrupa:

After inserting (5) for $\boldsymbol{R_2}$, the highest acceptable reverberation time which satisfies the specified reduction can be expressed as:

$$T_2 = 0{,}163V\left(\frac{1}{S} + \frac{16\pi r^2 + QR_1 - QR_1 10^{\frac{\Delta L}{10}}}{16\pi r^2 R_1 10^{\frac{\Delta L}{10}}}\right) \quad (8).$$

2 OMEJITVE

2 LIMITATIONS

Naslednja praktična uporaba takšnih analiz se nanaša na določitev najmanjše oddaljenosti ***r'*** od hrupnega vira, za katero je obravnavano zmanjšanje hrupa še dosegljivo. Če zahtevamo zmanjšanje ravni hrupa vsaj **ΔL'** , morajo vse kritične točke ležati na oddaljenostih, večjih od določene vrednosti ***r'***. S preureditvijo (7) lahko zapišemo izraz za to oddaljenost v obliki:

The next practical question which may be useful concerns the determination of the smallest distance ***r'*** from noise source at which room acoustical treatment is still reasonable. If attenuation of at least **ΔL'** is required, all critical points must lie at distances larger than ***r'***. Upon rearranging (7), this distance may be written as:

$$r' = +\sqrt{\frac{R_2 QR_1\left(10^{\frac{\Delta L'}{10}} - 1\right)}{16\pi\left(R_2 - R_1 10^{\frac{\Delta L'}{10}}\right)}} \quad (9).$$

Iz **ΔL'** > 0 izhaja, da je $10^{\frac{\Delta L'}{10}} > 1$, zato je števec pozitiven. Ker nas zanimajo samo realne vrednosti za ***r'***, mora biti pozitiven tudi imenovalec, iz česar izhaja naslednja neenačba:

The fact that **ΔL'** > 0 implies that $10^{\frac{\Delta L'}{10}} > 1$ and the numerator is consequently positive. In order to ensure real values for ***r'*** only, the denominator must be positive as well, which leads to the following inequality:

$$R_2 > R_1 10^{\frac{\Delta L'}{10}} \quad (10).$$

Če ta neenačba ni izpolnjena, postane ***r'*** imaginaren. To pomeni, da nikjer v prostoru ni mogoče doseči zahtevanega znižanja hrupa. Z drugimi besedami, samo z uporabo zvočno absorpcijskih materialov ne moremo doseči občutnejših znižanj ravni hrupa, ker sobne konstante ni mogoče povečevati prek vseh mej.

Po drugi strani pa obstajajo omejitve zmanjšanja hrupa, celo v primeru idealne akustične absorpcije v prostoru. Vzrok za to je navzočnost neposrednega zvočnega polja. V mejnem primeru, ko $R_2 \to \infty$, dobita enačbi (6) in (9) naslednjo obliko:

If this inequality does not hold, ***r'*** becomes imaginary. This means that there are no such points in the room where the required reduction in SPL can be achieved. In other words, if high reduction of SPL is required, this would be very hard to realize by using sound absorbent material only, since the room constant cannot in practice be increased infinitely.

On the other hand, even under ideal acoustical treatment of the room, the reduction of SPL cannot exceed the value which is dictated by the presence of a direct sound field. In order not to overestimate this kind of reduction, we consider its maximal possible attenuation, when $R_2 \to \infty$. In this limit case, equations (6) and (9) take the following form:

$$\Delta L = 10\log\left(1 + \frac{16\pi r^2}{QR_1}\right) \quad (11),$$

$$r' = +\sqrt{\frac{QR_1\left(10^{\frac{\Delta L'}{10}} - 1\right)}{16\pi}} \quad (12).$$

Zlasti pomembna je enačba (11), ki napoveduje največje mogoče zmanjšanje hrupa v dani točki, pri uporabi zvočno absorpcijskih materialov v sobi. Pri tem je ***r'*** najmanjša oddaljenost od hrupnega vira, pri kateri je takšen poseg še primeren.

Ta dva izraza veljata torej za primer prostega zvočnega polja, brez odbojnih površin. Dober približek za takšno stanje pomeni razširjanje hrupa na prostem (edina odbojna površina so tla).

Of special importance is equation (11), as it predicts the maximum possible noise attenuation at given points using only sound absorbent material in the room: ***r'*** is the smallest distance from the noise source at which acoustical treatment is still reasonable.

These are the expressions applyed when the source is in free field conditions, i.e. no reflecting surfaces are present, a condition to which the situation outdoors is an approximation (the only reflecting surface is the ground).

3 GRADIENT ZVOČNEGA TLAKA

Nadaljujmo nalogo z določitvijo gradienta ravni zvočnega tlaka v zaprtem prostoru, v odvisnosti od oddaljenosti ***r***. Čeprav gre za vektorsko količino, nas v prvi vrsti zanima njegova vrednost x v radialni smeri, v skladu z najhitrejšim pričakovanim padcem ravni zvočnega tlaka. Z odvajanjem enačbe (1) po r, dobimo:

$$\frac{d\left(L_p - L_w\right)}{dr} = 10M \frac{-\frac{2Q}{4\pi r^3}}{\frac{Q}{4\pi r^2}+\frac{4}{R}} = \frac{-20QMR}{r\left(QR+16\pi r^2\right)} \qquad (13),$$

kjer M = log e = 0,43429.

Pri tem se izkaže primerno preoblikovanje diferenciala argumenta r v logaritemsko obliko, kjer podvojitvi oddaljenosti ustreza prirastek 3 dB na dolžinski osi. Na oddaljenosti r lahko tako pričakujemo padec x dB pri podvojitvi oddaljenosti:

$$\frac{d\left(L_p - L_w\right)}{d\left(10\log r\right)} = \frac{x}{3} \qquad (14).$$

Razrešimo diferencial v imenovalcu:

$$d\left(10\log r\right) = 10M\frac{dr}{r} \qquad (15)$$

in vstavimo (15) v (14), kar da:

$$\frac{d\left(L_p - L_w\right)}{dr} = \frac{10Mx}{3r} \qquad (16).$$

Z izenačitvijo (13) in (16) dobimo:

$$\frac{20QMR}{r\left(QR+16\pi r^2\right)} = -\frac{10Mx}{3r} \qquad (17)$$

in

$$x = \frac{-6QR}{QR+16\pi r^2} \qquad (18).$$

Ta izraz pomeni fizikalno osnovo za oceno jakosti odmevnega polja na tem mestu. Negativni predznak poudarja dejstvo, da se raven zvočnega tlaka znižuje z oddaljenostjo. Za točke blizu vira (toda dovolj oddaljene, da lahko zanemarimo učinke bližnjega polja) lahko tako pričakujemo padec -6 dB pri podvojitvi oddaljenosti. Na velikih oddaljenostih, kjer prevladuje odmevno polje, se to zmanjšanje očitno približuje ničli. Z dvakratnim odvajanjem (1) po r dobimo:

$$\frac{d^2\left(L_p - L_w\right)}{dr^2} = -\frac{20QMR\left(QR+48\pi r^2\right)}{r^2\left(QR+16\pi r^2\right)} \qquad (19).$$

Tako lahko opišemo hitrost sprememb zvočnega polja pri prehodu iz neposrednega v odmevno polje. Blizu vira $(r \to 0)$ so te spremembe nagle, medtem ko na velikih oddaljenostih $(r \to \infty)$ postanejo zanemarljive.

3 SOUND PRESSURE GRADIENT

We will now proceed to the determination of the gradient of sound pressure level in an enclosed space as a function of r. Although this is a vector quantity, we are mainly interested in its value x in a radial direction in accordance with the fastest expected decrease on SPL. Differentiating equation (1) with respect to r, we get: (13),

where M = log e = 0.43429.

It will prove to be more advantageous to transform the differential of argument r into a logarithmic form, where doubling the distance means an increment of 3 dB on a distance scale. At distance r, a drop of x dB can be expected when doubling the distance: (14).

Upon expanding the differential in the denominator: (15)

and substituting (15) in (14) we obtain: (16).

Upon equating (13) and (16) we find: (17)

and (18).

This provides a physical basis for assessing the strength of the reverberant field at a given position. The negative sign indicates that SPL decreases with distance. For points situated close to a source (but far enough so that the near - field effects can be neglected), a drop of -6 dB when doubling a distance can be expected if, from these points outwards, the sound field is assumed to be homogeneous. On the other hand, at long distances, where the reverberant field predominates, this attenuation clearly approaches zero. Taking the second derivative of (1) with respect to r, we obtain: (19).

This allows a description of the speed with which the sound field changes its characteristics in its transition from a direct to a reverberant field. Close to the noise source $(r \to 0)$, these changes are considerable, while when they are far away $(r \to \infty)$, they become insignificant.

4 NASPROTNI PROBLEM

Sedaj poiščimo točke v prostoru, v katerih ima gradient ravni zvočnega tlaka vrednost x'. Z razrešitvijo kvadratne enačbe, zasnovane na (18), dobimo:

4 INVERSE PROBLEM

Here we are looking for such points in the rom, where the sound pressure level gradient takes the value of x' . Solving the quadratic equation based on (18) gives:

$$16\pi x' r'^2 + QRx' = -6QR \quad (20)$$

in

and

$$r' = +\sqrt{\frac{-QR(6+x')}{16\pi x'}} \quad (21).$$

To omogoča določitev množice točk z zahtevanimi akustičnimi lastnostmi oziroma določitev oddaljenosti r' , pri katerih je tendenca nižanja ravni zvočnega tlaka x' dB z vsako podvojitvijo oddaljenosti. Ker leži definicijsko območje funkcije $r'(x')$ znotraj intervala (-6,0), je njena zaloga vrednosti popolnoma na realni osi. Podobno kakor v enačbi (9) je smiselna samo pozitivna rešitev.

Which enables the location of points with the required acoustics properties, i.e. , the determination of distance r' where the sound pressure level tends to drop x' dB per doubling a distance. Since the domain of the function $r'(x')$ lies within the interval [-6,0], its range attains only real values. As in equation (9), only the positive solution makes sense.

5 SKLEP

Enačba (1) se v sobni akustiki pogosto uporablja, zlasti v prostorih z običajnimi izmerami. Za takšne primere lahko gornje enačbe uporabimo za različne napovedi hrupa po določenih legah v takšnih zaprtih prostorih. Ker so obravnavane enačbe frekvenčno odvisne, je treba opisane postopke ponoviti za vse frekvenčne pasove. Že z uporabo preprostih računalniških programov to ne pomeni pomembnejših težav. Te enačbe lahko uporabimo pri načrtovanju novih delovnih mest in hrupnih virov, pri protihrupnih ureditvah ali pri akustičnih spremembah v prostoru. So tudi dober pripomoček pri oceni uspešnosti uporabljenih zvočno absorpcijskih materialov. Zelo pomembno je, da pri teh ocenah ne potrebujemo podatkov o ravneh zvočne moči, ki so v večini primerov teže dostopni.

5 CONCLUSION

The equation (1) is often used for rooms with an approximately constant reverberant level, especially for spaces with normal proportions. In this case, the set of equations given above provides an opportunity for some predictions of noise behavior at given locations within such an enclosed space. Since the equations discussed are frequency dependent, this procedure must be repeated for each frequency band of interest. Using a simple computer program this can easily be performed. These equations can be used in working locations and in noisy equipment design, in the planning of noise reduction, or when acoustic changes in the workshop are expected. This can be a useful tool for assessing the efficiency of sound absorbing materials. It is worth noting here that in these estimations, no data about sound power levels are necessary.

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