FACTA UNIVERSITATIS
Series: **Working and Living Environmental Protection** Vol. 5, N° 1, 2008, pp. 1 - 10

THE ACOUSTIC TREATMENT OF AN INDUSTRIAL HALL

UDC 534.322

Nikola Holeček[1], Radivoje Bošnjaković[2]

[1]Head of Acoustics Dept., Administrative Head of Research Facilities, Gorenje d.d., Partizanska 12, SI-3503 Velenje, Slovenija, nikola.holecek@gorenje.si
[2]RAI d.o.o., Dunajska 128, SI-1000 Ljubljana, Slovenija

Abstract. *The acoustical conditions in Gorenje manufacturing plant were very unfavorable. The measurement of the medium equivalent noise levels yielded results in the interval from 88 to 102 dBA. An inspection and reference measurements indicated a difficult problem that involved exceeding the permitted noise level considerably; furthermore, the noise was of an impulse character. Last but not least, the frequencies most harmful to human health were also present. The primary sources of the noise consist of several noise sources: drive mechanisms, pneumatic systems, hydraulic systems, tools, material input/output mechanisms, mechanical brakes, etc. To start with, the process of sound transfer from particular sources was analyzed. We focused on the method of generating vibrations and transfer into the environment (floor, walls, and other mechanical structures). The correct application reduced the vibrations and/or dispersion of the noise generated by the machines. The first stage of the restoration included active noise reduction measures at the sources (tool machines, hydraulic pumps, electric drives, etc.). In the second stage of the restoration, noise dispersion from the source to the environment was prevented by setting up various barriers, screens, etc. In the third stage, we used cylindrical and prismatic noise absorbers to reduce the reflected noise (echo).*

Key Words: *Industrial noise, Noise reduction, Reverberation control, Sound isolation*

1. INTRODUCTION

There are several noisy presses and similar machines installed in the production hall, which are the main source of noise in these premises. The noise in a problem not only for the workers who operate the machines and are exposed to it, but also for other workers in the hall as well as for other staff and visitors who occasionally spend some time in the hall. As a rule, the latter are not exposed to particular risks of hearing damage due to the noise; however, communication and concentration are seriously disturbed. The hall consists of four production parts: bath line, cutting line, press and storage, drum and housing line [1].

Received October 8, 2008

The production hall walls are rigid and the ceiling has mainly reflexive characteristics. This results in a substantial reverberating field on the premises. This in turn resulted in an interference between direct and bounced waves, and high levels of noise on the premises, not only directly at the source of noise but also at greater distances, practically all over the hall. It was very difficult to communicate at greater distances.

As a rule, speech communication is disturbed in bigger rooms (dimensions exceeding 17 m) where the time difference between the direct and bounced sound reaching the ear exceeds 50 ms. A bounced sound wave results in increased noise in the hall, and workers as well as occasional visitors are exposed to it [2].

2. Description of the Production Hall Prior to the Rehabilitation

It was necessary to assess the equivalent sound-absorbing surfaces of individual materials or parts along the workshop walls, ceiling and floor:

1. Floor, concrete - smooth: 9200 m^2 with an average sound-absorbing coefficient of 0.04 and sound-absorbing surface of 368 m^2
2. Profile sheet metal surfaces, roof and walls: 6100 m^2 with an average sound-absorbing coefficient of 0.1 and sound-absorbing surface of 610 m^2
3. Concrete roughcast wall surfaces: 4365 m^2 with an average sound-absorbing coefficient of 0.3 and sound-absorbing surface of 1310 m^2
4. Rough concrete ceiling surfaces: 3635 m^2 with an average sound-absorbing coefficient of 0.3 and sound-absorbing surface of 1090 m^2
5. Glass: 410 m^2 with an average sound-absorbing coefficient of 0.02 and sound-absorbing surface of 8 m^2
6. Metal pillars, machines, processors and other similar metal material in the hall: about 1500 m2 with an average sound-absorbing coefficient of 0.1 and sound-absorbing surface of 150 m^2
7. Concrete pillars: approximately 1000 m^2 with an average sound-absorbing coefficient of 0.3 and sound-absorbing surface of 300 m^2

The total surface is about 26,210 m^2, while the equivalent sound-absorbing surface was 3,835m^2, volume 79,000 m^3 of which 90% is free volume in hall, that is, about 70,000 m^3. The average sound-absorbing coefficient was 0.15. A similar value was obtained from the average measured reverberation times, calculated with the help of the Sabin formula, which is described in detail more in the chapter below. The sound-absorbing coefficients of individual materials by octave frequency bands had to be taken into account in order to conduct a more detailed analysis. Estimations by individual frequencies are shown in the table below:

Table 1. Sound-absorbing coefficients of materials used in individual parts of the hall

	Frequency (Hz)						
Material	125	250	500	1000	2000	4000	8000
smooth concrete	0.02	0.03	0.03	0.04	0.05	0.05	0.04
window surfaces	0.1	0.04	0.03	0.02	0.02	0.02	0.04
smooth profile plate	0.06	0.2	0.15	0.14	0.1	0.05	0.12
rough concrete	0.3	0.4	0.3	0.3	0.4	0.3	0.3

In addition to the absorption due to the porosity of the materials, resonator absorption was also present to a lower extent due to concave surfaces on some parts of the presses and other machines, profile pillars and the like. Membrane absorption is negligible, as the plates (machine housings and similar) are mostly thick and solid and therefore their oscillation, and consequently absorption, is low, and is more substantial only at very low frequencies which are not relevant in our case.

3. Assessment and Measuring Method

3.1. Estimation of reverberation time and its impact on the noise

Firstly, the acoustic qualities of the room are described by a sound-absorbing coefficient or reverberation time. The longer the reverberation time, the worse the absorption in the room and consequently more noise and speech which cannot be understood [3]. Reverberation time is defined as the amount of time it takes for the sound pressure to drop by 60 dB after the end of the sound signal. In practice, it is defined by 20 dB (T_{20}) and 30 dB drops (T_{30}), which are extrapolated to the value of 60 dB drop.

Reverberation time T is connected with the absorption in the room by means of the Sabin equation

$$A = 0.163\frac{V}{T} = S\alpha \tag{1}$$

Where A is the equivalent absorption surface of the room, V is the volume, S is the total surface of all the walls, and α is the average sound-absorbing coefficient in the room. The existing absorption surface can be increased by mounting additional sound-absorbing materials on the internal surfaces of the production hall or along the ceiling. Strictly speaking, absorption in the air should also be taken into account; however, it is relevant only at high frequencies, exceeding 2 kHz.

$$T = 0.163\frac{V}{-S\ln(1-\alpha)} \tag{2}$$

The Sabin equation is applied with success to small sound-absorbing coefficients, values up to 0.2. However, the Eyring equation is usually applied to higher values of the sound-absorbing coefficient (which are expected after the rehabilitation), so that the equivalent absorption surface is expressed as

$$A = -S\ln(1-\alpha) \tag{3}$$

When sound-absorbing material with an absorption coefficient α_n and surface S_n is selected and mounted below the ceiling (the reduction of the volume of the room is minor), the reverberation time is decreased accordingly to the value T_1, based on the following equation

$$T_1 = \frac{0.163V}{S\alpha + S_n\alpha_n} \tag{4}$$

An increased absorption coefficient in the production hall would result in shorter reverberation time and thus lower general level of noise. Decrease of the noise level ΔL

depends on the change in reverberation time and it is expressed by means of the following equation

$$\Delta L = 10\log\frac{A_2}{A_1} = 10\log\frac{T_1}{T_2} \qquad (5)$$

where A_1 is the equivalent absorption surface of the hall prior to rehabilitation, and A_2 following the rehabilitation. Similarly, T_1 stands for the original reverberation time and T_2 for reverberation time when absorption has been added. It can be seen from the equation that the general level of noise in the production hall may be decreased by 3 dB, if the reverberation time is halved, while a four-time shorter reverberation time would also mean four-time lower noise energy values, or the level of noise would fall by 6 dBA, and a ten-time decrease by 10 dB.

In practice, a decrease of 10 dB is the upper limit which may be achieved by such measures. In our case a good reduction of the general level of noise in the hall can be expected. This is due to the emphasized ground plan dimensions of the space, which are several times longer than the height of the hall, and to a certain extent this space behaves like a two-dimensional space. Only the cutting department does not have this feature. In such spaces it is sensible to focus on the highest possible absorption of the ceiling, and also the floor, if possible; however, it is hardly feasible on the floor. This reduction could result in acceptable levels of noise and communication would be made significantly easier.

A further decrease of the general level of noise may be achieved by interventions on the sources of the noise themselves (sound insulated enclosures) and by enclosing the machines (insulation-absorption screens for machines) in their direct vicinity. The successful decrease of the noise level with new sound-absorbing materials mainly depends on the distance from the source(s) of noise, the existing absorption and size and shape of the space. In such space, sound consists of two components: a direct and indirect one. The indirect is a consequence of reverberations in space. In the vicinity of a noisy source the direct component prevails, and its level falls more rapidly in relation to the distance. At longer distances noise is reduced mainly because of absorption. In order to assess the success of noise reduction by mounting sound-absorbing materials, distances at which the reverberation noise component starts to prevail have to be defined. The sound power L_W of individual sources of noise is constant; however, the emission level of their sound pressure L_p changes with distance. The following equation describes their relationship in a given space with an average room constant R at a distance of r

$$L_p = L_W - 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \qquad (6)$$

Q is the direction factor. In our case it is approximated by the value 2, because machines are on the floor, that is above a horizontal, reverberating surface and are mostly at a sufficient distance from the walls. The first part in brackets on the right of the equation represents the contribution of the direct sound field from the source, and the second is the impact of the reverberation. Absorption starts becoming efficient when the second part becomes bigger than the first, that is

$$\frac{4}{R} > \frac{Q}{4\pi r^2} \qquad (7)$$

Or

$$r > \sqrt{\frac{QR}{16\pi}} \qquad (8)$$

The room constant is connected to absorption through the following equation

$$R = \frac{S\alpha}{1-\alpha} = \frac{A}{1-\alpha} \qquad (9)$$

where A is the equivalent absorption surface. Therefore, increased absorption has no effect on locations close to the sources of the noise, while it is efficient at greater distances. For proper absorption with an average sound-absorbing coefficient of 0.8 to 0.9 they, for cases involving distances, exceed $0.5\sqrt{A}$. In general, in the process of rehabilitation with sound-absorbing materials, a minimum value of the new room constant R_2 min has to be ensured, in accordance with the following equation:

$$R_{2\ \min} > R_1\ 10^{\ 0.1\ \Delta L} \qquad (10)$$

where ΔL is the required reduction of the noise level due to the increase of the room constant from the original value R_1.

In this regard the critical distance of r_c from the source of the noise is important, from where the required reduction of noise by ΔL is achieved when the room constant is increased from value R_1 to R_2:

$$r_c > \sqrt{\frac{R_2 Q R_1 (10^{0.1\Delta L} - 1)}{16\pi(R_2 - R_1 10^{0.1\Delta L})}} \qquad (11)$$

For spaces where one ground floor dimension is substantially longer than the height, reverberations from fitted walls have a minor effect, while the indirect component is mainly the consequence of reverberations between the floor and the ceiling [4].

Therefore, in such spaces it is reasonable to install absorption along the ceiling so that its average sound-absorbing coefficient exceeds the value of 0.9. In this case successful reduction does not depend only on the distance from the source, but also on the height of the ceiling. Better reduction is provided by a low ceiling than by a high one.

There are no universal recipes for the distribution of sound absorbers; however, in general, higher concentration is recommended above or in the vicinity of presses and other major sources of noise. In this way absorbers cover a bigger space angle than by being in the centre in noisy sources, and therefore a lower number of absorbers are required. The reduced indirect (reverberating) component of noise results in increased "acoustic comfort", better understanding of speech and it is also easier to assess where the noise is coming from, which is often an important factor for ensuring general safety at work in the hall [5].

3.2. Reverberation time measurements

Bruel & Kjaer instrumentation (precise modular sound meter Investigator, type 2260, with a module for construction acoustics BZ 7204, version 2) was used to measure reverberation times. A broadband impulse source of banger explosions, which were triggered at different locations in the hall, was used as the source of the sound [6]. The space reactions to those explosions were measured in different parts of the hall.

3.3. Measuring the level of noise in the hall

Measurements were done at several typical locations of the hall when most presses and other sources of noise were operating. In addition, a spectral analysis of noise in a 1/3 octave-band as shown on the graph in Figure 2 was conducted. Measuring points were selected to correspond to locations where reverberation times were examined [7].

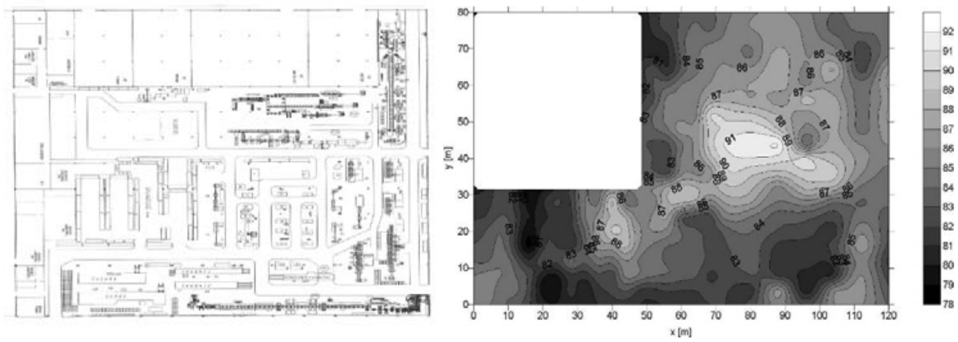

Fig. 1. Location of sources of noise (on the left) and
the sound pressure level field in hall (on the right)

The B&K noise meter type 2260, No. 1933831, equipped with a microphone type 4189, No. 2143114 was used. Internal calibration was conducted prior to the measurement.

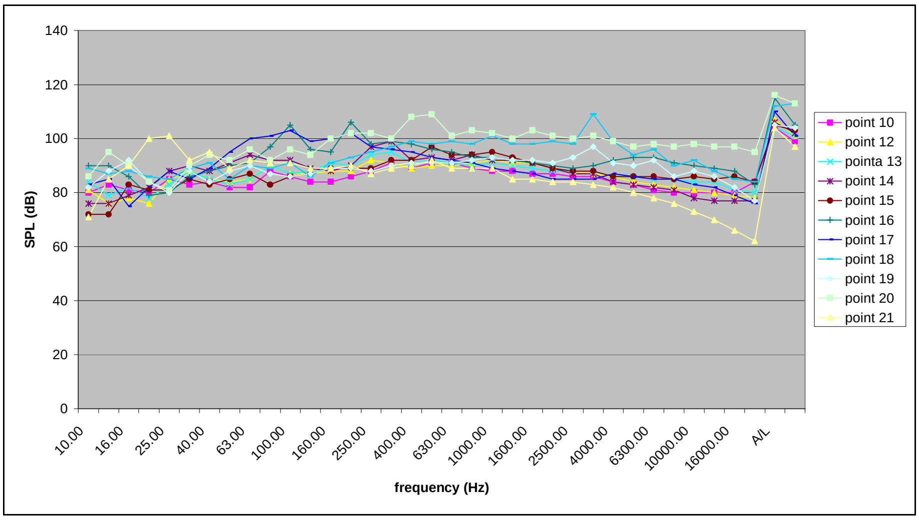

Fig. 2. 1/3 octave-band noise levels in the hall

4. ACOUSTIC TREATMENT

4.1. Discussion of the proposed measures

According to its geometric and acoustic characteristics, the hall in question is extremely heterogeneous. The height of the ceiling is different in different parts, and on the other hand, the ceilings and walls are not made of the same materials in all the parts of the hall. Additional problems are also caused by presses and other bigger objects in the hall, whose noise is absorbed only partly and a substantial part of it is reverberated. Due to the geometric shapes of these obstacles the picture of the reverberation field in their surroundings is complex. Therefore, the sizes and spectrum characteristic of the reverberation times are also different in different parts of the hall. In general, reverberation times are higher in the parts where the ceiling is the highest; their maximum is about 800 Hz.

High frequency components up to 10 kHz appeared in the noise spectrum of presses and similar machines, mainly as the consequence of impulsive pneumatic releases. In this area, reverberation times were about 2 s. In addition, lower frequency components were present during cutting or strokes, as a consequence of the resonance oscillations of individual constructions on presses from 300 Hz upward. The measured reverberation times in this part were about 3 s, except in parts with low ceilings or additional space limitations. In general, the frequency noise spectrums, due to work processes in the hall, were significant in the range from 300 Hz to 6 kHz. It is important that a substantial part of the noise energy is present at frequencies of about 1 kHz, where the hall response in general is the strongest.

The existing equivalent absorption surface is about 4000 m^2, and additional sound-absorbing materials would at least double it. This means that it is possible to decrease noise by more than 3 dB at distances of more than 20 m from individual noisy machines. It was recommendable to reach an additional 6000 m^2 of absorption surface, effective in the range of 250 Hz – 8 kHz.

4.2. Sound absorbers

Installation of two types of absorbers doubled the active absorption surface within the production hall, shortened reverberation time and decreased the general level of noise in the hall. Noise absorbers were installed on the ceiling of the production hall, with an increased number above the spots of noise emission.

Fig. 3. Sound absorber field

4.3. Acoustic barriers

Measurements of the emission of noise by the presses revealed that the major part of noise emissions is generated in these areas (noise levels exceed 90 dB) and results in excessive burden of the Press hall itself as well as other parts of the hall. Movable sound absorbing barriers were placed on the floor between individual machines in the Press hall. The installation of acoustic barriers prevents the emission of noise from the source of noise into the surroundings (Figure 4.).

Fig. 4. Sound absorbing barriers on the floor between individual machines.

4.4. Acoustic deflectors

Acoustic deflectors prevent the emission of noise, here mainly of an impulsive character, to the neighboring work places, along the transport paths or the entire hall (Figure 5.).

Fig. 5. Acoustic deflectors on the machines.

4.5. Sound insulated enclosures for the reduction of noise

As the installation of noise absorbers was not sufficient, individual machines were enclosed into sound insulated booths (Figure 6.)

Fig. 6. Noise level of individual machines was reduced by sound insulated enclosures

5. SUMMARY

Acoustic absorbers, barriers, deflectors and booths did very well in practice. It resulted in reduced reverberation time, reduced level of noise and much better understanding and communication of workers in the production hall. Final noise reduction results are shown in Table 3 [8].

Table 3. Values of Equivalent noise level in the untreated and treated hall

Equivalent noise level in the untreated and treated hall	
Equivalent noise level $L_{A\,eq}$ before the noise reduction	Equivalent noise level $L_{A\,eq}$ after the noise reduction
90,1	80,3

REFERENCES

1. HOLEČEK, N. Noise reduction in the Gorenje industrial hall. V: 15th International Congress on Sound and Vibration, ICSV15, Daejeon, Korea, 2008. *Proceedings*. Seol: The Korean Society for Noise and Vibration Engineering, 2008, str. 2269-2276
2. Deželak, F.: “Analysis of surface absorptive treatment in enclosed spaces, with applications”, Journal of Sound and Vibration., 179(2), 3627-368, (1995)
3. M. J. Crocker, Noise and vibration control, John Wiley &Sons, Inc. 1997.
4. Bošnjaković, R. Tomić D. : Acoustical treatment of multipurpose sport halls, proceedings of 3rd Congress of the Alps Adria Acoustics Association, 27–28 September 2007, Graz – Austria
5. HOLEČEK, N. Noise control by sound isolation at Gorenjes manufacturing plant. V: The 37th International Congress and Exhibition on Noise Control Engineering, Shanghai, China, 2008. *Proceedings of Inter-Noise 2008 : from silence to harmony*. [S. l.]: [Institute of Acoustics, Chinese Academy of Sciences], 2008,

6. D. Cvetković, M. Manić, M. Praščević, S. Milutinović, "Acoustic comfort optimization of industrial hale using intelligent technology", Facta Universitatis, Series: Working and Living Environmental Protection, pp. 9-18, 1999, Niš
7. *"Acoustics - Recommended practice for the design of low-noise workplaces",* SIST EN ISO TR 11690-1, 2, 31995, Slovenia organization for standardization, Ljubljana Slovenia
8. *Guidelines for the measurement and assessment of exposure to noise in a working environment:*, International Standard ISO 9612 (International Organization for Standardization, Geneva, Switzerland, 1997).
9. *Sound Level Meters*, International Standard IEC 651:1979 (International Electrotechnical Commission, Geneva, Switzerland, 1979).

AKUSTIČNA OBRADA INDUSTRIJSKIH HALA

Nikola Holeček, Radivoje Bošnjaković

Akustični uslovi u industrijskoj hali u Gorenju su bili izuzetno nepovoljni. Prisutno je bilo više od 50 različitih izvora koji emituju buku izvan dozvoljenih granica. Srednji ekvivalentni nivo buke se kretao u intervalu od 88 do 102 dBA. Merenja su pokazala izuzetno kompleksan problem prekoračenja buke koja je pored toka bila impulsnog karaktera. Prisutne su bile frekvence na frekventnom području vrlo neprijatnim što se tiče subjektivne percepcije i štetnom za ljudsko zdravlje. Primarni izvori buke su bili sastavljani od niza različitih sekundarnih izvora: pogonski i transportni mehanizmi, pneumatski alati, hidraulični sistemi, mehanički kočioni uređaji itd. Na početku sanacije buke smo analizirali mehanizme generiranja vibracija i njihovo prenošenje na druge strukture koje emituju buku. Za redukciju buke je najbolja primarna metoda na samim izvorima odnosno na mestu generisanja vibracija. Ako ta tretman ne dovede do zadovoljavajuće redukcije, pristupa se blokiranju prenosa vibracija na druge strukture koje šire buku u prostor. Upotrebljeni materijal, oblik, pozicija, broj akustičnih elemenata, dimenzije i vrste međusobne sprege imaju veliki uticaj na emisiju buke. Pravilni akustički tretman može bitno uticati na redukciju buke u prostor. U prikazanom primeru industrijske hale smo u prvom koraku upotrebili aktivne metode na primarnim izvorima. U drugoj fazi smo upotrebili pasivne metode koje su uključivale upotrebu pregrada, akustičnih zavesa i perforiranih ploča ispunjenje sa poroznim materijalom. U trećem koraku smo upotrebili porozne materijale u obliku površinskih i zapreminskih apsorbera cilindričnog i prizmatičnog oblika za redukciju reverberacijske buke u nekim delovima industrijske hale. Posle akustičnog tretmana smo postigli da je prosečni nivo buke u tretiranoj hali smanjen na vrednost 80 dBA.

Ključne reči: *Industrijska buka, redukcija buke, regulacija reverberacije, zvučna izolacija*