Woodworking industry (chipboard, plywood production)			
Carver operator (veneer manufacturing)	93	Plywood cutting equipment	Up to 13
Lathe operator (veneer manufacturing)	93	Veneer-cutting lathe	Up to 13
Chipper operator (veneer manufacturing)	93-103	Drum chippers	Up to 23
Raw material sorters at the line equipment (veneer manufacturing)	91	-	Up to 11
Food industry (packaging production)			
Packer (food production, packing workshop)	82-83	Line equipment, conveyor lines	Up to 3
Packing (food production, packing workshop) Up to 6	84-86	Line equipment, conveyor lines, hand-operated tools	Up to 6
Pulp and paper industry (pulp and paper mill)			
Papermaking machine operators	94-98	Papermaking machines	Up to 18

Tab. 1: Results of the workplace noise measurements of the various industrial enterprises

As it can be seen from the table, significant excess of the maximum permissible noise levels (up to 23 dBA) can be set at many workplaces of the enterprises of different industries. The availability of such exceedances suggests the need for the introduction of various complex noise mitigation measures – construction and acoustic, organizational and technical, taking into account all the equipment and premises characteristics.

3. NOISE MITIGATION MEASURES AND MANUFACTURING NOISE REDACTION SYSTEMS

Most often production facilities can be classified as a large-sized facility with a large (at least ~15) number of intensive sources, which create excessive noise levels.

According to [2], noise abatement means can be applied to the source (noise emission), between the source and the receiver (in the way of noise propagation) and at the workplace (noise receiver). In general, people at workplaces or in the immediate vicinity of the machine are exposed to direct noise emission from the machine itself. Therefore, the most effective solution to the problem of workplace noise reduction is to reduce noise at the source (primary measures). Additional measures applied in the noise propagation path (secondary measures) may be inconvenient in practical terms because of their impact on production targets and processes. Therefore, when assessing the state of noise reduction measures and methods from the labour safety point of view, the main priority is to reduce the noise emission from the source.

3.1 Noise reduction casing for machinery

Noise reduction casing in some cases are the only effective means of reducing noise from the manufacturing machinery or individual units. Noise reduction cover refers to the shell of the free form, made of enclosing structures with necessary ventilation and service openings, viewing windows, hatches and doors, fully covering the entire noise source or part of it with the aim of reducing air noise levels.

The minimum dimensions of the casing are determined by the condition that no part of the machine is in contact with the walls of the casing. Additional requirements for minimum dimensions may be due to the electromagnetic field of the machine.

In addition, the casing can cover the entire noise source and be installed on the floor of the facility or the noisiest part of the machine due to the peculiarities of operation and maintenance of the noise source and be attached to the frame through vibration insulating pads.

For the most efficient reduction of the sound power of the noise emitted by the source into the surrounding space as a result of installation of the noise reduction casing on the source, it is necessary to carry out a test calculation of the required sound insulation of the casing.

The required sound insulation of the casing ***Rcas.req.***, dB, is determined in eight octave bands with geometric mean frequencies 63 - 8000 Hz according to the formula (1):

$$R_{cas.req.} = L - L_{perm} + 5 \quad (1)$$

where

L is the octave level of sound pressure at the reference point from a single operating insulated machine, dB;

Lperm is the maximum permissible octave level of sound pressure at the reference point, dB.

Sound insulation of the casing depends on the casing walls design and material, its shape and the availability of the efficient sound-absorbing lining inside the casing, dust, treated parts and transmission of the structural noise to the casing. When designing the casing, it is necessary to predetermine the required sound insulation of its walls. For a solid sealed casing of the cubic shape (or in the form of a rectangular parallelepiped), completely covering the machine, the required sound insulation ***Rf.req.*** for each face of the casing will be the same and can be determined by formulas 2 and 3:

(a) for casings with sound-absorbing lining

$$R_{f.req.} = R_{cas.req.} - 10 lg \alpha_l \quad (2)$$

where

Rcas.req. is the required sound insulation of the casing, dB;

α_i is the absorption coefficient of the lining determined by supporting documentation or reference information;

b) for uncoated casings

$$R_{f.req.} = R_{cas.req.} - 10\lg\frac{S_{cas}}{S_s} \quad (3)$$

where

S_{cas} is the surface area of the casing, m^2;

S_s is the area of an imaginary surface closely surrounding the noise source, m^2.

In addition, it is significantly dependent on the number of viewing windows, communications exit points, availability of holes, the need for supply and release of the air from under the casing, the removal of dust, treated parts and the transmission of the structural noise to the casing. In casings with heterogeneous structure the average sound insulation of the casing faces ***Rf.a.*** should not be lower than ***Rf.req.*** and it is determined by the formula 4:

$$R_{f.a.}=10\lg\ 10\lg\frac{\sum_{i=1}^{m} S_i}{\sum_{i=1}^{m} S_i\cdot 10^{-0.1R_i}}, \quad (4)$$

where

S_i, R_i are respectively area, m^2, and sound insulation, dB, of the element in question;

m is the total number of face elements with different sound insulation.

According to [3], the following five groups of casings are distinguished depending on the differences in sound levels or (as a preliminary estimate) the difference in A-corrected sound pressure levels in the octave band with an geometric mean frequency of 500 Hz without the casing and with the casing sets the acoustic requirements for the casing, dBA:

a) up to 10 - no special requirements for the casing;
b) from 10 to 20 - typical casings, without significant leakage of sound;
c) from 20 to 30 typical casings with carefully excluded leakage of sound and flexible machine installation;
d) 30 to 40 - carefully designed and assembled high performance casings;
e) more than 40 - special casing designs.

It follows from the abovementioned, that the effeciency of the noise reduction casing provides high performance for its application as a noise protection measure. But the main disadvantage of noise-reducing casings is the complete covering of the production machinery and, as a result, the inability to perform manipulations beside the plant, if required by the technological process (conveyors with elements of manual assembly, welding and hand tools, stamping, sheet bending machines and guillotines without installed automated control systems).

3.2 Screen-baffle at the workplace

Installation of the baffle as one of the noise mitigation measures is aimed at reducing the direct sound of the source on its way to the workplace.

In this case, the installation of baffles with a height of at least 3 m is considered most often, and to achieve the greatest efficiency - with curved in plan at 45° upper edges. The linear dimensions of the baffle must be at least three times the linear dimensions of the noise sources. U-shaped screens are preferable. Depending on the operations performed by the employee, the baffle can be made of transparent materials and/or equipped with a transparent part for process control. It is worth noting that the production of baffles from opaque materials using sound-absorbing material inside/outside the structure will also increase the efficiency of the measure.

When the screen is installed in a room, its efficiency is reduced due to the appearance of sound reflected from the surfaces of the room and the sound emitted by other noise sources located in the room. The value of the sound pressure octave levels reduction in the reference point at joint application of screens and sound-absorbing cladding when there is no more than one screen on the sound propagation path from the noise source to the reference point, is determined using the formula 5:

$$\Delta L=L-L_{scr} \quad (5)$$

Where

L is the octave sound pressure level, dB, at the reference point of the room without sound-absorbing structures and without screens;

Lscr is the octave sound pressure level, dB, in the same reference point after installation of indoor sound-absorbing constructions (lining) and screens determined by the formula 6:

$$L_{scr} = \sum_{i=1}^{k} \alpha_{dir.i} 10^{0.1(L_{Wi}-\Delta L_{scr.i})} + \sum_{i=k}^{m} \alpha_{dir.i} 10^{0.1L_{Wi}} + \sum_{i=1}^{m} \alpha_{refl.i} 10^{0.1L_{Wi}} \quad (6)$$

where

$\alpha_{dir.i}$ is the coefficient characterizing the contribution of the direct sound at the reference point from the i[th] source;

L_{Wi} is the octave sound power level of the i[th] noise source, dB;

$\Delta L_{scr,i}$ is the acoustic efficiency of the screen, dB, separating the reference point from the i[th] source;

$\alpha_{refl.l.i}$ is the coefficient characterizing the contribution of the reflected sound in the reference point from the i[th] source, taking into account the availability of a sound-absorbing structure in the premises [4].

Its efficiency largely depends on the configuration and acoustic treatment of the premises. Thus, the efficiency evaluation of the noise barrier installation at the workplace under real-life conditions can provide a reduction of 1-2 dBA in the production environment, when there is large density of noise equipment per unit area in the facility and/or the production facility has small sound absorption coefficients (a large proportion of the reflected noise). In the case of applying a noise protection measures package aimed at improving the acoustic characteristics of the facility (the introduction of additional sound absorption) with a large amount of noisy equipment per unit area, the maximum noise reduction at the workplace can be no more than 3-5 dBA.

As in case of noise reducing casing, the main disadvantage of the baffles is the impossibility of manipulating close to the operating machinery, if required by the technological process. As a result, it is impossible to implement the measures in many industries (assemblers on conveyor lines, operators, hand-operated machinery mechanics).

3.3 Improving the acoustic performance of the premises – implementing additional sound absorption

The production facilities of the abovementioned industries most often have sufficiently large production areas and, as a rule, relatively small equivalent sound absorption areas, which creates significant levels of reflected noise. Therefore, in addition to reducing the direct noise from the equipment, it is necessary to reduce the reflected noise. One of the ways to reduce noise in the premises is their acoustic treatment, which includes:

1. Facing of the internal surfaces with sound-absorbing material or special sound-absorbing structures;
2. Installation of the single-piece sound absorbers (in close proximity to the noise source partially reduces the direct sound intensity).

The most efficient sound-absorbing lining and single-piece sound absorbers are in the area of reflected sound, far from the source, because the sound field in these areas is determined mainly by the energy density of the reflected sound waves.

Sound-absorbing lining is usually placed on a ceiling and walls of the premises (the top part). In the premises with a height of more than 6 meters it is recommended, if possible, to install the suspended ceiling. To achieve the greatest effect it is recommended that the lining is not less than 60 % of the area of the premises surfaces. [5]

For an acoustically untreated premises, the premises constant (B, [m^2]) is determined by reference data or by calculation taking into account the sound absorption coefficients of all enclosing surfaces in the premises.

To calculate the efficiency of the measure, the formula 7 is used, which allows to evaluate the efficiency of noise reduction in the premises when using sound absorption means:

$$\Delta L_{sa} = 10 lg \frac{A_2}{A_1} \tag{7}$$

where
A1 and A2 are equivalent areas of sound absorption in the premises before and after using sound-absorbing material, respectively:

$$A_1 = \sum_{i=1}^{n} \propto_{i_1} S_{i_1} \tag{8}$$
$$A_2 = \sum_{i=1}^{m} \propto_{i_2} S_{i_2} \tag{9}$$

where
$\propto_{i_1}$, $\propto_{i_2}$ and S_{i_1}, S_{i_2} are, respectively, the sound absorption coefficient and the area of the ith enclosing surface (m^2) before (index '1') and after (index '2') the acoustic treatment [6].

For rooms with the same type of equipment, when the average range of sound pressure is known, as well as for rooms without its own noise sources, the design of sound-absorbing cladding can be selected without prior calculation. Thus according to the table [item 8.5 [5]] of acoustic characteristics of sound-absorbing facing the designs with the most suitable frequency characteristic of sound pressure in the considered room are selected.

The maximum possible reduction of sound levels in production facilities with the introduction of the maximum possible sound absorption area for sources with a pronounced mid - and high-frequency spectrum (since the greatest efficiency of absorption of ZPM lies in this range) can reach 8-10 dBA in the reflected noise zone.

It is also important that ZPM is also a mandatory element of such noise protection structures as soundproof enclosures, shelters and noise dampers (in the area of noise damping ventilation systems).

3.4 Noise dampers for ventilation systems

High workplace noise levels can often be caused not only by direct noise emitted by the manufacturing machinery, but also by noise from ventilation systems that contribute greatly to the overall noise levels (background levels) in the production facility.

At the same time, the machinery can be located in the manufacturing premises (supply and exhaust systems, fan heaters, air conditioners), as well as installed on the enterprise premises (chillers, fans, refrigeration units, etc.) and have a harmful effect as a direct noise source or penetrate into the production facility through the enclosing structures, windows and doorways.

In ventilation equipment, the source of radiation is the fan, and the noise is emitted as a secondary source through the open ends of the ducts in which the fan is located.

The main noise mitigation measure for the ventilation units is using noise-reducing mufflers, as the design solutions of the muffler are optimally suited for their installation at the air duct ends.

When determining the required noise reduction for the reference points in the premises protected from the noise of ventilation, air conditioning or air heating systems, the total number of noise sources taken into account should be included in the calculation of the required noise reduction of the supply or exhaust system fan (calculation of the central muffler) - the number of systems serving this facility (facility with the reference point). Otherwise noise levels from the ventilation systems can be determined based on measurements with other sources (machinery) disconnected.

It is necessary to apply absorption mufflers (tubular, cylindrical, plate-like, channel) as noise mufflers of the ventilation systems, air conditioning and air heating and if necessary - chamber mufflers and the air ducts lined from within with sound-absorbing materials and their turns. The design of the muffler is selected depending on the size of the air duct and the permissible air flow rate. The approximate efficiency of the muffler in the form of a set of chambers is determined by the formula 10:

$$\mathbf{L_m} = \sum_{i=1}^{n} 10lg \frac{A_i}{S_i} \tag{10}$$

where
$\mathbf{A_i} = \boldsymbol{\alpha_i} \mathbf{S_i}$ is the sound absorption of a single chamber;
$\mathbf{S_i}$ и $\boldsymbol{\alpha_i}$ are the area and sound absorption coefficient of the ith chamber, respectively; n-number of chambers.

The required cross section of the muffler is calculated by the formula 11:

$$\mathbf{S_m} = \frac{Q_m}{\vartheta_{perm}} \tag{11}$$

where
Q_m is the volume air flow rate through the muffler [illegible]

... is the permissible air velocity in the muffler (...=4–12 m/s).

...e the noise emitted by the air duct walls, they are in-...ed with an additional sound insulation coating (SIC).

...und insulation cabins

...operators of manufacturing machinery, which can be ...ided with remote control and do not require operator's in-...vention in the process for the purpose of control and man-...ement, it is recommended to use sound insulation cabins.

...und insulation cabins, depending on the application, ...ided into two groups: the first group includes control ...surveillance cabins used in production facilities, which we ...going to consider, are called stationary, as well as the sec-... group – transportation vehicle cabins.

...ationary cabins, in turn, are divided into frame and fra-... Cabins are assembled from: prefabricated elements, ... heavy building structures with high SI, lightweight ...ctures [6].

...e cabins are classified into four categories according to ...airborne noise insulation (Tab. 2).

Class	Airborne noise insulation, dB	SI used
[illegible]	25-45	Heavy SI
[illegible]	15-44	Ordinary SI
[illegible]	5-34	Assembled from prefabricated panels
[illegible]	4-24	Made of lightweight prefabricated structures

... Cabins classification according to SI

...selection is made in accordance with the exceedance ...workplace.

...the cabin must meet the following requirements:

... equipment-free volume of the cabin shall not ... less than 15 m³ per worker. Cabin height shall be ... less than 2.5 m. The size and shape of the cabin should ... determined to suit the dimensions of the equipment ...stalled in it in accordance with the requirements [7].

...ize and location of the cabin windows should be cho-... taking into account the possibility of a good overview ... the equipment and manufacturing process control at ... relevant production site. It is necessary to provide for ... possibility of safe periodic cleaning of the cabin win-...

...ventilation and maintenance of the optimum temper-... inside the cabin, it must be equipped with air con-...tioning or connected to the general shop heating and ...ventilation system.

...interior surfaces of the cabin shall be lined with sound-...sorbing materials or structures. For sound-absorbing ... it is recommended to choose non-combustible ma-... with sound absorption coefficients from 0.5 to 0.9 in ... frequency region where the greatest noise reduction ...ciency is required.

...should be possible to equip workplaces according to [8] ... in the cabin. For quick information exchange be-...ween the personnel directly servicing the manufacturing ...machinery and the dispatcher, the cabin shall be equipped ...with telecommunication equipment.

6. Places of cables and pipelines input through cabin walls shall be sound- and vibro-insulated. The number of individual holes in the cabin walls and intersections should be reduced to a minimum due to the arrangement of collectors. Cabins made of prefabricated elements must have a minimum number of seams and joints.

To verify the sufficient airborne noise isolation of the designed cabin, it is necessary to carry out a test calculation of the expected noise reduction provided by the cabin ***Rcab***, dB, according to the formula 12:

$$R_{cab}=10lg\,B_{\kappa}-10lg\sum_{i=1}^{m}S_i\cdot10^{-0.1R_i} \qquad (12)$$

where

S_i, R_i are the values of the area, m² and airborne noise isolation of the individual cabin enclosure elements, dB, respectively;

V_C is the acoustic constant of the cabin compartment, m², determined by the formulae 13, 14:

$$V_C=\frac{\alpha_a S_i}{1-\alpha_a} \qquad (13)$$

$$\alpha_a=\frac{\sum_{i=1}^{n}\alpha_i S_i+\sum_{j=1}^{k}A_j}{S_{comp}} \qquad (14)$$

where

α_a is the average sound absorption coefficient of the surfaces in the compartment;

α_i is the reverberation coefficient of the surface element sound absorption with the area S_i, m²;

n is the number of surfaces in the room;

A_j is the equivalent area of sound absorbers in the compartment (in this case A_j=0, ***since k***=0 – the number of single-piece sound absorbers in the compartment);

S_{com} is the total area of the surfaces in the cabin compartment, m².

It follows from tab. 2 that sound insulation cabins can have high efficiency of noise reduction (up to 25 dBA), which is a great advantage of this workplace noise mitigation method. However, its use is limited, as it can be seen from Tab. 1, not all manufacturing machinery can be equipped with remote control, in some cases, an operator's intervention in the manufacturing process for control and management purposes is necessary.

4. CONCLUSION

According to the results of in situ noise level measurements over the last 3 years, at many enterprise workplaces in different industries significant exceedances of the maximum permissible noise levels (up to 23 dBA) can be identified. Availability of such exceedances suggests the need for introducing a set of various noise mitigation measures – construction, acoustic, organizational and technical, taking into account all the machinery and premises characteristics.

In order to comply with the maximum permissible noise levels, various types of structures are used, aimed at reducing both direct and reflected noise, and reducing noise levels on its propagation path. Tab. 3 shows the estimated efficiency of the most common noise reducing structures.

No.	Noise mitigation measure title	Estimated efficiency
1	Noise reduction casing for machinery	Up to 40 dBA
2	Screen-buffle at workplaces	Up to 5 dBA
3	Introducing additional sound absorption	Up to 10 dBA (reflected noise)
4	Noise mufflers for ventilation systems	Up to 15 dBA (only in relation to the ventilation system)
5	Sound-insulated cabins	Up to 25 dB

Tab. 3: Estimated efficiency of the abovementioned measures

REFERENCES

[1] SanPiN 2.2.4.3359-16 Sanitarno-ehpidemiologicheskie trebovaniya k fizicheskim faktoram na rabochih mestah (in Russian)
[2] GOST R 52797.2-2007 (ISO 11690-2:1996) Acoustics. Recommended practice for the design of low-noise workplaces containing machinery. Part 2: Noise control measures
[3] GOST 31326-2006 (ISO 15667:2000) Acoustics. Guidelines for noise control by enclosures and cabins
[4] SP 254.1325800.2016 Zdaniya i territorii. Pravila proektirovaniya zashchity ot proizvodstvennogo shuma (in Russian)
[5] Yudin, E.Y.: Spravochnik proektirovshchika: zashchita ot shuma., M.: Strojizdat, p. 64-66, 127-131, (in Russian), 1974
[6] Ivanov, N.I.: Inzhenernaya akustika. Teoriya i praktika bor'by s shumom., M.: Logos, ISBN 978-598704-286-0, p. 186, 188-194, 2008 (in Russian)
[7] GOST 12.2.049-80 Sistema standartov bezopasnosti truda (SSBT). Oborudovanie proizvodstvennoe. Obshchie ehrgonomicheskie trebovaniya (in Russian)
[8] GOST 12.2.032-78 Sistema standartov bezopasnosti truda (SSBT). Rabochee mesto pri vypolnenii rabot sidya. Obshchie ehrgonomicheskie trebovaniya (in Russian)
[9] GOST 12.2.033-78 Sistema standartov bezopasnosti truda (SSBT). Rabochee mesto pri vypolnenii rabot stoya. Obshchie ehrgonomicheskie trebovaniya (in Russian)

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