

Research Paper

Assessment of Occupational Risk in the Case
of the Ultrasonic Noise Exposure

Dariusz PLEBAN*, Jan RADOSZ, Bożena SMAGOWSKA

*Central Institute for Labour Protection – National Research Institute
Warsaw, Poland*

*Corresponding Author e-mail: daple@ciop.pl

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Increased efficiency of production and improved quality have contributed to the development of ultrasonic technological applications, in which low frequency ultrasounds are generated to operate, accelerate as well as to facilitate technological processes. Technological ultrasonic devices (i.e. sources of ultrasonic noise in the work environment, e.g. ultrasonic washers, ultrasonic welding machines) have relatively high power and their nominal frequencies are in the range from 18 kHz to 40 kHz. In Poland, ultrasonic noise (defined as noise containing high audible and low ultrasonic frequencies from 10 kHz to 40 kHz) is included in the list of factors harmful to health in the work environment and therefore the admissible values of ultrasonic noise in the workplaces are established. The admissible values of ultrasonic noise and the new ultrasonic noise measurement method make it possible to perform the assessment of occupational risk related to ultrasonic noise. According to this method, the scope of the measurements includes the determination of the equivalent sound pressure levels in the 1/3 octave bands with the centre frequencies from 10 kHz to 40 kHz. This paper presents the description of both, i.e. the method for ultrasonic noise measurements and the method of the assessment of occupational risk related to ultrasonic noise. The examples of the results of the assessment of occupational risk related to exposure to ultrasonic noise are also discussed.

Keywords: occupational risk; ultrasonic noise; workplaces; measurement; assessment; occupational safety; airborne ultrasound.

1. Introduction

Since the 1960s and the following 1970s (till now) questions relating to ultrasonic noise (i.e. airborne ultrasound) have been subjects of many research projects and publications in many countries, e.g. (GRIGORIEWA, 1965, cited by ŚLIWIŃSKI (2013); ACTON, 1974; HOLMBERG *et al.*, 1995; SCHUST, 1996; LAWTON, 2001; 2013; PAWLACZYK-ŁUSZCZYŃSKA *et al.*, 2001a; 2001b; 2007; HOWARD *et al.*, 2004; ASH-HARA *et al.*, 2006; DOBRUCKI *et al.*, 2010; MARTIN, 2011; MIKULSKI, 2013; PLEBAN, 2013; DUDAREWICZ *et al.*, 2017; PLEBAN, MIKULSKI, 2018). Last and current researches on airborne ultrasound cover primarily human effects, e.g. (VAN WIERINGEN, GLORIUEUX, 2018; FLETCHER *et al.*, 2018a; 2018b; DUCK, LEIGHTON, 2018), measurement techniques, e.g. (RADOSZ, 2012; 2014; 2015; KLING *et al.*, 2015; 2017; ULLISCH-NELKEN *et al.*, 2018; SCHÖNEWEISS *et al.*, 2018; RADOSZ, PLEBAN, 2018; VAN WIERINGEN, GLORIUEUX, 2018; MAPP, 2018; PAXTON

et al., 2018; FLETCHER *et al.*, 2018c; DOLDER *et al.*, 2018; CIESLAK *et al.*, 2020), calibration of measurement instrumentation for airborne ultrasound, e.g. (BARRERA-FIGUEROA, 2018; TAKAHASHI, HORIUCHI, 2018) and novel applications of airborne ultrasound, e.g. (MIEGEL *et al.*, 2018; ØYERHAMN *et al.*, 2018).

Increased efficiency of production and improved quality have contributed to the development of ultrasonic technological applications, in which ultrasounds are generated to operate, accelerate or facilitate technological processes. Technological ultrasonic devices have relatively high power, emit high frequency noise and their nominal frequencies are between 18 and 40 kHz. Ultrasonic washers are the most common devices. They are sources of emission of ultrasounds which sound pressure levels at operator workplaces reach the values of 110–135 dB (AUGUSTYŃSKA, ZAWIESKA, 1999; SMAGOWSKA, 2013). According to (HOLMBERG *et al.*, 1995) the ratings of annoyance and discomfort are high during exposure to noise from ultrasonic washers. The ultrasonic washers are followed

by ultrasonic welding devices and ultrasonic drilling machines. They radiate into the air ultrasonic waves of sound pressure levels of up to 145 dB (SMAGOWSKA, MIKULSKI, 2008). Besides technological ultrasonic devices, there is also a large group of industrial machines and devices which also emit ultrasounds as an unintended, accompanying additional factor. In this case, the sources of the ultrasounds are phenomena of the aerodynamic nature or of the mechanical nature.

Low frequency ultrasounds, generated by the above mentioned sources (technological ultrasonic devices, in particular), can penetrate the human body by means of contact (e.g. contact with an ultrasonic transducer or ultrasound-excited fluid). However, the sound energy originating from those sources is always transferred to the human body by means of air. Working in the environment of the abovementioned technological ultrasonic devices, machines and devices therefore creates hazards not only to the organ of hearing (ACTON, 1974; ASHIHARA *et al.*, 2006; LAWTON, 2001; SMAGOWSKA, PAWLACZYK-ŁUSZCZYŃSKA, 2013) but it can be also annoyance (HOLMBERG *et al.*, 1995; SMAGOWSKA, 2015) and even harmful due to extra-auditory effects of ultrasounds (SMAGOWSKA, ŁUSZCZYŃSKA, 2013). It is estimated that about 25,000 employees are exposed in Poland to ultrasonic noise emitted by technological ultrasonic devices and a similar number of employees are exposed to ultrasonic noise emitted by other machines and pieces of equipment.

In view of the above, ultrasonic noise (in Poland defined as the broadband noise containing high audible and low ultrasonic frequencies from 10 kHz to 40 kHz (KORADECKA, 2010)) is assigned to the group of physical agents harmful to health in the working environment. As a result, the admissible values of ultrasonic noise at workplaces are established in Polish legislation (Announcement of Minister of Family, Labour and Social Policy, 2018). And besides, in accordance with the requirements of the national law (Act Labour Code, 1974) occupational risk assessment associated with exposure to harmful agents belongs to the basic obligations of the employer. Occupational risk assessment is also the main tool used in occupational safety and health management which is required by the European Directive 89/391/EEC (Council Directive, 1989).

There are no international and European standards relating to the ultrasonic noise measurements in the working environment. Furthermore, there are no international regulations on ultrasonic noise exposure assessment. Ultrasonic noise is also defined differently from country to country. The result of that is a lack of publications on occupational risk assessment related to ultrasonic noise. Poland is one of the few countries in which there are specified both limit values for ultrasonic noise, as a method for measuring the ultrasonic noise in the workplaces. Therefore, the purpose of the paper is to present the new ultrasonic noise measure-

ment method and the method of assessment of occupational risk related to ultrasonic noise. Examples of the results of the assessment of occupational risk related to ultrasonic noise exposure are also presented.

2. Test method

2.1. General

The assessment of occupational risk related to ultrasonic noise exposure is a complex process consisting of the following stages:

- estimation of ultrasonic noise exposure,
- comparison of the obtained ultrasonic noise exposure with the maximum allowable intensity (MAI) values,
- assessment of the occupational risk related to ultrasonic noise.

Having regard to the above stages, the following subsections describe the essential steps of the assessment of occupational risk related to ultrasonic noise exposure.

2.2. Maximum allowable intensity values for ultrasonic noise

The current legislation (Announcement of the Minister of Family, Labour and Social Policy, 2018), prescribes that ultrasonic noise is characterized by:

- equivalent sound pressure levels in the 1/3 octave bands (with the centre frequencies, f , 10 kHz, 12.5 kHz, 16 kHz, 20 kHz, 25 kHz, 31.5 kHz, and 40 kHz) normalized to a nominal 8-hour working day, $L_{f_{eq,8h}}$, or to a working week, $L_{f_{eq,w}}$ (in the case of exposure to ultrasonic noise at an irregular manner over each day in a week or if a person works another number of days a week than 5 days),
- maximum sound pressure levels in the above mentioned 1/3 octave bands, $L_{f_{max}}$.

In accordance with the abovementioned Announcement, the maximum allowable intensity (MAI) values for ultrasonic noise at workplaces are given in Table 1.

Table 1. MAI values for ultrasonic noise at workplaces.

Frequency, f [kHz]	$L_{f_{eq,8h}}$ or $L_{f_{eq,w}}$ [dB]	$L_{f_{max}}$ [dB]
10; 12.5; 16	80	100
20	90	110
25	105	125
31.5; 40	110	130

2.3. Method for measuring ultrasonic noise

Measurement methods and strategies for audible noise in a workplace are defined in the International

Standard ISO 9612:2009 (International Organization for Standardization, 2009). Specifications for measuring instruments are defined in relevant international standards IEC. There is, however, no currently applicable analogous international standard on ultrasonic noise. In the 1980s, the results of studies on sources of ultrasonic noise in the working environment and on its effects on humans contributed to the development of standardisation works in this field. Researchers at the Central Institute for Labour Protection were the authors of the first Polish Standard PN-86/N-01321 (Polish Committee for Standardization, 1986) containing the admissible values of ultrasonic noise at work places and the general requirements for measurements. In 2001, as the result of the cooperation with the Nofer Institute of Occupational Medicine, a procedure for ultrasonic noise measurements was published (PAWLACZYK-ŁUSZCZYŃSKA *et al.*, 2001b). The new ultrasonic noise measurement procedure was developed (on the basis of the results of studies carried out in the Central Institute for Labour Protection-National Research Institute) and was published by RADOSZ (2015). This measurement procedure was implemented in the Polish Standard PN-Z-01339:2020 (Polish Committee for Standardization, 2020).

The Polish Standard PN-Z-01339:2020 specifies both: a method for measuring ultrasonic noise in the work environment and a method for determining of equivalent sound pressure levels of ultrasonic noise. The Standard also specifies a method for taking account of amendments related to the influence of the metrological characteristics of the measuring devices and the influence of a microphone protective grid on measurement results. The developed measurement method requires the observation and analysis of the ultrasonic noise exposure conditions in order to control the quality of measurements. Therefore, the Polish Standard PN-Z-01339 allows to estimate uncertainty measurements in order to determine the quality of the measurements. According to this Standard the ultrasonic noise measurements shall be carried out in the presence of the worker at the workplace. During the measurements the microphone should be located at a distance of approximately 10 cm from the external ear canal, on the side of the ear exposed to higher value of the sound pressure level. Workplaces at which ultrasonic noise occurs, particularly workplaces related to ultrasonic technological devices, are usually stationary positions, and tasks carried out in these workplaces may be divided into clear time intervals depending on the work of these devices. In such a case, the most effective method of measuring is the task based measurements strategy – the strategy determined the International Standard ISO 9612:2009. For that reason the working time on the tested workplace shall be divided into the duration of the individual tasks. The total duration of the tasks should encompass the full

working shift. At least 3 sound pressure measurements shall be carried out for each task. The equivalent sound pressure levels for the m -th task shall be determined by using Eq. (1):

$$L_{fi,eq,Tm} = 10 \log \left(\frac{1}{J} \sum_{j=1}^J 10^{0.1L_{fi,eq,Tm,j}} \right), \quad (1)$$

where $L_{fi,eq,Tm}$ – the equivalent sound pressure level in the i -th 1/3 octave band for the m -th task, in dB, $L_{fi,eq,Tm,j}$ – the equivalent sound pressure level in the i -th 1/3 octave band, and for the j -th measurement for the m -th task, in dB, J – the number of measurements for the m -th task.

The maximum sound pressure level for the m -th task, $L_{fi,max,Tm}$, is the greatest value obtained during the measurements.

The result of the equivalent sound pressure level measurement in the i -th 1/3 octave band and the result of the maximum sound pressure level measurement in the i -th 1/3 octave band, L_{fi} , shall be adjusted according to Eq. (2):

$$L_{fi} = L'_{fi} + K_{apfi} - K_{gfi}, \quad (2)$$

where L_{fi} – the corrected meter/analyser reading in the i -th 1/3 octave band, in dB, L'_{fi} – the meter/analyser reading in the i -th 1/3 octave band, in dB, K_{apfi} – the amendment related to metrological characteristics of measurement equipment, in dB (data from the certificate of calibration), K_{gfi} – the amendment related to the influence of microphone protection grid, in dB.

The equivalent sound pressure levels in the i -th 1/3 octave bands, normalized to a nominal 8-hour working day, $L_{fi,eq,8h}$, are determined by using Eq. (3):

$$L_{fi,eq,8h} = 10 \log \left[\sum_{m=1}^M \frac{T_m}{T_0} 10^{0.1L_{fi,eq,Tm}} \right], \quad (3)$$

where $L_{fi,eq,8h}$ – the equivalent sound pressure level in the i -th 1/3 octave bands, normalized to a nominal 8-hour working day, in dB, $L_{fi,Tm}$ – the equivalent sound pressure level in the i -th 1/3 octave band, and for the m -th task, in dB, T_m – the duration of the m -th task, in h, T_0 – reference time interval, $T_0 = 8$ h, m – the number of tasks, M – the total number of tasks during the working shift.

2.4. Instrumentation

Ultrasonic noise measurements shall be made with sound level meter/analysers which:

- meet the requirements of IEC 61672-1 and IEC 61260-1 (International Electrotechnical Commission, 2013; 2014) in the frequency range up to 20 kHz for class 1 measuring instruments,

- are equipped with 1/3 octave band filters with centre frequency range at least from 10 kHz to 40 kHz, meeting the requirements of IEC 61260-1,
- are equipped with free-field microphones meeting the requirements of IEC 61094-4 (International Electrotechnical Commission, 1995).

A measurement microphone in combination with a sound level meter/analyser should ensure a flat frequency response covering the frequencies of the tested range (± 0.5 dB). It should be primarily used in the no protection grid configuration. Using the microphone in configuration with the protection grid is possible provided that its influence on the microphone's frequency response is known.

2.5. Assessment of occupational risk related to ultrasonic noise exposure

Occupational risk is defined as a combination of the likelihood of an occurrence of a hazardous event and the severity of injury or damage to the health of people caused by the event. According to (KORADECKA, 2010) occupational risk assessment is the process by which work-related hazards are identified and the risks resulting from their presence are then estimated and evaluated. The Polish Standard PN-N-18002 (Polish Committee for Standardization, 2011) recommends a three-point risk-level estimator. In accordance with the principles given in the Polish Standard PN-N-18002, occupational risk related to ultrasonic noise can be estimated on the value of multiplicity of MAI values for ultrasonic noise, k . The multiplicities of MAI values for ultrasonic noise, k , are determined by using Eqs (4) and (5):

- in case of the equivalent sound pressure levels in the 1/3 octave bands (with the centre frequencies, f , 10 kHz, 12.5 kHz, 16 kHz, 20 kHz, 25 kHz, 31.5 kHz, and 40 kHz):

$$k = 10^{(L_{fi,eq,sh}) - (L_{fi,eq,sh,MAI})/10}, \quad (4)$$

where $L_{fi,eq,sh}$ – the equivalent sound pressure level in the i -th 1/3 octave bands, normalized to a nominal 8-hour working day, in dB, $L_{fi,eq,sh,MAI}$ – the MAI value of the equivalent sound pressure level in the i -th 1/3 octave band normalized to a nominal 8-hour working day, in dB,

- in case of the maximum sound pressure levels in the 1/3 octave bands (with the centre frequencies, f , 10 kHz, 12.5 kHz, 16 kHz, 20 kHz, 25 kHz, 31.5 kHz, and 40 kHz):

$$k = 10^{(L_{fi,max}) - (L_{fi,max,MAI})/20}, \quad (5)$$

where $L_{fi,max}$ – the measured maximum sound pressure level in the i -th 1/3 octave band, in dB, $L_{fi,max,MAI}$ – the MAI value of the maximum sound pressure level in the i -th 1/3 octave band, in dB.

The maximum value of the calculated multiplicities is the basis for the assessment of occupational risk related to ultrasonic noise exposure accordance with the principle given in Table 2.

Table 2. Principle of the assessment of occupational risk related to ultrasonic noise exposure.

Multiplicity of MAI value, k	Risk estimation
$k < 0.5$	Low – acceptable
$0.5 \leq k \leq 1$	Medium – acceptable
$k > 1$	High – unacceptable

3. Test results

As mentioned earlier, the main sources of ultrasonic noise in the working environment are the ultrasonic technological devices. In this case the ultrasonic washers and ultrasonic welding devices are the most common devices. Therefore, the workplaces associated with the operation of five of the most common ultra-

Table 3. Values of the equivalent sound pressure levels in the 1/3 octave bands normalized to a nominal 8-hour working day at the workplaces, $L_{fi,eq,sh}$, in dB.

Workplace	Frequency, f [kHz]						
	10	12.5	16	20	25	31.5	40
Ultrasonic washer No. 1 operator	63.8	66.5	75.2	85.9	76.0	94.4	108.9
Ultrasonic washer No. 2 operator	55.2	65.8	61.0	81.3	97.8	76.0	63.0
Ultrasonic washer No. 3 operator	55.5	58.0	68.8	72.0	63.3	76.7	92.0
Ultrasonic washer No. 4 operator	64.8	77.6	68.5	83.4	96.5	81.6	80.1
Ultrasonic washer No. 5 operator	74.3	85.6	75.4	74.6	100.4	81.8	68.1
Ultrasonic welding device No. 1 operator	72.4	52.0	53.0	78.8	57.9	56.7	51.8
Ultrasonic welding device No. 2 operator	93.0	75.4	76.5	102.2	86.0	88.4	90.4
Ultrasonic welding device No. 3 operator	65.0	50.3	51.3	78.2	58.4	56.6	51.6
Ultrasonic welding device No. 4 operator	97.0	85.2	100.8	121.2	102.5	100.0	117.5
Ultrasonic welding device No. 5 operator	71.5	68.5	76.5	96.0	81.5	75.0	87.0

Table 4. Values of the maximum sound pressure levels in the 1/3 octave bands at the workplaces, $L_{fi,max}$, in dB.

Workplace	Frequency, f [kHz]						
	10	12.5	16	20	25	31.5	40
Ultrasonic washer No. 1 operator	75.4	77.7	86.7	97.5	88.1	107.1	121.3
Ultrasonic washer No. 2 operator	73.0	82.0	68.0	97.0	113.5	91.0	78.0
Ultrasonic washer No. 3 operator	71.5	72.5	79.5	85.6	78.2	93.6	108.9
Ultrasonic washer No. 4 operator	79.1	91.9	82.8	97.2	115.5	95.6	93.9
Ultrasonic washer No. 5 operator	79.8	86.9	77.3	75.9	101.1	82.2	69.7
Ultrasonic welding device No. 1 operator	78.8	58.2	68.4	85.1	63.5	60.2	58.5
Ultrasonic welding device No. 2 operator	99.3	80.0	82.6	107.7	90.7	92.1	95.8
Ultrasonic welding device No. 3 operator	71.7	56.8	57.3	83.9	56.7	62.1	57.9
Ultrasonic welding device No. 4 operator	106.0	92.0	108.0	128.0	110.5	106.5	126.0
Ultrasonic welding device No. 5 operator	89.0	86.0	98.0	118.0	99.0	92.0	106.0

Table 5. Results of the assessment of occupational risk related to ultrasonic noise exposure.

Workplace	Maximum value of k	Risk estimation
Ultrasonic washer No. 1 operator	0.78	Medium – acceptable
Ultrasonic washer No. 2 operator	0.27	Low – acceptable
Ultrasonic washer No. 3 operator	0.09	Low – acceptable
Ultrasonic washer No. 4 operator	0.58	Medium – acceptable
Ultrasonic washer No. 5 operator	3.63	High – unacceptable
Ultrasonic welding device No. 1 operator	0.17	Low – acceptable
Ultrasonic welding device No. 2 operator	19.95	High – unacceptable
Ultrasonic welding device No. 3 operator	0.07	Low – acceptable
Ultrasonic welding device No. 4 operator	1318.26	High – unacceptable
Ultrasonic welding device No. 5 operator	3.98	High – unacceptable

sonic washers and the workplaces associated with the operation of five of the most common ultrasonic welding devices in Poland were chosen as the test objects. Ultrasonic noise measurements at the workplaces were carried out in accordance with the above described method. The measurements were taken using sound analysers SVANTEK type SVAN 912 AE and SVANTEK type SVAN 979 both with G.R.A.S. preamplifiers type RA0019 and G.R.A.S. type 40BF microphones.

The results of measurements, expressed as the equivalent sound pressure levels in the 1/3 octave bands normalized to a nominal 8-hour working day, $L_{fi,eq,8h}$, and as the maximum sound pressure levels in the 1/3 octave bands, $L_{fi,max}$, are given respectively in Tables 3 and 4. However, the results of the assessment of occupational risk related to the ultrasonic noise exposure are given in Table 5.

4. Discussion

The measured sound pressure levels are consistent with earlier results for ultrasonic washers and for ultrasonic welding devices, e.g. (HOLMBERG *et al.*, 1995; PAWLACZYK-ŁUSZCZYŃSKA *et al.*, 2001a;

2007a; 2007b; SMAGOWSKA, PAWLACZYK-ŁUSZCZYŃSKA, 2013; DUDAREWICZ *et al.*, 2017).

On the basis of the results of the ultrasonic noise measurements at the workplaces associated with the operation of the ultrasonic washers, the authors can state that:

- the equivalent sound pressure levels in the 1/3 octave bands normalized to a nominal 8-hour working day reached values between 55.2 dB and 108.9 dB,
- the highest values of the equivalent sound pressure levels normalized to a nominal 8-hour working day were determined in the 1/3 octave bands with centre frequencies 25 kHz (the ultrasonic washer No. 5) and 40 kHz (the ultrasonic washer No. 1),
- the maximum sound pressure levels in the 1/3 octave bands reached values between 71.3 dB and 121.3 dB,
- the highest values of the maximum sound pressure levels were measured in the 1/3 octave bands with centre frequencies 25 kHz (the ultrasonic washer No. 4) and 40 kHz (the ultrasonic washer No. 1),
- the values of ultrasonic noise exposure in the tested workplaces did not exceed the MAI values

for ultrasonic noise except the ultrasonic washer No. 5,

- the assessment of occupational risk related to ultrasonic noise exposure indicated that occupational risk was acceptable except for the ultrasonic washer No. 5. This risk was low in the case of the ultrasonic washers No. 2 and No. 3 and it was medium in the case of the ultrasonic washers No. 1 and No. 4,
- in the case of the ultrasonic washer No. 5, the result of the assessment of occupational risk related to ultrasonic noise exposure was unacceptable, i.e. risk was high.

On the other hand, on the basis of the results of the ultrasonic noise measurements at the workplaces associated with the operation of the ultrasonic welding devices the authors can state that:

- the equivalent sound pressure levels in the 1/3 octave bands normalized to a nominal 8-hour working day reached values between 50.3 dB and 121.2 dB,
- the highest values of the equivalent sound pressure levels normalized to a nominal 8-hour working day were determined in the 1/3 octave bands with centre frequencies 20 kHz (the ultrasonic welding device No. 4) and 40 kHz (the same ultrasonic welding device, i.e. No. 4),
- the maximum sound pressure levels in the 1/3 octave bands reached values between 56.8 dB and 128.0 dB,
- the highest values of the maximum sound pressure levels were measured in the 1/3 octave bands with centre frequencies 20 kHz (the ultrasonic welding device No. 4) and 40 kHz (the same ultrasonic welding device, i.e. the device No. 4),
- the values of ultrasonic noise exposure in the tested workplaces did not exceed the MAI values for ultrasonic noise only in the case of the ultrasonic welding devices No. 1 and No. 3,
- the assessment of occupational risk related to ultrasonic noise exposure indicated that occupational risk was acceptable only for the ultrasonic welding devices No. 1 and No. 3 – the risk was low in the case of these both devices,
- in the case of the ultrasonic welding devices No. 2, No. 4, and No. 5, the results of the assessment of occupational risk related to ultrasonic noise exposure were unacceptable, i.e. risk was high.

5. Conclusions

Ultrasonic noise is one of the common harmful factors in the working environment. Applying a standardised measurement method for ultrasonic noise can be

a support for the assessment and eliminating or reducing occupational risk related to this type of noise. Although there are not:

- legal acts of the European Union relating to ultrasonic noise exposure in the workplaces,
- international and European standards for the measurements of ultrasonic noise in the workplaces,

issues on the assessment of occupational risk related to ultrasonic noise exposure may be considered as solved in Poland. This assessment was made possible through the MAI values for ultrasonic noise at workplaces and the ultrasonic noise measurement method. The ultrasonic noise measurement method described in this paper and included in the Polish Standard PN-Z-01339 includes in particular: description of proceeding during measurements, requirements relating to measurement apparatus and correction of measurement results.

The presented results of the assessment of occupational risk related to ultrasonic noise exposure showed that risk can be high (i.e. some ultrasonic technological devices can pose threat to employees' health). Reduction of occupational risk related to ultrasonic noise exposure can be achieved among others by encapsulation of ultrasound sources, enclosures, remote controls of technological processes and wearing personal protective equipment (including hearing protectors).

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