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PROPOSED CRITERIA FOR ASSESSING LOW FREQUENCY NOISE ANNOYANCE IN OCCUPATIONAL SETTINGS

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Abstract
Objectives: The aim of the study was to recommend methods for assessing low frequency noise (LFN) in the occupational environment to prevent annoyance and its effects on work performance. Three different evaluating methods and corresponding admissible values were proposed: (i) method I – frequency analysis in 1/3-octave bands within the range of 10–250 Hz, (ii) method II – consisting in 1/3-octave band measurements and determination of low frequency equivalent-continuous A-weighted sound pressure level (SPL) in the frequency range of 10–250 Hz, and (iii) method III – based on equivalent-continuous A-weighted SPL corrected due to the presence of low frequencies and tonal character of LFN. Separate noise limits were recommended for workplaces in control rooms and office-like areas. **Materials and Methods:** The proposed criteria were verified in laboratory and field studies. The laboratory study included 55 volunteers, aged 21.8±2.1 years, with normal hearing (<25 dB HL). The subjects listened to different noises at A-weighted SPL of 45–65 dB, and evaluated annoyance using a 100-score graphical rating scale. In the field study, 35 male workers, aged 40.1 ± 7.2 years, exposed to LFN at A-weighted SPL of 48–61 dB, were asked to rate noise annoyance at their workplaces using a similar graphical scale. The subjective ratings of LFNs were compared to objective results from various assessing methods. The relations between annoyance and excesses of proposed limits were analyzed using Pearson's correlation coefficient (r). **Results:** Linear relationships between the subjective ratings and results from all proposed exposure criteria were observed ($0.550 \le r \le 0.673$; $p < 0.001$). In the field conditions, however, the highest correlation coefficient was found for method II ($r = 0.673$), while during the laboratory study for method I ($r = 0.612$) and criterion curves based on hearing threshold level (HTL). **Conclusions:** All proposed criteria, especially the evaluation method based on the low frequency equivalent-continuous A-weighted sound SPL (method II) as well as the frequency analysis in 1/3-octave bands 10(20)–250 Hz (method I) and criterion curves based on HTL or A-weighting characteristics, seem to be able to quite well predict annoyance experienced from LFN at workplaces.

Key words:
Low frequency noise, Annoyance, Measuring methods, Exposure limits

INTRODUCTION

Polish regulations, currently in force, specify maximum admissible intensity (MAI) values for noise and infrasonic noise in the occupational environment [1]. However, in many workplaces, especially in industrial control rooms and office-like areas, noise with the dominant content frequency from 10 to 250 Hz that is termed low frequency noise (LFN) is often present. LFN includes a wider range

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of frequencies than infrasonic noise and only a small part of the frequency range that is taken into consideration in case of audible noise. However, in the literature different definitions of LFN can be found. Sometimes, the frequency range of LFN is limited to the band within 20–250 Hz [2,3].

Ventilation systems, air pumps, compressors, diesel engines, gas turbine power stations or means of transport, may be quoted as some examples of common sources of LFN. Its prevalence in offices and industrial control rooms is mainly due to indoor network installations, ventilation, heating and air conditioning systems, but also due to outdoor sources and poor attenuation of low frequency components by the walls, floors and ceilings. The LFN occurrence is not only limited to occupational settings as it is also present in the general environment (in dwellings) [2–4].

Since LFN includes both infrasonic and low audible frequencies, numerous effects attributed to infrasound are also reported to be induced by LFN, e.g., pressure sensation in the middle ear, resonant vibrations in some parts of the human body (mainly chest and stomach), speech interference, temporary loss of hearing acuity, and vestibular disturbance (although the latter effect is disputable in case of infrasound). Most of those effects are due to exposures at high sound pressure levels, exceeding the hearing perception threshold [2,3,5–10].

It has been shown that long-term occupational exposure (≥ 10 years) to LFN (f ≤ 500 Hz) at high sound pressure levels (SPL ≥ 90 dB) causes vibroacoustic disease (VAD). VAD symptoms include various abnormalities of the respiratory, cardiovascular and nervous systems. Recently, it has mainly been diagnosed among aeronautical workers [11–14].

However, annoyance is the major and the most frequent effect of LFN exposure on human subjects [2,3,15]. By definition, annoyance is a feeling of discomfort associated with any agent or condition known or believed by an individual or a group of subjects to have an adverse effect on them [3].

Annoyance related to LFN has been recognized as a special environmental noise problem, particularly to sensitive people, who experience noise in their homes [3,15]. Many studies have shown differences in the degree of annoyance caused by noise at the same A-weighted sound pressure levels but with different frequency composition. Annoyance resulting from LFN is greater than that from noises without dominant low frequency components. It is frequently experienced at relatively low sound pressure levels that comply with ordinary environmental noise-based guidelines. Moreover, many studies have indicated that A-weighted sound pressure level is a less suitable descriptor for assessing effects of LFN [3,15,16]. The same seems to be true for the G-weighting characteristics (ISO 7196:1997) intended for infrasound assessment since it does not cover all dominant frequency components of LFN, but only the infrasonic range [17].

The importance of LFN in the general environment was pointed out in the WHO document on community noise [18]. The specific regulations on its control in the residential areas are in use in some European countries [19−23]. However, no guideline for the work environment has yet been established. Only outline recommendations for LFN in the occupational environment to prevent annoyance and its effects on work performance have already been proposed in Sweden [24]. Whereas, there is a growing body of data showing that LFN at the levels normally occurring in control rooms and office-like areas (40−50 dB) can be perceived as annoying and adversely affecting the human mental performance, particularly when more demanding tasks have to be executed. Moreover, the subjects recognized as high-sensitive to LFN may be at a higher risk [25−28]. Thus, LFN could possibly lead to work impairment, particularly in case of jobs requiring selective attention and/or processing of high load of information.

The major aim of the study was to recommend methods for assessing LFN and propose limits to prevent its annoyance and effects on work performance in the occupational environment. A further objective was to verify the proposed exposure criteria in laboratory and field studies.

CRITERIA FOR THE LFN ASSESSMENT

Review of existing evaluation methods

Over the years many different methods have been suggested for the assessment of LFN in the general environment (dwellings). Exposure criteria are in use or are proposed in Germany, Sweden, Denmark, the Netherlands, the United Kingdom, and Poland.

Generally, all of them are based on the frequency analysis in 1/3-octave bands in various frequency ranges from 8 Hz to 250 Hz. In the majority of cases, measured sound pressure levels are compared with criterion curves (Table 1). In the Danish method, however, the nominal A-weighting corrections are added to the spectra, and the weighted spectrum is summed up to form the A-weighted sound pressure level (SPL) in the frequency range of 10–160 Hz ($L_{pA,\ LF}$). Moreover, a 5 dB penalty for impulsive noise is taken into consideration. In the German method, if the noise is not tonal the A-weighted SPL in the 10–80 Hz frequency range ($L_{A(10–80\ Hz)}$) is calculated based only on bands exceeding the hearing threshold. Whereas, for tonal noise, the level of the 1/3-octave band with tone is compared with the hearing threshold modified by penalty, depending on the frequency and a time of the day.

According to the Danish method, the $L_{pA,\ LF}$ level (averaged over 10 min) in dwellings should not exceed 20 dB in the evening and night period or 25 dB during the day. On the other hand, in Germany if the noise is not tonal then the maximum acceptable level of $L_{A(10–80\ Hz)}$ is 35 dB and 25 dB for day/night period, respectively [19–23].

An outline Swedish recommendation for assessing LFN at workplaces is based on 1/3-octave band measurements in the frequency range of 25–200 Hz and three criterion curves (S40, S60 and S80) representing A-weighted SPL groups, 40 dB, 60 dB and 80 dB [24].

It is worth noting that sometimes, irrespective of exposure criteria for LFN, specific regulations concerning infrasound are in use. For example, in Denmark, the above mentioned guidelines for the measurement and assessment of environmental LFN were established along with

Table 1. Reference curves used in various criteria concerning environmental exposure to low frequency noise (LFN) together with hearing threshold level (HTL) according to ISO 226:2003 and an outline Swedish recommendation for workplaces [19–24,29]

1/3-Octave bands (Hz)	Reference curve								
	German	Swedish	Dutch	Polish	British	HTL	S40	S60	S80
	Sound pressure level (dB)								
8	103 +5/0*								
10	95 +5/0			80.4	92				
12.5	87 +5/0			73.4	87				
16	79 +5/0			66.7	83				
20	71 +5/0		74	60.5	74	78.5			
25	63 +5/0		64	54.7	64	68.7	70	80	90
31.5	55.5 +5/0	56	55	49.3	56	59.5	61	71	81
40	48 +5/0	49	46	44.6	49	51.1	54	64	74
50	40.5 +5/0	43	39	40.2	43	44	48	58	68
63	33.5 +5/0	41.5	33	36.2	41.5	37.5	46.5	56.5	66.5
80	28 +10/5	40	27	32.5	40	31.5	45	55	65
100	23.5 +10/5	38	22	29.1	38	26.5	43	53	63
125		36		26.1	36	22.1	41	51	61
160		34		23.4	34	17.9	39	49	59
200		32		20.9		14.4	37	47	57
250				18.6		11.4			

* Penalty for an equivalent-continuous level in case of tonal noise in the day/night period.

exposure limits for infrasound (expressed in G-weighted sound pressure levels). The recommended levels are set at 85 dB and 90 dB for dwellings, classrooms, offices, and other rooms in enterprises, respectively [21].

Similar situation occurs in Sweden in case of occupational noise, where present limits for infrasound (in 1/3-octave bands in the frequency range of 2–20 Hz) corresponding to G102 curve (AFS 1992:10) have been complemented by the above mentioned proposals for LFN [30]. (The G102 curve is expressed as: L_f=102-$K_{G,\,f}$ where: L_f is the sound pressure level for the f-th 1/3-octave band, in dB; $K_{G,\,f}$ is the relative response of the G-weighting frequency characteristic for the f-th 1/3-octave band, in dB).

Proposed criteria for the assessment of LFN in occupational settings

The proposed criteria for assessing occupational exposure to LFN are based on literature data concerning LFN effects on humans, the existing evaluation methods and the results of LFN measurements at workplaces.

First of all, an assumption was made that the difference between C- and A-weighted sound pressure levels (L_C-L_A) exceeding 15 dB indicates the occurrence of LFN. Three different evaluation methods and corresponding admissible values were proposed:

- method I – a frequency analysis in 1/3-octave bands within the range of 10–250 Hz;
- method II – consisting in 1/3-octave band measurements and the determination of low frequency equivalent-continuous A-weighted SPL (in the 10–250 Hz frequency range) using the following formula (1):

$$L_{A\,(10-250\,Hz)} = 10\log\sum_f 10^{0.1(L_f + K_{fA})}\ \text{(dB)} \qquad (1)$$

Where:

L_f – is the equivalent-continuous SPL in the 1/3-octave bands from 10 to 250 Hz, in dB;

K_{fA} – is the relative response of the A-weighting frequency characteristics for the f-th 1/3-octave band, in dB;

- method III – based on the equivalent-continuous A-weighted SPL corrected due to the presence of low frequencies (K_1) and the tonal character of noise (K_2), expressed by equation (2):

$$L_{A\,(LFN,\,ton)} = L_{Aeq,Te} + K_1 + K_2\ \text{(dB)} \qquad (2)$$

Where:

$L_{A\,eq,Te}$ – is the equivalent-continuous A-weighted SPL, in dB;

K_1 – is the penalty for the presence of low frequency components in the spectrum, K_1 = 8 dB for 15 dB ≤ L_C-L_A < 20 dB, K_1 = 10 dB for L_C-L_A ≤ 20 dB;

K_2 – is the penalty for the tonal character of noise, K_2 = 5 dB; the noise is said to be tonal if the level in a particular 1/3-octave band is 5 dB or more above the level in the two neighboring bands.

Generally, separate noise limits were recommended for workplaces requiring an increased mental processing and/or selective attention and located in the control rooms and office like-areas. Thus, two series (A and B) of various criterion curves were proposed for method I:

- curves HTL20, DIN20, S70, UK18 and A40 (Fig. 1) – suitable for workplaces in the office-like areas (series A),
- curves HTL30, DIN30, S90, UK28 and A50 – relating to control rooms (series B).

The reference curves, HTL20 and DIN20, from series A exceed the hearing threshold level by 20 dB according to ISO 226:2003 [29] and the criterion curve from the German method [19]. The S70 curve corresponds to an outline Swedish recommendation for workplaces, but lies 5 dB above curve S60 [24]. On the other hand, curve UK18 is modeled after the British proposal [23], but it is 18 dB higher, while curve A40 is based on A-weighting characteristics and is expressed as L_f = 40-K_{fA} (where: L_f is the sound pressure level for the f-th 1/3-octave band, in dB; K_{fA} is the relative response of the A-weighting frequency characteristics for the f-th 1/3-octave band, in dB).

It is worth noting that all criterion curves from series B are 10 dB higher than corresponding curves from series A. Moreover, low frequency A-weighted SPLs ($_{LA\ 10–250\ Hz}$) related to all aforesaid criterion curves are approximately 50 dB and 60 dB for series A and series B, respectively.

In method II as recommended, LFN limits of 60 dB and 50 dB for workplaces in control rooms and office-like areas, respectively, were proposed.

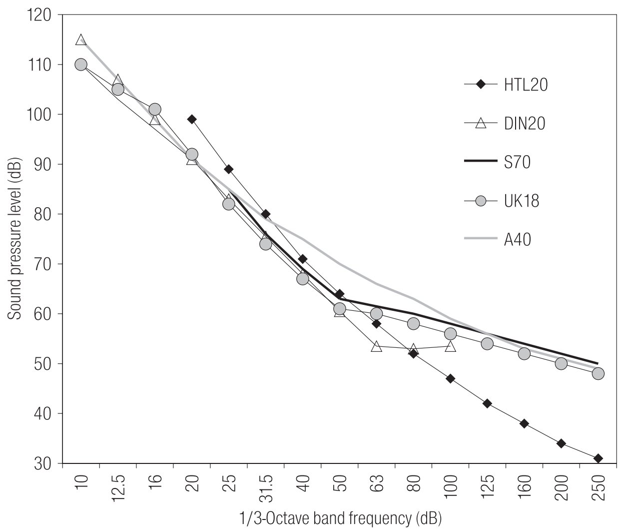

Fig. 1. Comparison of proposed various criterion curves for assessing low frequency noise (LFN) at workplaces in office-like areas (criterion curve: (i) HTL20 – is 20 dB higher than hearing threshold level according to ISO 226:2003 [29], (ii) DIN20 – lies 20 dB above the reference curve from DIN 45680: 1997 [19], (iii) UK18 – is based on the curve proposed in the UK, but is 18 dB higher [23], (iv) S70 – corresponds to Swedish recommendation for workplaces [24]; and (v) A40 – is expressed as $L_f = 40\text{-}K_{fA}$, where: L_f is the sound pressure level for the f-th 1/3-octave band, in dB; K_{fA} is the relative response of the A-weighting frequency characteristics for the f-th 1/3-octave band, in dB).

Current Polish Standard PN-N-01307:1994, along with measurement methods for the evaluation of occupational exposure to noise, specifies admissible values to ensure proper working conditions at selected categories of workplaces (Table 2) [31]. Therefore, in evaluation method III, the PN-N-01307:1994 admissible values, 65 dB and 55 dB, were incorporated, respectively into noise limits for workplaces in industrial control rooms and office-like areas.

VERIFICATION OF PROPOSED EXPOSURE CRITERIA FOR LFN

The proposed exposure criteria for evaluating LFN were verified in laboratory and field studies of the subjective noise annoyance rating.

Materials and methods

Laboratory study

Study group. The study group included 55 pre-selected female and male volunteers, aged 21.8 ± 2.1 years, mainly high school or university graduates.

Table 2. Admissible values of noise to ensure workers' proper conditions for performing basic functions at selected work posts as specified in PN-N-01307:1994 [31]

Workplace	An equivalent-continuous A-weighted sound pressure level (dB)
In cabins for direct control without telephone communications, in laboratories with noise sources, in rooms with counting machines, typewrites, teleprinters.	75
In observation cabins and remote control with telephone communications, on premises for precise works.	65
On premises for administration, design offices, research work, data handling.	55

Candidates were selected from 117 persons, recruited by advertising, based on their scores on two questionnaires used to evaluate separately individual sensitivity to noise in general and to LFN in particular. The way, the subjects were categorized in terms of individual sensitivity to noise was described in detail elsewhere [28]. Only persons recognized as highly sensitive (high-sensitive) or less sensitive (low-sensitive) to noise in general and/or to LFN were eligible for the investigation. Additionally, each person underwent the hearing test and only those with normal hearing (< 25 dB HL) participated in the study.

In the study group, 30 subjects were recognized as higher sensitive to LFN and 33 – as higher sensitive to noise in general, but the two sensitivity distributions were not identical. This means that higher sensitivity to LFN was not necessarily connected with higher sensitivity to noise in general.

Study design. The study subjects listened to different noises, at A-weighted SPL of 45−65 dB. They were asked to imagine that in such noise conditions they would have to perform jobs requiring increased mental processing and selective attention. Immediately after completion of each noise sample, they assessed the noise annoyance, loudness and the degree of disturbing effect of noise in case of routine jobs and more demanding tasks involving mental processing and selective attention. Self-evaluation of noises was presented on a paper form, using 100-score graphical rating scales. Prior to the exact listening tests, the subjects

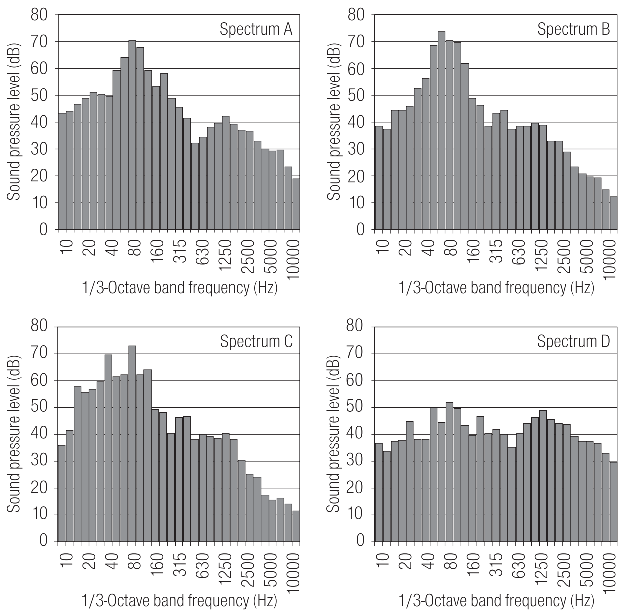

Fig. 2. Frequency spectra of noise samples at approximately A-weighted sound pressure level (SPL) of 55 dB used in the laboratory study (spectra A, B and C – low frequency noises, spectrum D – a broadband noise without dominant content of low frequencies).

Table 3. Parameters of low frequency noise (LFN) samples used in the laboratory study

Noise spectra	Nominal level (dB)	Equivalent-continuous SPL (dB)			L_C-L_A (dB)
		A-weighted $L_{A\ eq.T}$	C-weighted $L_{C\ eq.T}$	G-weighted $L_{G\ eq.T}$	
Spectrum A	45	45.5	63.4	56.2	17.9
	50	50.3	68.3	57.6	18
	55	55.0	73.2	61.7	18.2
	60	60.0	78.1	65.9	18.1
	65	64.9	83	70.8	18.1
Spectrum B	45	45.4	66.7	54.7	21.3
	50	50.3	71.7	56.1	21.4
	55	55.2	76.5	59.5	21.3
	60	60.0	81.5	63.1	21.5
	65	65.0	86.4	67.9	21.4
Spectrum C	45	44.7	64.8	60.3	20.1
	50	49.6	69.7	64.5	20.1
	55	54.4	74.7	69.2	20.3
	60	59.7	80.1	74.2	20.4
	65	65.4	86.8	79.2	21.4

SPL – sound pressure level.

were trained in using four noise examples. After the test session, they were asked to complete a questionnaire aimed at symptoms experienced during the tests and subjective rating of noise-related fatigue. The subjects received financial compensation for their participation in the study. The local Ethics Committee approved the study design.

Exposure conditions. The experiment was performed in a special chamber for psychological and audiometric tests (6.2 m^2 area). Four stationary noises of artificial origin with different frequency contents were chosen for the listening tests, including three LFNs and one noise without dominant content of low frequencies (Fig. 2). They were presented at nominal equivalent-continuous A-weighted SPLs of approximately 45, 50, 55, 60, and 65 dB, corresponding to levels normally occurring in industrial control rooms and office-like areas [32–34]. All presentations, lasting 30 s, were made once and the sequence of presentation was randomized.

The noises were generated using a set of loudspeakers and subwoofer. Noise exposure conditions during the listening session were monitored and evaluated with use of proposed assessing methods (Table 3).

Field study

The field study subjects comprised 232 male workers, aged 26–62 years, employed in the control rooms of three Polish electric power stations and one cement plant. The majority of them were high school graduates.

A questionnaire was applied as a main tool of the study. The subjects were asked to assess the annoyance related to noise at workplace on a 100-score graphical rating scale. Noise conditions in control rooms were verified by *in situ* measurements and evaluated according to the proposed assessment criteria.

The noise annoyance rating was supplemented by inquiries: (i) about basic information on age, education, workplace, years of employment; (ii) identifying sources of noise in control rooms and describing its character; (iii) describing the feelings and complaints subjectively related with exposure to noise at workplace; (iv) answering the question on what does the noise annoyance consist in; and (v) self-assessment of hearing status. Results of the questionnaire have been partly described elsewhere [32,33].

Generally, the inquired persons were exposed to rather steady-state noise at an equivalent-continuous: (i) A-weighted SPLs of 48–66 dB; (ii) C-weighted SPLs of 59–79 dB, and (iii) G-weighted SPLs of 59–92 dB. The noise comprised low frequency components (10–250 Hz), but their incidence in the spectra was diversified (the difference between C- and A-weighted sound pressure levels ranged from 3.7 to 20.2 dB). However, only in 19.4% of cases under study, the $L_C - L_A$ difference exceeded 15 dB, while in almost half of the cases (46.6%) it was greater than 10 dB. Therefore, only 35 subjects, aged 40.1 ± 7.2 years, without any hearing problems (see the questionnaire mentioned above), exposed to actual LFN at A-weighted sound pressure levels of 48–61 dB (Fig. 3), were selected for further analysis.

Statistical analysis

In both studies, laboratory and field, subjective ratings of LFNs were compared with objective results from the proposed exposure criteria. However, together with various evaluation methods intended for the LFN assessment, conventional methods based on the measurement of the equivalent-continuous A- and G-weighted SPLs ($L_{Aeq,T}$ and $L_{Geq,T}$) were also analyzed.

Exposure limits for $L_{Aeq,T}$ (55 and 65 dB) were taken from PN-N-01307:1994 (Table 2), while G-weighted sound pressure levels were compared to 85 and 90 dB, i.e., Danish limits for infrasound in offices and other rooms in enterprises, respectively [21].

Relationships between excesses of limits, corresponding to each evaluating method and noise-related annoyance assessments as well as relations between other variables were analyzed using Pearson's correlation coefficient (r).

In the laboratory study, one-way analysis of variance ANOVA for independent data were performed to evaluate the impact of sensitivity to noise or gender on subjective ratings of LFN samples. On the other hand, the influence of spectrum or nominal A-weighted SPL of noise samples on subjective assessments were analyzed using one-way ANOVA for dependent data.

All tests were two-tailed and probability values (p) below 0.05 were considered statistically significant. The statistical analysis employed SPSS software for Windows (Chicago, IL, USA).

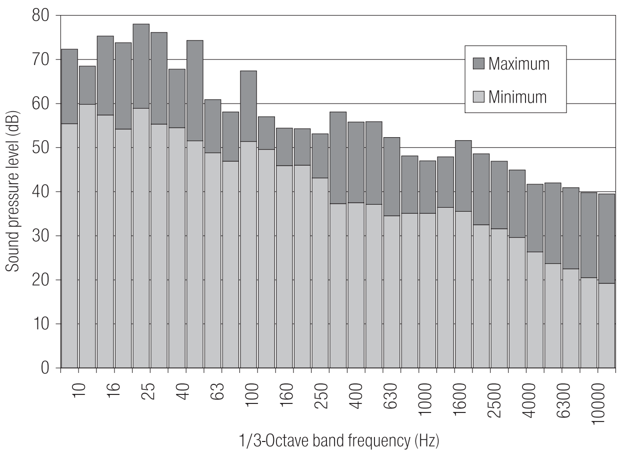

Fig. 3. Frequency spectrum of low frequency noise (LFN) occurring in control rooms (ranges of measured sound pressure levels in 1/3-octave bands from 10 to 10 000 Hz).

RESULTS

In the laboratory study, the subjects categorized in terms of sensitivity to noise were asked to assess annoyance related to LFN as well as loudness and the degree of its disturbing effect in case of routine and more demanding tasks. Regardless of individual sensitivity to noise, close relations between all subjective assessments were found. Thus, in the following part of the study, only the annoyance rating was considered. However, it is worth noting that the highest value of correlation coefficient was observed between the subjective rating of noise annoyance and the degree of its disturbing effect in case of mentally demanding tasks (Table 4).

Table 4. The relation between various subjective ratings in the laboratory study

Subjective ratings	Annoyance: Pearson's correlation coefficient r ($p < 0.0001$)
Loudness	0.863
Disturbing effect in	
Routine tasks	0.931
Mentally demanding tasks	0.863

Table 5. Subjective evaluations of low frequency noise (LFN) in laboratory and field conditions

Laboratory study – noise spectrum/ nominal level	Annoyance rating (Mean ± SD)						
	All subjects	Females	Males	Subjects LFN-	Subjects LFN+	Subjects NG-	Subjects NG+
A/ 45 dB	31.1 ± 23.4	26.9 ± 22.5	35.1 ± 24	29.3 ± 23.5	32.6 ± 23.7	27.9 ± 21.9	33.2 ± 24.5
A/ 50 dB	43.2 ± 22.3	42.6 ± 23.0	43.6 ± 22.1	38.2 ± 23.0	47.3 ± 21.2	35.3 ± 20.3*	48.4 ± 22.3*
A/ 55 dB	54.3 ± 20.8	52.7 ± 20.5	55.7 ± 21.4	50.1 ± 19.0	57.7 ± 21.9	46.8 ± 19.7*	59.3 ± 20.3*
A/ 60 dB	61.8 ± 21.7	60.4 ± 22.0	63.1 ± 21.7	55.7 ± 21.9	66.9 ± 20.5	57.5 ± 24.4	64.7 ± 19.5
A/ 65 dB	78.1 ± 17.8	81.4 ± 16.0	75.0 ± 19.1	72.3 ± 19.0*	83.1 ± 15.3*	74.6 ± 20.7	80.5 ± 15.4
B/ 45 dB	22.9 ± 20	22.1 ± 19.8	23.7 ± 20.5	19.0 ± 18.9	26.2 ± 20.7	14.6 ± 10.5*	28.4 ± 22.9*
B/ 50 dB	35 ± 21.7	37.9 ± 23.6	32.2 ± 19.8	24.4 ± 19.6*	43.8 ± 19.7*	21.5 ± 14.4*	44.0 ± 21.3*
B/ 55 dB	49.5 ± 22.5	48.5 ± 23.8	50.4 ± 21.6	42.2 ± 20.1*	55.5 ± 22.9*	40.2 ± 19.9*	55.7 ± 22.3*
B/ 60 dB	52.8 ± 23.8	53.7 ± 24.7	52.0 ± 23.5	43.2 ± 21.9*	60.9 ± 22.7*	44.3 ± 24.3*	58.6 ± 22.1*
B/ 65 dB	73.9 ± 18.8	75.6 ± 18.9	72.2 ± 18.9	68.2 ± 19.9*	78.6 ± 16.7*	69.7 ± 21.4	76.7 ± 16.7
C/ 45 dB	23.9 ± 21.5	21.4 ± 20.3	26.4 ± 22.8	19.5 ± 19.9	27.6 ± 22.5	16.3 ± 14.6*	29.0 ± 24.0*
C/ 50 dB	36.4 ± 23.6	35.8 ± 22.8	36.9 ± 24.7	28.2 ± 21.4*	43.2 ± 23.5*	25.8 ± 18.4*	43.4 ± 24.3*
C/ 55 dB	49.4 ± 21.2	46.1 ± 22.7	52.7 ± 19.5	45.2 ± 18.8	52.9 ± 22.8	41.8 ± 17.6*	54.5 ± 22.1*
C/ 60 dB	50.2 ± 25.1	50.5 ± 29.0	49.8 ± 21.2	41.0 ± 22.0*	57.8 ± 25.3*	42.7 ± 22.8	55.1 ± 25.6
C/ 65 dB	76.8 ± 20.3	77.9 ± 20.2	75.6 ± 20.7	69.6 ± 23.6*	82.7 ± 15.1*	69.8 ± 25.6*	81.4 ± 14.5*
Field study	47.3 ± 24.3						

SD – standard deviation;
LFN+ – subjects classified as high-sensitive to LFN;
NG+ – subjects classified as high-sensitive to noise in general;
LFN- – subjects classified as low-sensitive to LFN;
NG- – subjects classified as low-sensitive to noise in general;
* Significant differences between subgroups of various sensitivity to noise in general/to LFN.

As expected, the statistical analysis showed that spectrum and nominal A-weighted SPL of noise samples had significant influence on the subjective evaluation.

The subjective assessment of annoyance related to LFN in laboratory and field conditions are summarized in Table 5, while objective results from various assessment criteria are presented in Tables 6 and 7.

A considerable diversity of the annoyance ratings was observed in both field and laboratory conditions (Figs. 4 and 5). It is important to note that in the latter case, there were no significant differences in annoyance assessments between men and women. On the other hand, a significant influence of subjective sensitivity to noise in general and/or to LFN noise on annoyance rating was observed in some noise samples, especially in the B and C spectra (Table 5). The influence of gender and noise sensitivity on responses given in the questionnaire completed after the listening test will be analyzed elsewhere.

Generally, linear relationships between noise annoyance ratings and all proposed criteria for assessing LFN were found in both studies. Similar relations were also noted in the conventional method based on equivalent-continuous A- and G-weighted SPLs (Table 8). Moreover, the correlation coefficients (r) and thus the degree of explanation (r^2) were similar for all proposed LFN criteria and the conventional method based on $L_{Aeq,T}$. Neither in the labora-

Table 6. Objective assessments of low frequency noise (LFN) based on proposed exposure criteria in the laboratory study

Noise spectrum/ nominal level	Method I/criteria curve					Method II/exposure limit		Method III/exposure limit	
	HTL20/30	DIN20/30	S70/90	UK18/28	A40/50	50 dB	60 dB	55 dB	65 dB
	Excesses (dB)								
A/ 45 dB	14.3/4.3	7.8/-2.2	0.8/-9.2	2.8/-7.2	-1.2/-11.2	-6.1	-16.1	3.5	-6.5
A/ 50 dB	19.3/9.3	12.8/2.8	5.8/-4.2	7.8/-2.2	3.8/-6.2	-1.1	-11.1	8.3	-1.7
A/ 55 dB	24.2/14.2	17.6/7.6	10.6/0.6	12.6/2.6	8.7/-1.3	3.8	-6.2	13	3
A/ 60 dB	29.1/19.1	22.6/12.6	15.6/5.6	17.6/7.6	13.7/3.7	8.7	-1.3	18	8
A/ 65 dB	34/24	27.4/17.4	20.4/10.4	22.4/12.4	18.5/8.5	13.6	3.6	22.9	12.9
B/ 45 dB	12.7/2.7	10.4/0.4	2.4/-7.6	3.9/-6.1	0.7/-9.3	-5.3	-15.3	0.4	-9.6
B/ 50 dB	17.7/7.7	15.4/5.4	7.4/-2.6	8.9/-1.1	5.7/-4.3	-0.3	-10.3	5.3	-4.7
B/ 55 dB	22.7/12.7	20.4/10.4	12.4/2.4	13.9/3.9	10.7/0.7	4.6	-5.4	10.2	0.2
B/ 60 dB	27.5/17.5	25.2/15.2	17.2/7.2	18.7/8.7	15.5/5.5	9.5	-0.5	15	5
B/ 65 dB	32.5/22.5	30.2/20.2	22.2/12.2	23.7/13.7	20.5/10.5	14.5	4.5	20	10
C/ 45 dB	12.1/2.1	9.9/-0.1	2.9/-7.1	4.9/-5.1	-0.1/-10.1	-6.7	-16.7	4.7	-5.3
C/ 50 dB	17.2/7.2	14.9/4.9	7.9/-2.1	9.9/-0.1	4.9/-5.1	-1.7	-11.7	9.6	-0.4
C/ 55 dB	22.1/12.1	19.8/9.8	12.8/2.8	14.8/4.8	9.8/-0.2	3.2	-6.8	14.4	4.4
C/ 60 dB	27.3/17.3	24.7/14.7	17.7/7.7	19.7/9.7	14.7/4.7	8.5	-1.5	19.7	9.7
C/ 65 dB	33.4/23.4	29.1/19.1	22.1/12.1	24.1/14.1	19.4/9.4	14.6	4.6	20.4	10.4

Table 7. Objective assessments of low frequency noise (LFN) based on proposed exposure criteria in the field study

Excesses (dB)						
Method I/criterion curve					Method II/exposure limit	Method III/exposure limit
HTL20/30	DIN20/30	S70/90	UK18/28	A40/50	50/60 dB	55/65 dB
13.8 ÷ 22.1/ 3.8 ÷ 12.1	-2.1 ÷ 13.9/ -12.1 ÷ 3.9	-4.2 ÷ 11.3/ -14.2 ÷ 1.3	-2.2 ÷ 13.3/ -12.2 ÷ 3.3	-3.2 ÷ 8.4/ -13.2 ÷ -1.6	-8.0 ÷ 2/ -18.0 ÷ 8.0	5.7 ÷ 18.5/ -4.3 ÷ 8.5

Table 8. The relation between subjective noise annoyance ratings and limit excesses corresponding to various proposed criteria for evaluating low frequency noise (LFN) (methods I, II and III) as well as assessment methods based on A- or G-weighted sound pressure level

Exposure conditions	Pearson's correlation coefficient r ($p < 0.001$)								
	Method I/criterion curve					Method II/ exposure limit	Method III/ exposure limit	$L_{Aeq,T}$	$L_{Geq,T}$
	HTL20/30	DIN20/30	S70/90	UK18/28	A40/50	50 dB/60 dB	55dB/65 dB	55dB/65 dB	85dB/90 dB
Laboratory	0.612	0.574	0.582	0.584	0.586	0.599	0.582	0.604	0.437
Field	0.641	0.550	0.595	0.595	0.653	0.673	0.552	0.580	0.386*

*$p < 0.05$.

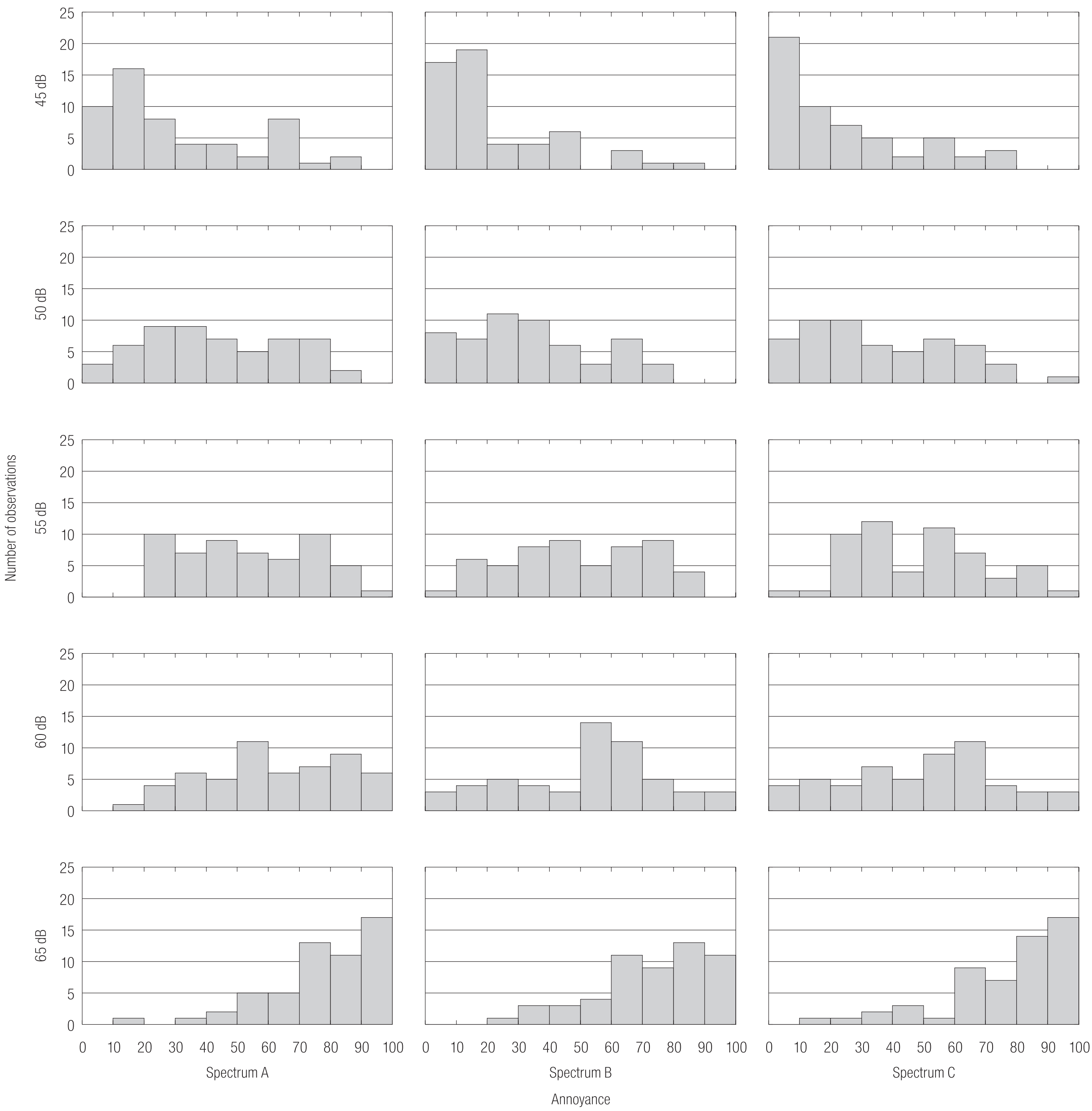

Fig. 4. Distributions of noise annoyance assessments in laboratory exposure conditions.

tory, nor in the field study, significant differences between aforesaid correlation coefficients were found.

However, the results from evaluation method I (the frequency analysis) and criterion curves HTL20/ HTL30 gave the highest value of correlation coefficient with subjective annoyance rating in the laboratory study, while in the field study method II provided the highest correlation.

Under laboratory conditions, the other best method was either method II or the conventional method based on $L_{A\ eq,T}$. In the field study, the second best method was frequency analysis and criterion curves based on A-weighting characteristics or hearing threshold level.

Regardless of exposure conditions, the worst correlation between subjective annoyance rating and objective results was noted for G-weighting. However, significant differences between correlation coefficients obtained for the method based on $L_{G\ eq,T}$ and other evaluating methods ($p < 0.0001$) were observed only in the laboratory study.

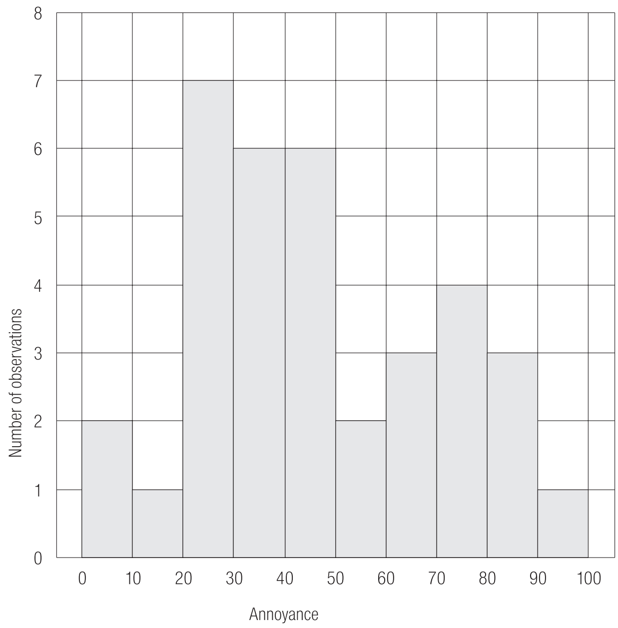

Fig. 5. Distributions of noise annoyance assessments in field exposure conditions.

DISCUSSION AND CONCLUSIONS

The major objective of this study was to recommend assessment criteria for occupational exposure to LFN in order to prevent its annoyance and effects on work performance. Thus, three different evaluation methods were proposed. Two of them, method I and method II, are based on frequency analysis in 1/3-octave bands. However, in the latter, like in the Danish assessment method for LFN in dwellings, nominal A-weighting corrections are added to spectra, and the weighted spectrum is summed up to form the low frequency A-weighted SPL. Method III is simply based on the equivalent-continuous A-weighted sound pressure level, but penalties due to the presence of low frequency components in the spectrum and tonal character of noise are added.

Separate exposure limits were proposed for workplaces in industrial control rooms and office-like areas. These limit values were intended for jobs requiring the increased mental processing and selective attention.

Admissible levels for method III were taken from current Polish Standard PN-N-013307:1994. For method II, exposure limits 5 dB lower than those for method III were recommended. For method I, various criterion curves were proposed in order to find out the best one. Most of them were modeled after existing reference curves for assessing LFN in the general environment. They include various frequency ranges and differ significantly from about 40 Hz. Therefore, they will give different results, although low frequency A-weighted SPLs related to all curves are similar, i.e., equal to approximately 50 dB and 60 dB for series A (office-like areas) and series B (control rooms), respectively.

Proposed criteria for assessing LFN were verified in laboratory and field studies of noise annoyance rating. The disadvantage of the laboratory testing compared to the field study was that noise samples of artificial origin were used making them probably not realistic enough. On the other hand, the advantage was that it was possible to control almost all experimental conditions (noises, levels, presentation sequence, subjects).

Regardless of research methodology (laboratory or field testing), there was quite good agreement between all proposed criteria for assessing LFN and the subjective annoyance rating. In the field conditions, however, the highest correlation coefficient was found for method II, while during the laboratory study for method I and criterion curves based on hearing threshold level (HTL20 and HTL30).

Recently, in order to compare various national criteria for assessing LFN in dwellings, a similar study was carried by Poulsen [35]. He played different environmental LFNs at relatively low A-weighted sound pressure levels (20–35 dB) to subjects in the laboratory and carried out an analysis to find out which method was the best predictor of their subjective annoyance assessment. He found that the Danish method gave the best correlation with subjective evaluations, but it depended on the 5 dB penalty for impulsive noise (e.g., from discotheque music). Without this penalty, the Danish method is similar to the Swedish and German (tonal and non-tonal) methods. Thus, these results do not differ significantly from our findings presented in this paper. In fact, in both studies all the analyzed methods seem to give similar results with non-impulsive LFN.

In this study, subjective noise annoyance assessments were additionally compared with objective results from conventional methods based on A- and G-weighting.

G-weighting, specifically designed for infrasound, falls off rapidly above 20 Hz, whereas between 2 and 20 Hz, it has the same slope (close to 12 dB per octave) as hearing perception threshold curves, equal loudness curves and equal annoyance curves. No wonder that it was shown that the G-weighing curve provides an objective measure correlating well with subjective annoyance ratings of infrasound [36]. But in this study, regardless of exposure conditions, the relations between subjective ratings and excesses of infrasound limits of 85 dB/90 dB (Danish recommendations for offices and other rooms in enterprises) were relatively weak in comparison with the results obtained for all proposed exposure criteria for LFN as well as with the method based on A-weighting. Relatively small values of correlation coefficients may be explained by frequency compositions of noise spectra (Figs. 2 and 3) since both studies were intended to verify exposure criteria for low frequency noise not for infrasound. However, these results do not rule out the need to propose exposure limits for G-weighting in order to prevent annoyance caused by infrasound, especially as infrasound only slightly above hearing threshold may be annoying and it is assumed that the sound pressure levels found on the G86 curve are the limit values of the hearing threshold that is exceeded in 90–95% of the population [37].

It is surprising that in this study the correlation between annoyance ratings and the conventional assessment method based on A-weighted SPL was quite good. In particular, relatively high value of correlation coefficient was noted during the laboratory testing. In the study [35] cited above, this relationship was not analyzed. However, it was only pointed out that the noise example, the nominal level and the measured A-weighted SPL had a significant influence on the subjective annoyance assessments.

Earlier field and laboratory studies have shown a weak relationship between A-weighted SPL and annoyance. The underestimation of LFN effects by A-weighting is about 6 dB at levels of approximately 40−50 dB and somewhat higher for higher SPLs [3,15,16,24]. In contrary to residential areas, where noise levels are often low, LFN occurring in industrial control rooms is usually well above the hearing threshold and therefore represents problem different from that faced in homes. However, only scant data are available for workplaces with higher noise levels.

Nevertheless the presented findings suggest that all proposed exposure criteria for LFN, especially the assessment method based on the low frequency equivalent-continuous A-weighted sound SPL (method II) as well as frequency analysis in 1/3-octave bands from 10 (20) to 250 Hz (method I) and criterion curves based on the hearing threshold level or A-weighting characteristics seem to be able to quite well predict annoyance experienced from LFN in occupational settings.

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