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MEASUREMENTS OF ACOUSTIC PROPERTIES FOR LEVEL-DEPENDENT EAR-MUFFS

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The aim of this paper is to present methods of acoustic measurements of level-dependent ear-muffs with an electronic sound restoration system switched off and on, according to EN 352-4. Measurements of sound attenuation and H, M, L criterion levels were carried out for a model of a level-dependent earmuff. The acoustic properties of test sites, sound field requirements and test signals are discussed. Measurements of sound attenuation were carried out in a chamber for testing hearing protectors. The chamber fulfilled the requirements of PN-EN 24869-1. Measurements of the H, M, L criterion levels were carried out in a reverberation room where the sound field of the test site complied with the requirements specified in ISO/DIS 11904-1. Both the chamber for testing hearing protectors and the reverberation room are the part of the laboratory of noise in the Central Institute for Labour Protection in Warsaw, Poland.

1. Introduction

Hearing protectors are often the only immediate countermeasure against the negative effects of noise on human hearing. The most common situations in which hearing protectors are usually used are noisy workplaces with steady noise. In these workplaces conventional, passive hearing protectors are mostly applied and they usually provide good results. Yet, for unexpected and intermittent impulse noise (for example, shooting) level-dependent ear-muffs are recommended. They are designed to provide increased protection when the noise level increases and to improve speech intelligibility and perception of warning signals when the noise level decreases. The acoustic performance of level-dependent ear-muffs is achieved with an electronic sound restoration circuit, which is fitted inside the ear-muffs' cups.

Level-dependent ear-muffs have to meet the acoustic and mechanical requirements of EN 352-4. Acoustic measurements of ear-muffs are carried out for their passive and active modes (i.e. for the 'off' and 'on' modes). In the passive mode sound attenuation is determined according to PN-EN 24869-1. In the active mode, with the sound transmission system turned on and set at full gain, A-weighted equivalent diffuse sound pressure levels (measured under the cups) are measured and H, M, L criterion levels are determined. For these measurements the 'microphone-in-real-ear' technique (MIRE) is used according to ISO/DIS 11904-1.

2. Sound attenuation measurements

Measurement of sound attenuation is a basic test of acoustic performance of all kinds of hearing protectors. During the measurements an electronic circuit is turned off and a level-dependent earmuff acts as a passive hearing protector. In this section the most important requirements and conditions regarding this test method are discussed. Measurement results of sound attenuation for level-dependent ear-muff are also presented.

2.1. Test site

Measurements of sound attenuation of hearing protectors were carried out in a special chamber where sound field requirements could be met. These requirements were fulfilled in a test chamber within a limited space called the test site. The test site is defined as the space inside of a sphere with a 15-cm radius and with its centre at reference point *R* (Fig. 1). The reference point was located about 115 cm above the floor of the test chamber, and at the midpoint of the line between the conchae of the test subject normally seated in the test chamber during measurements.

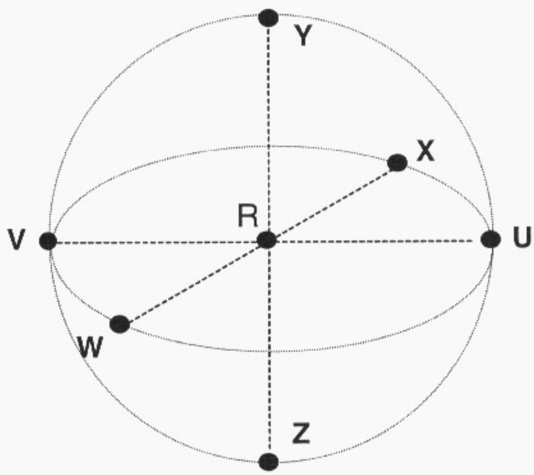

Fig. 1. A diagram of the test site.

According to the requirements in PN-EN 24869-1 in order to carry out measurements of sound attenuation of hearing protectors it is necessary to establish a diffuse sound field at the test site. The sound field should fulfil some conditions.

The first two conditions refer to the diffusivity of the sound field. According to the first condition sound pressure levels measured with an omnidirectional microphone, with the subject and the subject's chair absent, at reference point R and at six points: U, V, W, X, Y, Z on the sphere of with a 15-cm radius, should not differ by more than ± 2.5 dB (within the range of 50 Hz to 10 kHz). Because measurements are carried out for both ears, sound pressure levels between the measurement points at the extreme right and extreme left (U, V or W, X – depending on the subject orientation) should not differ by more than ± 3 dB. For this test, the axis of the microphone should be fixed in the same direction. A diagram showing the location of the measurement points at the test site is presented in Fig. 1.

The differences in the measured sound pressure levels are presented in Table 1. The differences in the sound pressure level calculated for all measurement points did not exceed the required value of ± 2.5 dB (and ± 3 dB for extreme points: U, V or W, X).

Table 1. The differences in sound pressure levels measured at the seven points of the test site in the test chamber.

	ΔL, dB							
f, Hz	63	125	250	500	1000	2000	4000	8000
$L_U - L_R$	– 0.7	1.5	0.7	0	0	0.6	0	0.2
$L_W - L_R$	– 1.1	1.3	– 1.7	0.1	0.2	– 0.5	– 0.4	– 0.1
$L_V - L_R$	– 1.5	– 1.0	1.9	0.7	0.2	– 1.2	– 1.1	0.3
$L_X - L_R$	0.6	– 1.2	– 0.1	– 0.5	– 0.9	1.0	0.7	0
$L_Y - L_R$	– 2.5	– 1.2	– 0.3	0.2	0.1	– 0.8	– 0.9	0.9
$L_Z - L_R$	2.1	– 0.6	0.4	– 1.2	0.3	– 1.2	1.1	0.2
$L_U - L_V$	0.8	2.5	1.2	0.7	0.2	1.9	1.1	0.1
$L_X - L_W$	1.7	2.5	1.6	0.7	1.1	1.5	1.1	0

In order to check the second condition for the diffuse sound field at the test site the maximal difference between sound pressure levels measured with a unidirectional microphone at frequencies equal to and higher than 500 Hz at the reference point for two directions of measurements, has to be observed. The observed maximal difference should not exceed a certain value corresponding to the front-to-random sensitivity index of the directional microphone used. The front-to-random sensitivity index of the microphone should be at least 4 dB. The measurements were carried out with a directional microphone (KM 84 Neuman, Germany) with the front-to-random sensitivity index of 5 dB. In this case the permissible maximum difference of sound pressure levels should not exceed 5 dB for any one-third-octave band of noise with centre frequency from 500 Hz to 8 kHz. The microphone was fixed on a rotating boom and the measurements were carried out in three planes perpendicular to one another. The maximal difference of the octave band sound pressure levels at reference point R for two directions of measurement equal to 4.9 dB was observed for 8 kHz.

The next condition that should be fulfilled in order to accept a test site for measuring sound attenuation according to PN-EN 24869-1 is the appropriate reverberation time characteristics. Reverberation time should not exceed 1.6 s for any test band. To determine the reverberation time curve the classical method was used. Reverberation time for a given frequency was determined from the 60 dB – decay curves. Pink noise filtered in the octave bands was used as the test signal. The measurements of reverberation time were repeated three times, for three different positions of the sound source. Reverberation time was lower than 1.6 s for all test bands. In Fig. 2 average reverberation time characteristics is shown.

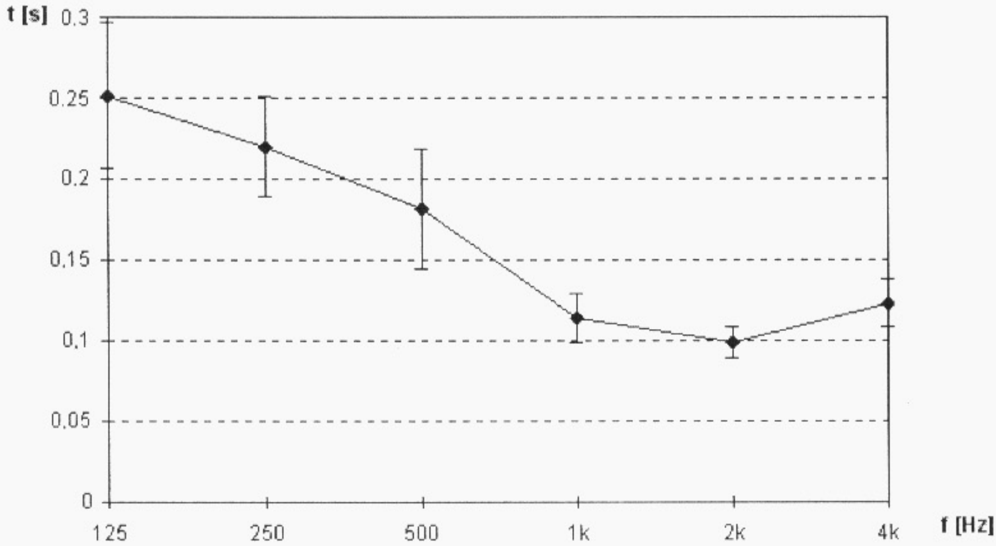

Fig. 2. Reverberation time characteristics measured in the test chamber.

The last condition applies to maximum permissible background sound pressure levels. In order to check if the levels were not exceeded 24-hour continuous broad band spectrum measurements were carried out. Spectra were recorded every 90 s which resulted in 980 one-second spectrum records. In comparison with the maximum permissible background sound pressure levels (from PN-EN 24869-1) the obtained results did not exceed critical values.

2.2. Test facility and test equipment

The test facility for measuring sound attenuation of hearing protectors was situated in a special test chamber that was built for acoustic measurements of hearing protectors. The subjects were seated inside the chamber during the measurements. A schematic diagram of the facility is presented in Fig. 3.

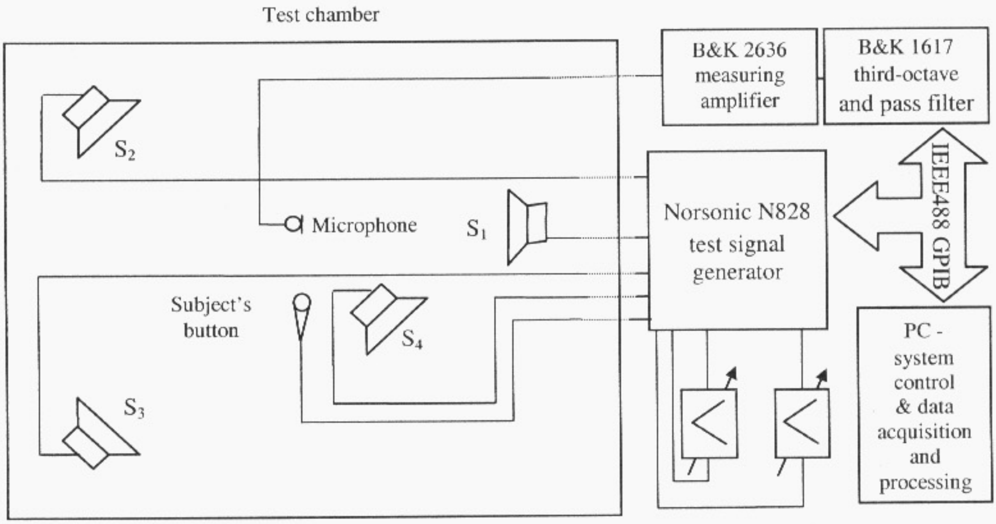

Fig. 3. A schematic diagram of the test facility for measuring sound attenuation.

The instrumentation set used for generating test signals and obtaining test results was an important part of the facility. The set for generating and controlling the test signal consisted of the following devices:

- a Norsonic N828 signal generator (four-channel noncoherent sine/noise generators), Norsonic AS,
- a subject's button (connected to a Norsonic N828 signal generator),
- two two-channel QUAD 520f power amplifiers. QUAD Electroacoustics Ltd.,
- a PC – a computer control unit with an IEEE 488 interface card. Baza Computer,
- four JBL 4208 Monitor loudspeakers, JBL Professional,

Devices used for calibrating test signals in particular channels prior to measurements were part of the instrumentation set, too. They were:

- a Bruel & Kjaer type 2636 measuring amplifier, Bruel & Kjaer,
- a Bruel & Kjaer type 1617 third-octave and octave band-pass filter, Bruel & Kjaer,
- a Bruel & Kjaer type 4165 microphone with a Bruel & Kjaer type 2619 preamplifier, Bruel & Kjaer.

All the devices except for the loudspeakers, the microphone and the subject's button were situated outside the test chamber. The loudspeakers were placed in the test chamber in such a way that the central points of their front planes formed a tetrahedron.

2.3. Test subjects

According to the test procedure a group of 16 subjects were needed to carry out the measurements of sound attenuation of hearing protectors. The subjects could not have the hearing threshold level above a specified limit (15 dB for frequencies up to 2 kHz and 25 dB for higher frequencies. for each ear). The build of their heads and ears could not affect the fitting of the hearing protectors. Additionally the test subjects had to be able to give stable responses during the tests – the subjects' thresholds of hearing at corresponding centre frequencies determined during three consecutive audiograms for the test signals shouldn't differ by more than 6 dB.

2.4. Test signals

The test signals used for determining sound attenuation of hearing protectors were pink noise based signals filtered through one-third-octave bands with the following centre frequencies: 63 Hz (optional), 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz.

2.5. Test procedure

In order to determine sound attenuation of hearing protectors it is necessary to measure hearing thresholds of 16 properly selected test subjects. Hearing thresholds must be measured twice: with open ears (unoccluded threshold) and with hearing protectors in place (occluded threshold). Both measurements must be carried out in a test chamber under exactly the same conditions (a detailed description of hearing thresholds measurements can be found in ISO 8253-1 and ISO 8253-2). Then sound attenuation should be calculated. In order to do that for a given frequency the value of occluded threshold should be subtracted from the value of unoccluded threshold. Finally, the mean of the sixteen results (mean sound attenuation m_f) together with standard deviation (s_f) for each test frequency should be determined.

The number of samples used for the test is 4 for ear-muffs (or ear-muffs attached to an industrial safety helmet) and 16 for earplugs.

Four samples of level-dependent earmuffs were equally distributed among the test subjects.

2.6. Test results

The object tested was a prototype model of a level-dependent earmuff designed in the Central Institute for Labour Protection. The results of measurements are presented in Table 2.

Table 2. Results of sound attenuation measurements.

Mean sound atte-nuation. in dB	12.4	13.8	17.1	24.8	19.0	19.1	33.8	37.4
Standard deviation in dB	4.2	4.2	2.7	4.2	3.3	2.9	3.7	3.8

3. Criterion level measurements

At the beginning of this section it is important to define the parameters (H, M, L criterion levels) which describe the acoustic performance of a level-dependent earmuff with an electronic circuit switched on. The electronic circuit provides 'dynamic' protection of hearing because it is able to change the sound attenuation characteristics of an earmuff in real time. The extent to which sound attenuation of the earmuff changes depends on the level of ambient noise and the noise spectrum.

The H, M, L criterion levels are A-weighted sound pressure levels of respective H, M, L – test noise signals for which the A-weighted equivalent diffuse field sound pressure level when a level-dependent ear-muff is worn first exceeds 85 dBA as a mean for eight subjects (16 cups). The A-weighted equivalent diffuse field sound pressure level is calculated from the one-third-octave band spectrum of noise measured with a miniature microphone in the concha of a given subject, corrected by subtracting the transfer function, which is specific for each subject.

3.1. Test site

EN 13819-2 recommends establishing a diffuse sound field for tests. On the other hand during the measurements of H, M, L criterion levels it is sometimes necessary to generate test signals reaching up to 120 dBA. Therefore the test site for the measurements was located in the centre of the reverberation room.

The requirements for the test site are given in ISO/DIS 11904-1 and IEC 60268-7. Just like in the case of sound attenuation measurements the test site is defined as the space inside of a sphere with a 15-cm radius, with its centre at reference point R (the definition of the reference point is also analogous to that previously mentioned). Similarly, two diffuse sound field requirements must be fulfilled. If the measurements are to be done with both ears the requirements are almost identical except that the frequency range of the test signals is 100 Hz to 12.5 kHz and the test signals are broad band noises.

The differences in the measured sound pressure levels (for the flat spectrum and three test signals) at reference point L_R and successively at six points on the sphere – L_U, L_V, L_W, L_X, L_Y, L_Z are presented in Table 3. The location diagram of the measurement points at the test site is presented in section 2.1 in Fig. 2.

Table 3. The differences in the sound pressure levels measured at the seven points of the test site in the reverberation room.

	Δ L. dB			
	Flat spectrum	Signal H	Signal M	Signal L
$L_U - L_R$	0	0	0.1	0.1
$L_W - L_R$	0.1	0.3	0.1	– 0.1
$L_V - L_R$	– 0.2	0	– 0.2	– 0.1
$L_X - L_R$	– 0.2	0.2	– 0.2	– 0.5
$L_Y - L_R$	– 0.2	– 0.7	– 0.1	– 0.2
$L_Z - L_R$	0.4	0.4	0.1	0.1
$L_U - L_V$	0.2	0	0.3	0.2
$L_X - L_W$	– 0.3	– 0.1	– 0.3	– 0.4

Regardless of the signal, sound pressure level differences calculated for all measurement points did not exceed the maximum permissible value of ± 2.5 dB. The maximum difference of – 0.7 dB was observed for point Y. The differences between sound pressure levels measured at opposite points (U-V and W-X) did not deviate by more than ± 3 dB, either. The maximum difference of – 0.4 dB was observed for points W-X and test signal L.

The second condition for the diffuse sound field was checked in accordance with the procedure described in Sec. 2.1. This time the measurements were carried out with a directional microphone (Mc 381 Tonsil, Poland) with the front-to-random sensitivity index of 5 dB. In this case the permissible maximum difference of sound pressure levels could not exceed 5 dB for any one-third-octave band of noise with centre frequency from 500 Hz to 12.5 kHz. The maximum differences of the one-third-octave band sound pressure levels at reference point *R* for two directions of measurement are presented in Fig. 4. The maximal difference of 2.9 dB was observed for 800 Hz.

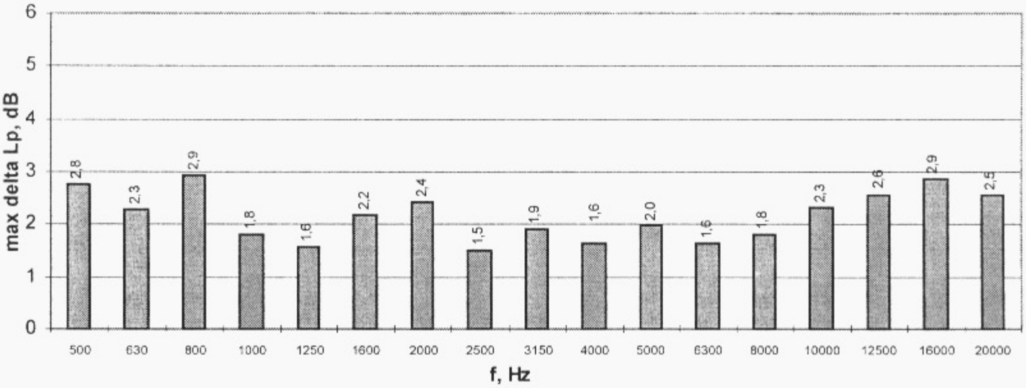

Fig. 4. The measured maximum differences of the one-third-octave band sound pressure levels at reference point *R* for two directions of measurement.

3.2. Test facility

The test facility for criterion level measurements was situated in a reverberation room. The test subject was seated in the reverberation room with miniature microphones fixed in conchae. The instrumentation including signal generation devices and measurement devices is presented in Fig. 5.

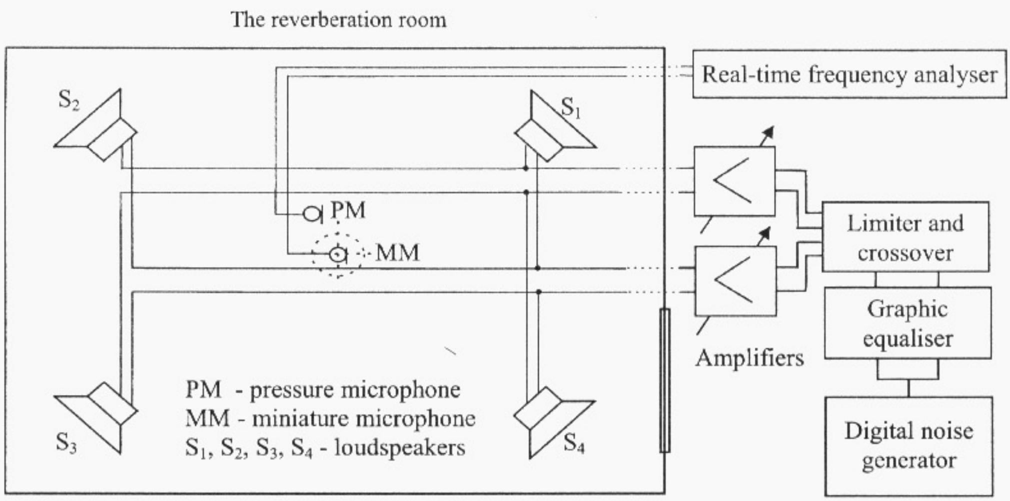

Fig. 5. A schematic diagram of the test facility for measuring *H*, *M*, *L* criterion levels.

The instrumentation set for signal generation consisted of the following devices:

- a Bruel & Kjaer 1049 digital noise generator, Bruel & Kjaer,
- two CROWN MacroTech MA2400 amplifiers, Crown International,
- a JBL Digital System Controller DSC 260 integrated limiter and crossover, JBL Professional,
- a YAMAHA YDG 2030 programmable digital graphic equalizer, YAMAHA Corporation,
- four JBL SR 4722A loudspeakers, JBL Professional.

The receiving part of the electroacoustic channel was used for measuring sound pressure levels at the reference point of the test site and in the concha of each subject. Sound pressure level measurements were carried out using the following devices:

- a two-channel Bruel & Kjaer 2144 real-time spectrum analyzer, Bruel & Kjaer,
- a Bruel & Kjaer 4193 pressure-field microphone with a Bruel & Kjaer 2669 preamplifier, Bruel & Kjaer,
- a Knowles BL 1785 miniature microphone, Knowles Electronics Inc.,
- a Bruel & Kjaer Nexus conditioning amplifier, Bruel & Kjaer.

All the devices, except for the loudspeakers and the miniature microphones with the conditioning amplifier, were situated outside the reverberation room. The loudspeakers were facing the subject.

3.3. Test subjects

The subjects who took part in measuring the criterion level had to be free from inflammations or other pathologies of the outer ear and the middle ear. The ear canals of the subjects could not be too narrow, flat or severely bent. The test subjects could not have eardrum defects. Eight subjects, who fulfilled these requirements, were chosen for the tests. According to ISO/DIS 11904-1 for group data evaluation a minimum of 8 subjects should be used in measurements.

3.4. Test signals

Three test signals: high (H), medium (M) and low frequency (L). were based on pink and white noise. The test signals were generated in the A-weighted sound pressure level range from 60 dB up to approximately 120 dB for H noise. 115 dB for M noise and 110 dB for L noise. The sample of measured spectra, A-weighted and C-weighted sound pressure level of the test signals are presented in Fig. 6. The measurements were done at the reference point of the test site with the subject absent. The differences between A-weighted and C-weighted sound pressure levels are: – 1.2 dB for H noise, – 2 dB for M noise and 6 dB for L noise.

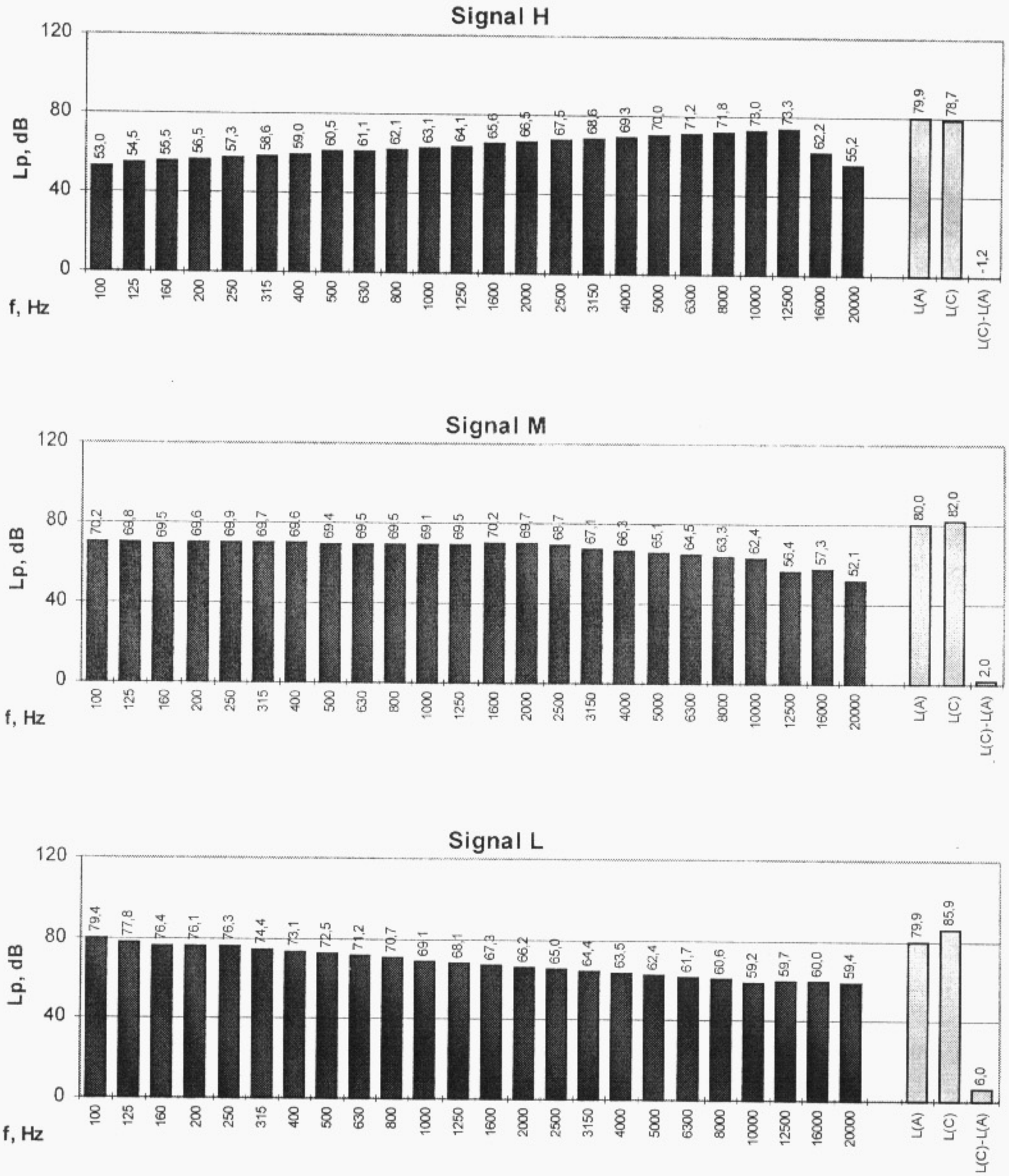

Fig. 6. An example of test signal spectra.

3.5. Test procedure

Determining the transfer function for each of the eight subjects was the first task of the measurement procedure. Transfer function $C(f_i)$ describes differences in one-third-octave band sound pressure levels measured with the reference microphone at reference point R of the test site with the subject absent (L_{ref}) and with a miniature microphone in the concha of the subject (L_{ear}). During the measurements with the miniature microphone, the subject has to be situated at the test site in such a way that the midpoint of the line between his/her conchae is at the reference point in the sound field. The test signal for measuring the transfer function is a flat spectrum signal with fairly constant one-third octave band sound pressure levels (within $\pm$ 5 dB) and with sound pressure levels equal to approximately 70 dB for all frequency bands. The transfer functions were individually determined for both ears.

In the next step of the procedure the tested level-dependent ear-muff with the electronic system in operation at full gain is situated on the subject's head without changing the position of the miniature microphones in the subject's ears. Then, test signal H (M, L) is generated at specified levels. The level of the test signal is increased in 5-dB steps until it reaches the maximal required value. For each test signal level one-third-octave spectra are measured in the subject's both conchae. Taking into account the previously determined transfer functions, the A-weighted equivalent diffuse field sound pressure levels $L_{\mathrm{A.eq.dyf}}$ are calculated according to formula (1).

$$L_{\mathrm{A.eq.dyf}} = 10 \log \left[\sum_{i=1}^{21} 10^{(L(f_i) \; + \; C(f_i) \; + \; K_A(f_i))} \right], \tag{1}$$

where: $L(f_i)$ – one-third-octave band sound pressure level measured in the ear canal, $C(f_i)$ – transfer function, $K_A(f_i)$ – frequency weighting A in accordance with IEC 651, f_i – centre frequency of the one-third-octave band.

For each type of test signal a chart of the mean, for all samples and all subjects, of the A-weighted equivalent diffuse field sound pressure level $L_{\mathrm{A.eq.dyf}}$ as a function of the external A-weighted sound pressure level $L_{\mathrm{A.external}}$ had to be prepared. Then using graphical interpolation values of $L_{\mathrm{A.external}}$ for which $L_{\mathrm{A.eq.dyf}}$ is equal to 85 dBA had to be found. Next, three obtained values (H, M, L) of the external A-weighted sound pressure level had to be plotted on another chart in the way presented in Fig. 8.

Using extrapolation and assuming a linear relationship for the change in $L_{\mathrm{A.external}}$ with the (L_C–L_A) value the predicted external levels $L_{\mathrm{A.external}}$ for the H test signal at (L_C–L_A) = – 2 dB and L test signal at (L_C–L_A) = 10 dB had to be determined. The linear relationship concerns either side of the M-value of (L_C–L_A) = 2 dB (see Fig. 9). These values are respective H, M, L criterion levels.

3.5. *Experimental results*

Transfer functions $C(f_i)$ for eight subjects, determined as the average value for data measured in the subject's left and right ears, are presented in Fig. 7.

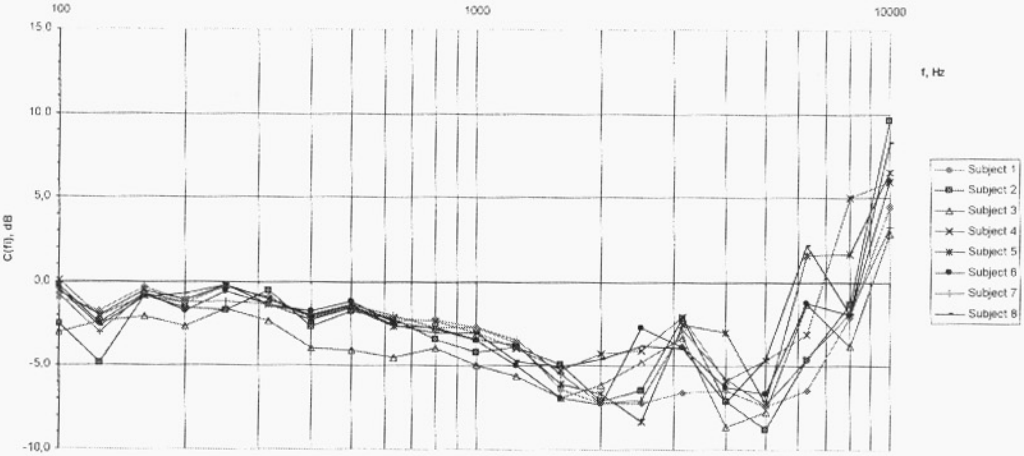

Fig. 7. Transfer functions of eight subjects (each curve is a mean for the left and right ears).

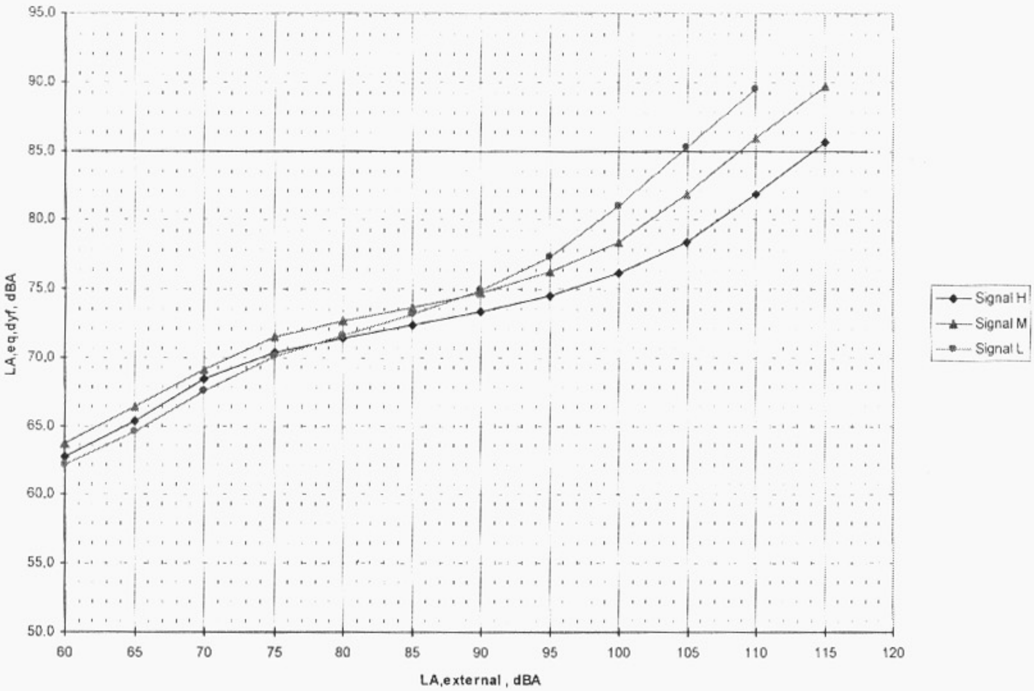

Fig. 8. The A-weighted equivalent diffuse field sound pressure level under the cup of the level-dependent ear-muff for the external sound pressure levels.

The A-weighted equivalent diffuse field sound pressure level $L_{A.eq.dyf}$ as functions of the external A-weighted sound pressure level $L_{A.external}$ determined for three test signals H, M, L are presented in Fig. 8.

As described above, the criterion levels are determined using graphical interpolation (Fig. 8) and extrapolation (Fig. 9).

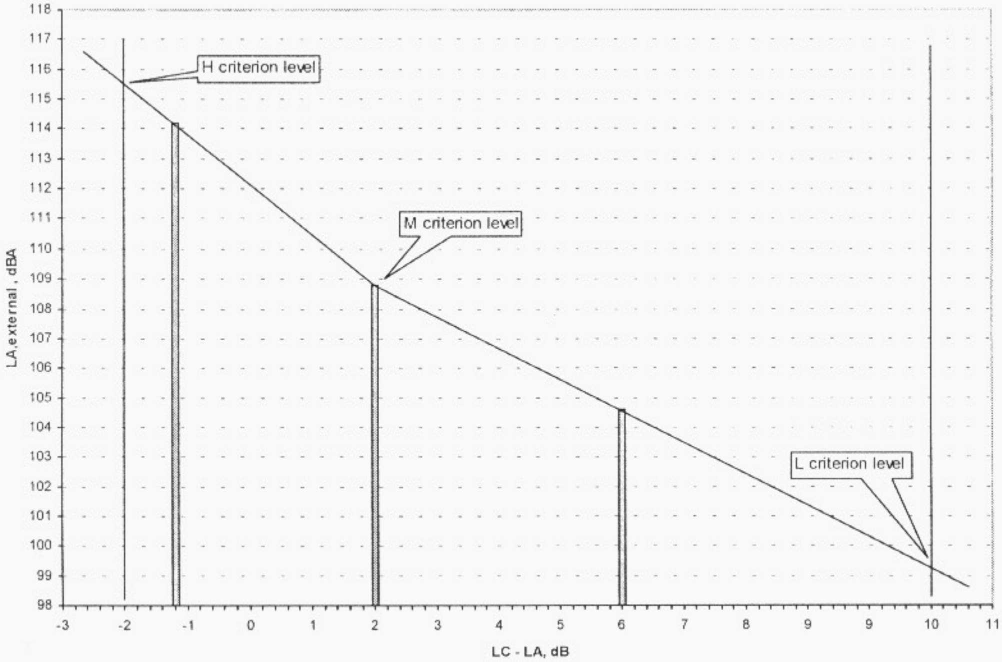

Fig. 9. The chart used for determining H, M, L criterion levels.

For the tested level-dependent ear-muff the criterion level values are as follows: H criterion level = 115.6 dB, M criterion level = 108.8 dB, L criterion level = 99.3 dB.

The A-weighted equivalent diffuse field sound pressure levels with standard deviations (four samples of ear-muffs, eight subjects, both ears) of the level-dependent ear-muff tested, for the external test signal sound pressure levels are presented in Table 4.

Table 4. The A-weighted equivalent diffuse field sound pressure levels with standard deviations.

Test signal level, dB	Signal H		Signal M		Signal L	
	Mean, dB	Std Dev., dB	Mean, dB	Std Dev., dB	Mean, dB	Std Dev., dB
60	62.8	1.9	63.7	2.1	62.1	2.0
65	65.4	2.0	66.4	2.2	64.6	2.1
70	68.4	2.2	69.1	2.3	67.6	1.7
75	70.3	2.3	71.5	1.4	70.0	1.3
80	71.4	2.3	72.7	1.3	71.7	1.1
85	72.4	2.2	73.7	1.3	73.1	1.1
90	73.4	2.2	74.7	1.2	74.9	1.2
95	74.6	2.1	76.2	1.1	77.3	1.6
100	76.2	2.1	78.4	1.1	81.0	2.0
105	78.4	2.0	81.8	1.3	85.3	2.2
110	81.9	2.1	85.9	1.5	89.5	2.1
115	85.7	2.2	89.7	1.6	–	–

4. Conclusion

Hearing protectors with electronic circuits appeared on the market a few years ago and because of their undisputed functionality users appreciate them. Especially level-dependent earmuffs have become popular as they offer a good relation between the price and their performance. Nowadays, almost all leading producers of hearing protectors offer at least one model of level-dependent earmuffs. It is therefore very important to develop methods of testing level-dependent earmuffs. Measuring the acoustic performance of an earmuff's electronic circuit seems to be a significant part of these tests as malfunctioning electronics can result in insufficient protection of the earmuff's user's hearing or even in a noise-induced hearing loss.

The test methods presented in the paper have been drawn up by members of ISO and CEN Technical Committees. The described methods present the state of the art on measuring the acoustic performance of level-dependent ear-muffs.

Acknowledgements

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