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RELATION OF EAR PROTECTOR ATTENUATION TO NOISE SPECTRA AND METHODS FOR ITS DETERMINATION

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454 spectra of industrial noise the sound level of which exceeded 90 dB (A), i.e. the maximum permissible values as established by the Polish Standard PN-70/B-02151 were analyzed. The real-ear attenuation for seven ear protectors was investigated and attenuation values for each of 454 noise spectra were calculated. An analysis of the attenuation of ear protectors as a function of the noise spectrum index Δ_{CA} was made and the regression curves for $S_A = f(\Delta_{CA})$ were determined. Several methods for the determination of attenuation were given and a comparative analysis of the results was made. It follows from the analysis that the best method for determination of the attenuation uses the mean spectrum.

1. Introduction

As established by Polish Standards PN-70/B-02151 [10] and PN-77/N-01310 [12] and by the recommendations of ISO/R 1999-1971 (*E*) [7], the weighted noise level expressed in dB (A) is the criterion for the estimation of the harmful effect of noise on the human organism. Thus, when considering the ear protector performance, one should use the levels reaching the ears when protectors are used, as measured in these units. Knowledge of the quantity defined as attenuation in Polish Standard PN-76/N-01309 [11] has practical significance for the estimation of the performance and choice of ear protectors. Ear protector attenuation is the quantity determining the sound level reduction at the tympanum due to the use of ear protector. As established by the recommendation ISO/R 1999-1971 (*E*) and the above mentioned Polish Standard, the attenuation S_A is expressed in dB (A) and calculated from the formula

$$S_A = L_A - 10\log \sum_f \operatorname{antilog} \frac{L_f - S_f + K_{A,f}}{10} \quad \mathrm{dB(A)}, \tag{1}$$

where L_A — sound level in dB(A) occurring at the work place, L_f — band pressure level (in dB) in an octave band of centre frequency f, S_f — mean real-ear attenuation of ear protectors (in dB) at the frequency f, $K_{A,f}$ – coordinates of correction curve A for the sound level meter (in dB) at a frequency f ($f = 63$, 125, 250, 500, 1000, 2000, 4000, 8000 Hz).

It follows from formula (1) that the value of the ear protector attenuation depends on the spectral distribution of the noise considered and for one type of ear protector can vary over a range of a dozen dB(A) or so, depending on the spectral distribution of the noise [4, 8, 15-19]. Calculation of the attenuation S_A from formula (1) also requires the determination from measurements of: eight values of the band pressure level L_f in octave bands, eight values of the real-ear attenuation S_f of the ear protectors, and the performance of rather complicated calculations. Thus for several years investigators have looked for a simpler way of characterizing the noise spectra than that of giving the values of the band pressure level in eight octave or (24) 1/3-octave bands and for a rapid method – as little dependent on the noise spectrum as possible – for the determination of ear protector attenuation or the sound level L_s of the noise in dB(A) reaching the ears when using ear protector. Research in this direction was initiated by Botsford [2-4].

Taking into consideration the difference between the correction curves A and C used in acoustic meters, Botsford postulated a thesis that the difference between the weighted sound levels $L_C - L_A = \Delta_{CA}$, subsequently called the *noise spectrum index*, determines the noise spectral distribution. He analyzed about 1000 spectra, including 580 spectra of industrial noise, and stated that the relation suggested is valid for two thirds of real noise sources.

On the basis of Botsford's verified theory, Waugh [18] divided industrial noise into five categories depending on the value of the Δ_{CA}-index (Table 1).

Table 1. Division of noise spectra into categories

Category	1	2	3	4	5
Δ_{AC} [dB]	$\leqslant 0$	0.1-2.0	2.1-4.0	4.1-9.0	> 9

For comparison, he standardized noise spectra so that sound level was the same for each spectrum, e.g. $L_A = 90$ dB(A). It is achieved by subtracting from the band pressure level in each octave band the number of decibels by which the sound level of noise considered exceeds the chosen value of L_A.

Standardization of the noise spectrum does not change the value of the attenuation S_A for ear protectors under the assumption (consistent with the results of investigations previously obtained [13]) that the real-ear attenuation of ear protectors does not depend on the sound pressure level.

Waugh investigated 619 spectra of individual noise sources and determined a mean spectrum for each category. Comparing values of the attenuation S_A for 30 types of ear protectors, calculated from formula (1), on the basis of the above-mentioned mean spectra and 619 specific noise spectra, Waugh found that the attenuation S_A, determined from the mean noise spectrum for a given category, is different from the mean attenuation determined on this basis of all spectra which belong to the given category by about 1 dB(A). Thus in practice for the selection of ear protectors it is enough to estimate the attenuation on the basis of the mean spectrum for the category comprising the noise spectrum considered.

Botsford assumed that there is a quantity characteristic of ear protectors which does not depend on the spectral distribution of the noise [3, 4]. As a result of an investigation on the six mean noise spectra he found that the difference $L_C - L_S$ = SLC is the desired quantity, where L_S is the sound level of noise in dB(A) corrected by the ear protector. The quantity SLC (short for *Sound Level Conversion*) permits determination of the sound level reaching an ear protected by an ear protector when the sound level L_C — of the noise is known. Changing the noise spectrum index Δ_{CA} from 0 to 20 dB, Botsford obtained a change in the value of SLC for different types of ear protectors over a range of only several decibels, whereas their attenuation S_A varied over more than 20 decibels.

The quantity SLC is related to the attenuation S_A and noise spectrum indices Δ_{CA} by the following relation:

$$\mathrm{SLC} = S_A + \Delta_{CA}. \tag{2}$$

Substituting into formula (2) the mean value of SLC for a given type of ear protector instead of SLC and the value of Δ_{CA}, Botsford obtained values of attenuation S_A which differed at most by 0 ± 3 dB(A) from the values determined in an exact manner from formula (1).

On the basis of the values of attenuation S_A determined for the six spectra of Botsford [4], Johnson and Nixon [8] obtained equations for the regression curves of the attenuation S_A as a function of noise spectrum index Δ_{CA} for different types of ear protectors, i.e. determining the coefficients b aid m in the equation

$$S_A = b + m\Delta_{CA} \tag{3}$$

by the method of least squares. By comparison of the values of attenuation S_A determinated by the linear regression method (formula (3)), the exact method (formula (1)) and SLC method (formula (2)), Johnson and Nixon found that the method they used gave attenuation values closest to those obtained by the exact method. Although slightly less exact, Botsford's method was, however, far simpler.

The present paper includes part of results of investigations [16] aimed the determination of ear protector attenuation for noise spectra occurring in domestic industry and at the creation of a method for rapid selection of the domestically available ear protectors most suitable for the noise involved. In the present paper, the discussion is limited to the investigation of real-ear attenuation of ear protectors, analysis of industrial noise spectra and the investigation of the relation of ear protector attenuation to the spectral distribution of the noise.

2. Characteristics of real-ear attenuation of ear protector

The real-ear attenuation S_f of ear protectors was determined by an audiometric method using the audibility threshold shift of a group of ten people, complying with the requirements of Polish Standard PN-76/01309 [11, 16]. The values of the realear attenuation S_f, found for seven selected types of ear protectors and the appropriate standard deviations s, are shown in Table 2.

Table 2. Real-ear attenuation S_f of ear protectors and standard deviation s [dB]

Type of ear protectors	Quantity	Frequency [Hz] 63	125	250	500	1000	2000	4000	8000
TD-1A	S_f	6.3	4.4	0.0	14.6	25.8	23.2	26.3	22.4
	s	4.9	3.7	5.0	3.9	4.8	6.3	5.1	6.5
TD-5	S_f	8.0	6.6	7.3	16.2	27.2	22.1	29.4	25.1
	s	4.2	3.0	3.3	3.0	2.9	4.6	4.4	4.6
Saturn II	S_f	10.7	10.3	13.2	12.4	13.8	21.5	29.7	29.2
	s	8.6	8.2	7.0	6.8	7.5	10.0	7.9	11.1
E-A-R	S_f	18.8	18.2	21.0	19.9	23.0	30.9	42.2	35.0
	s	3.8	3.9	4.9	5.5	6.4	5.8	7.9	7.2
Ear defender	S_f	16.5	13.7	15.1	13.6	17.3	25.6	27.7	26.5
	s	9.5	7.9	8.1	7.8	6.8	7.5	6.2	7.7
3M Brand No 8773	S_f	21.4	17.3	18.9	18.8	19.1	23.9	25.9	31.8
	s	3.6	2.9	4.3	4.8	2.3	7.0	7.9	6.7
Contraphon wool	S_f	6.2	6.5	8.5	8.6	11.5	21.2	27.1	28.5
	s	3.3	3.3	4.5	3.3	3.6	5.3	6.2	5.0

Ear muffs TD-1A and TD-5 and ear plugs Saturn II are the latest types of domestically produced ear protectors, contraphon wool is imported from the GDR. The other types are only sporadically used domestically.

It can be concluded from Table 2 that the ear muffs TD-5 are characterized by a higher real-ear attenuation for low and medium tones, compared with ear muffs TD-1A, whereas amongst ear plugs, E-A-R have the best and contraphon wool the worst properties.

3. Analysis of noise spectra in domestic industry

For the investigation of spectral distributions of noise occurring in the Polish industry, 454 records were selected from about 900 spectra of quasi stationary noises and analyzed. The sound level of the selected noises exceeded 90 dB(A) — the maximum acceptable value, as established by the Polish Standards PN-70/B-02151 and PN-77/N-01310, p. 01 [10, 12].

These spectra were gathered from measurements made by the Technological Acoustic Department of the Central Institute of Occupational Safety, Sanitary and Epidemiological Board in Warsaw, and the Research and Design Office of the Textile Industry in Łódź. These results comprised values of the octave band pressure level over a range of central frequencies of 63-8000 Hz.

Having the values of pressure levels, L_f, in octave bands at mean frequencies $f = 63, 125, 250, 500, 1000, 2000, 4000, 8000$ Hz for the noise considered, the sound levels of the noise L_A and L_C were determined from the relations

$$L_A = 10 \log \sum_f 10^{0.1(L_f + K_{A,f})}, \tag{4}$$

$$L_C = 10 \log \sum_f 10^{0.1(L_f + K_{C,f})}, \tag{5}$$

and also the difference

$$\Delta_{AC} = L_C - L_A, \tag{6}$$

where $K_{A,f}$ and $K_{C,f}$ are the coordinates of correction curves A and C of a sound level meter, with values given in Table 3. For the above calculations

Table 3. The coordinates of the correction curves A and C

f [Hz]	63	125	250	500	1000	2000	4000	8000
$K_{A,f}$ [dB]	−26.2	−16.1	−8.6	−3.2	0	1.2	1.0	−1.1
$K_{C,f}$ [dB]	−0.8	−0.2	0	0	0	−0.2	−0.8	−3.0

a special analytical programme for a Hewlett Packard 9810 *A* minicomputer was designed, which was included as a subprogramme in the analytical programme for calculating the attenuation S_A, the reduced attenuation S_{As}, and the SLC of the types of ear protectors investigated.

The noise spectra investigated were divided into five categories, depending on the values of noise spectrum index $\Delta_{CA} = L_C - L_A$ in accordance with Table 1, and a mean noise spectrum was determined for each category. The octave band pressure level values for mean noise spectra standardized to the value $L_A = 90$ dB(A) are given in Table 4.

Table 4. The mean noise spectra for domestic industry standardized to 90 dB(A)

Category	Octave band centre frequencies [Hz]								
	63	125	250	500	1000	2000	4000	8000	Δ_{CA} [dB]
1	67.8	69.8	71.8	76.1	80.8	84.0	84.9	82.8	−1.1
2	75.5	78.5	80.9	84.3	85.8	84.0	80.0	75.1	0.8
3	82.1	84.6	85.9	87.6	85.6	82.4	77.0	70.9	2.9
4	88.6	88.5	89.5	88.0	85.3	81.1	75.3	68.1	5.2
5	99.1	97.4	91.2	88.4	83.5	78.1	71.3	62.1	11.6

4. Determination of the attenuation S_A and reduced attenuation $S_{A,S}$ for ear protectors

The attenuation of ear protectors investigated was determined for two cases:

1. When using as a starting point the mean real-ear attenuation S_f of ear protectors – the attenuation thus determined aws denoted by S_A.

It follows from statistical considerations that in such a case the ear protectors will diminish the noise sound level by at least S_A dB(A) for about 50% of the users.

2. When using as a starting point the reduced real-ear attenuation $S_{f,s}$, equal to the mean value of the real-ear attenuation $S_{f,s}$ reduced by standard deviation s ($S_{f,s} = S_f - s$) – the attenuation calculated in this way was named "reduced" and denoted by $S_{A,S}$. Accounting for standard deviation, diminution of the sound level by at least $S_{A,s}$ dB(A) is achieved by ear protectors for about 85% of the users.

The attenuation S_A and reduced attenuation $S_{A,s}$ for a set of noise spectra, occurring in domestic industry, and the mean values of $\bar{S}_A$ and $\bar{S}_{A,s}$ for each spectrum category were determined [16]. Calculated values of S_A and $S_{A,s}$ for each type ear protector were plotted on the coordinate systems Δ_{CA}, S_A and Δ_{CA}, $S_{A,s}$. A graphic representation of the calculations for E-A-R plugs is presented in Fig. 1, as an example. Mean values of $\bar{S}_A$ and $\bar{S}_{A,s}$ are given in Table 5.

As can be seen in Fig. 1 and Table 5, with increasing value of the noise spectrum index Δ_{CA}, i.e. when passing from noises whose spectra contain strong

Table 5. The mean attenuation $\bar{S}_A$ and mean reduced attenuation $\bar{S}_{A,s}$ of ear protectors [dB(A)]

Type of ear protectors	Quantity	The noise spectrum category				
		1	2	3	4	5
TD-1A	$\bar{S}_A$	21.2	16.2	12.0	8.9	5.8
	$\bar{S}_{A,s}$	15.7	11.3	7.1	4.1	1.1
TD-5	$\bar{S}_A$	23.6	20.3	17.2	14.5	11.2
	$\bar{S}_{A,s}$	19.4	16.7	13.9	11.3	8.0
Saturn II	$\bar{S}_A$	20.5	16.3	14.8	14.1	13.0
	$\bar{S}_{A,s}$	12.1	8.6	7.4	6.6	5.2
E-A-R	$\bar{S}_A$	29.3	25.0	23.1	22.2	21.0
	$\bar{S}_{A,s}$	23.1	19.0	17.3	16.6	15.8
Ear defender	$\bar{S}_A$	22.7	18.9	17.1	16.2	15.3
	$\bar{S}_{A,s}$	15.5	11.6	9.7	8.6	7.6
3 M Brand No. 8773	$\bar{S}_A$	23.9	21.3	20.2	19.7	19.1
	$\bar{S}_{A,s}$	18.0	16.7	16.0	15.6	15.1
Contraphon wool	$\bar{S}_A$	18.2	13.6	11.7	10.6	9.3
	$\bar{S}_{A,s}$	14.1	9.9	8.0	6.9	5.6

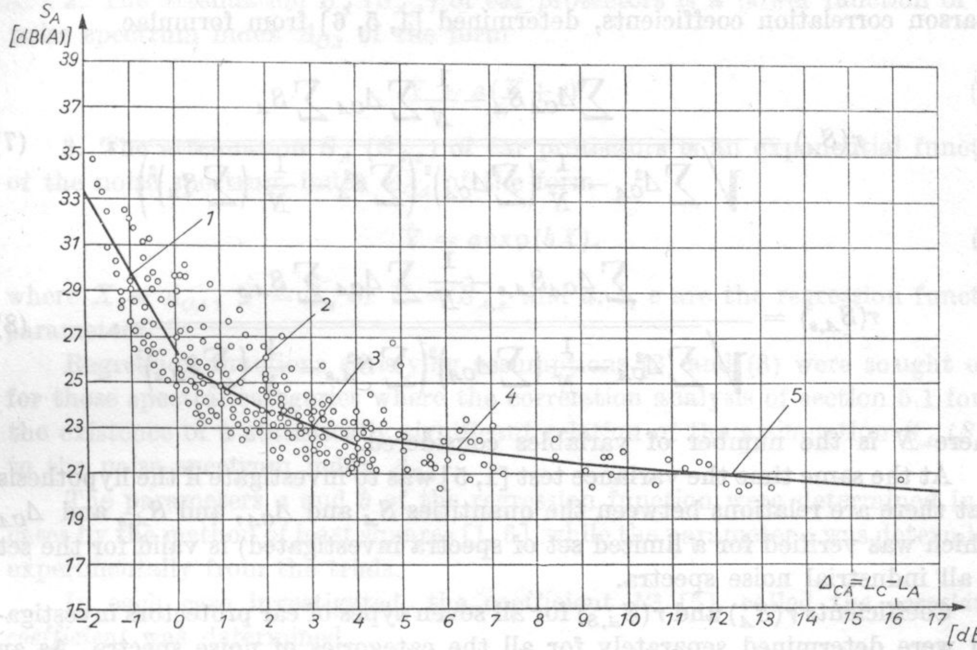

Fig. 1. Attenuation S_A of E-A-R plugs; linear regression curves and their equations $1 - S_A = 26.4 - 3.5\,\Delta_{CA}$; $2 - S_A = 26.0 - 1.1\,\Delta_{CA}$; $3 - S_A = 25.6 - 0.8\,\Delta_{CA}$; $4 - S_A = 23.4 - 0.2\,\Delta_{CA}$; $5 - S_A = 22.6 - 0.1\,\Delta_{CA}$

high frequency components to noises with strong low frequency components, the attenuation S_A and the reduced attenuation $S_{A,S}$ of all types of ear protectors decrease. The most rapid variation in the attenuation S_A and the reduced attenuation $S_{A,s}$ occurs with categories of noise spectra 1-3 for all types of ear protectors. The ear plugs are characterized by a lower relation of the attenuation S_A and the reduced attenuation $S_{A,S}$ to the noise spectral distribution, compared to the ear muffs. The relative variation in values of the attenuation S_A and the reduced attenuation $S_{A,s}$ is 5-11 dB(A) for the ear plugs and 11-20 dB(A) for the ear muffs.

5. Analysis of the results

The spacing of the analytic points on the curves relating S_A and $S_{A,s}$ to the value of the noise spectrum index Δ_{CA} suggests the existence of a correlation between these variables and functional relations $S_A = f(\Delta_{CA})$ and $S_{A,s} = f(\Delta_{CA})$. The correlation was investigated and regression relations determined.

5.1. Investigation of the correlatien. The existence of correlation between the quantities S_A and Δ_{CA}, and $S_{A,s}$ and Δ_{CA} was investigated using the

Pearson correlation coefficients, determined [1, 5, 6] from formulae

$$r(S_A) = \frac{\sum \Delta_{CA} S_A - \frac{1}{N}\sum \Delta_{CA} \sum S_A}{\sqrt{\sum \Delta_{CA}^2 - \frac{1}{N}\left(\sum \Delta_{CA}\right)^2 \left(\sum S_A^2 - \frac{1}{N}\left(\sum S_A\right)^2\right)}}, \tag{7}$$

$$r(S_{A,s}) = \frac{\sum \Delta_{CA} S_{A,s} - \frac{1}{N}\sum \Delta_{CA} \sum S_{A,s}}{\sqrt{\sum \Delta_{CA}^2 - \frac{1}{N}\left(\sum \Delta_{CA}\right)^2 \left(\sum S_{A,s}^2 - \frac{1}{N}\left(\sum S_{A,s}\right)^2\right)}}, \tag{8}$$

where N is the number of variables considered.

At the same time the variance test [1, 5] was to investigate if the hypothesis that there are relations between the quantities S_A and Δ_{CA}, and $S_{A,s}$ and Δ_{CA} (which was verified for a limited set of spectra investigated) is valid for the set of all industrial noise spectra.

Coefficients $r(S_A)$ and $r(S_{A,S})$ for all seven types of ear protectors investigated were determined separately for all the categories of noise spectra. As an example, values of the coefficients $r(S_A)$ and $r(S_{A,s})$ for E-A-R plugs are given in Table 6. It was found that in general the attenuation S_A and the reduced

Table 6. The correlation coefficients $r(S_A)$ and $r(S_{A,s})$ for E-A-R plugs

Noise category	1	2	3	4	5
$r(S_A)$	−0.726	−0.425	−0.467	−0.284	−0.502
$r(S_{A,s})$	−0.681	−0.391	−0.424	−0.200	−0.390

attenuation $S_{A,s}$, of the ear protectors considered, depend strongly on the value of Δ_{CA} for spectral categories 1, 2 and 3 (a strong negative relationship), whereas it is almost independent of the noise spectral distribution for noises in categories 4 and 5.

5.2. Investigation of the regression. The analysis carried out in section 5.1 showed the existence of the distinct relation of attenuation S_A and reduced attenuation $S_{A,s}$ to the noise spectrum index Δ_{CA}, and thus to the noise spectrum. In order to determine the form of this dependence, regression analyses were made with the following assumptions:

1. The attenuation S_A ($S_{A,S}$) of ear protectors is a linear function of the noise spectrum index Δ_{CA} for each category of noise spectra:

$$\hat{Y} = aX + b. \tag{9}$$

2. The attenuation S_A ($S_{A,s}$) of ear protectors is a power function of the noise spectrum index Δ_{CA} of the form

$$\hat{Y} = a(X+c)^b. \tag{10}$$

3. The attenuation S_A ($S_{A,s}$) of ear protectors is an exponential function of the noise spectrum index Δ_{CA} of the form

$$\hat{Y} = a\exp(bX), \tag{11}$$

where $X = \Delta_{CA}$, $\hat{Y} = S_A$ or $\hat{Y} = S_{A,s}$ and a, b, c are the regression function parameters.

Regression functions satisfying assumptions (2) and (3) were sought only for those spectral categories where the correlation analysis of section 5.1 found the existence of a statistically significant relation of the attenuation S_A ($S_{A,s}$) to the noise spectrum index Δ_{CA}.

The parameters a and b of the regression function were determined in all cases by the method of least squares [1, 6], while the parameter c was determined experimentally from the trials.

In each case investigated, the coefficient R^2 [5], called the *correlation coefficient* was determined,

$$R^2 = \frac{\sum Y^2 - \frac{1}{N}\left(\sum Y\right)^2 - \sum (Y-\hat{Y})^2}{\sum Y^2 - \frac{1}{N}\left(\sum Y\right)^2}, \tag{12}$$

where Y is a variable (in the present case $Y = S_A$ or $Y = S_{A,s}$), N – the number of variables considered, $\hat{Y}$ – the value determined from the regression equation for a given X (here $X = \Delta_{CA}$).

The coefficient R^2 can take values from 0 to 1, and the larger R^2, the better the regression function Y describes the dependence considered [1, 5].

5.2.1. Linear regression of the ear protector attenuation in different categories of noise spectra. The equations for curves describing the dependence the attenuation S_A and reduced attenuation $S_{A,s}$ on the noise spectrum index Δ_{CA} were determined by a linear regression analysis. The linear regression dependences are statistically significant at the level $\alpha = 0.05$. A significant linear dependence of attenuation S_A and reduced attenuation $S_{A,s}$ on Δ_{CA}, i.e. on the noise spectral distribution, occurs for all ear protectors investigated in spectral categories 1, 2 and 3, in category 4 for the following types of protectors: TD-1A, Saturn II, E-A-R, contraphon wool, and in category 5 for the plugs Saturn II and E-A-R only.

Fig. 1 shows regression curves of the attenuation S_A in particular noise spectral categories for E-A-R plugs.

5.2.2. Curvilinear regression of the ear protector attenuation. On the sample of 3*M* Brand No. 8773 plugs it was found that the mean values $\bar{S}_A$ ($\bar{S}_{A,s}$) and $\bar{\Delta}_{CA}$ in particular categories had practically the same regression equations as all the individual values S_A ($S_{A,s}$) and Δ_{CA} over the ranges of these quantities considered. Thus, when looking for a general regression function that would not only be valid within one category, the mean values $\bar{S}_A$, $\bar{S}_{A,s}$ and $\bar{\Delta}_{CA}$ for the different categories were used. Using the method of least squares and with the experimental determination for the case of the square regression (formula (10)) of such a value of the parameter c that the coefficient R^2 would reach the maximum possible value, curvilinear regression equations were obtained as presented in Tables 7 and 8.

Table 7. Equations of curvilinear regression of the attenuation S_A of ear protectors ($\hat{S}_A$ in dB(A) and Δ_{CA} in dB)

Type of ear protectors	Equation of curvilinear regression	Regression coefficient		Regression in spectral categories
		curvilinear R^2	linear R^2	
TD-1A	$\hat{S}_A = 75.5\,(\Delta_{CA}+5)^{-0.902}$	0.994	0.981	1 – 4
	$\hat{S}_A = 18.5\exp(-0.135\,\Delta_{CA})$	0.994		
TD-5	$\hat{S}_A = 21.9\exp(-0.075\,\Delta_{CA})$	0.994	0.979	1 – 4
Saturn II	$\hat{S}_A = 23.5\,(\Delta_{CA}+3)^{-0.236}$	0.943	0.706	1 – 5
	$\hat{S}_A = 17.7\exp(-0.033\,\Delta_{CA})$	0.761		
	$\hat{S}_A = 20.5\,(\Delta_{CA}+2)^{-0.187}$	0.974		
E-A-R	$\hat{S}_A = 32.5\,(\Delta_{CA}+3)^{-0.175}$	0.952	0.734	1 – 5
	$\hat{S}_A = 31\,(\Delta_{CA}+2.5)^{-0.157}$	0.967		
Ear defender	$\hat{S}_A = 28.2\,(\Delta_{CA}+3)^{-0.284}$	0.994	0.936	1 – 3
3M BRAND No 8773	$\hat{S}_A = 22.7\exp(-0.044\,\Delta_{CA})$	0.928	0.917	1 – 3
Contraphon	$\hat{S}_A = 22.9\,(\Delta_{CA}+3)^{-0.356}$	0.975	0.742	1 – 5

For comparison, the values of the coefficient R^2 for the linear regression are also given in these tables. It was found that curvilinear regression equations describe the observed dependencies of the attenuation $\hat{S}_A$ ($\hat{S}_{A,s}$) on the noise spectrum index Δ_{CA} better than the linear regression equations (R^2 for curvilinear regressions is greater than R^2 for linear regressions), and the square law regression proved better than the exponential for all cases except the ear muffs TD-1A and TD-5.

In Fig. 2 points corresponding to the values of $\bar{S}_A$ and $\bar{\Delta}_{CA}$ for E-A-R plugs for particular categories are plotted, and the regression curves obtained drawn together with the regression linear curves within particular spectral categories.

Table 8. Equations of curvilinear regression of the reduced attenuation $S_{A,s}$ of ear protectors ($\hat{S}_{A,s}$ in dB(A) and Δ_{CA} in dB)

Type of ear protectors	Equations of curvilinear regression	Regression coefficient curvilinear R^2	Regression coefficient linear R^2	Regression in spectral categories
TD-1A	$\hat{S}_{A,S} = 20144954.7\,(\Delta_{CA}+20)^{-4.748}$	0.996	0.97	1 – 4
	$\hat{S}_{A,S} = 13.4 \exp(-0.214\,\Delta_{CA})$	0.999		
TD-5	$\hat{S}_{A,S} = 18.1 \exp(-0.085\,\Delta_{AC})$	0.999	0.988	1 – 4
Saturn II	$\hat{S}_{A,S} = 16.5\,(\Delta_{CA}+3)^{-0.44}$	0.987	0.78	1 – 5
	$\hat{S}_{A,S} = 9.8 \exp(-0.064\,\Delta_{CA})$	0.883		
E-A-R	$\hat{S}_{A,S} = 28.6\,(\Delta_{CA}+3)^{-0.288}$	0.986	0.917	1 – 3
	$\hat{S}_{A,S} = 25.7\,(\Delta_{CA}+3)^{-0.198}$	0.922	0.677	1 – 5
Ear defender	$\hat{S}_{A,S} = 21.4(\Delta_{CA}+3)^{-0.434}$	0.991	0.865	1 – 4
3M BRAND	$\hat{S}_{A,S} = 19.1\,(\Delta_{CA}+3)^{-0.094}$	0.971	0.791	1 – 5
No 8773	$\hat{S}_{A,S} = 17.1 \exp(-0.013\,\Delta_{CA})$	0.811		
Contraphon	$\hat{S}_{A,S} = 20.6\,(\Delta_{CA}+3)^{-0.519}$	0.992	0.857	1 – 4

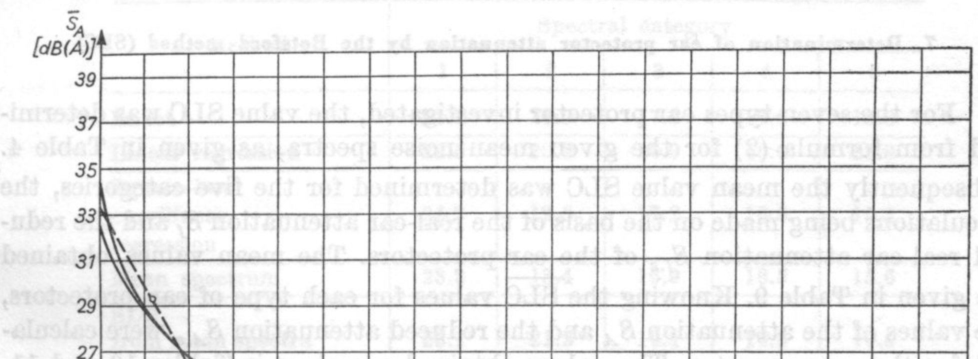

Fig. 2. Regression curves of the attenuation $\bar{S}_A$ of inserts E-A-R plugs (Optac) and their equations
$1 - S_A = 32.5\,(\Delta_{CA}+3)^{-0,175}$; $2 - S_A = 30.953(\Delta_{CA}+2.5)^{-0.157}$

Analyzing the linear and curvilinear regression curves separately for each type of ear protector, it was found that curvilinear regression curves with a high coefficient R^2 are the optimal regression curves for the sets of values of S_A ($S_{A,s}$) and Δ_{CA} considered.

6. Determination of ear protector attenuation on the basis of mean noise spectra

For the seven types of ear protector investigated the attenuation S_A and the reduced attenuation $S_{A,s}$ were determined by the exact method for five mean noise spectra, as shown in Table 4. The values obtained for each type of ear protector were plotted on diagram analogous to Fig. 1. The curves were plotted through the points thus obtained and extrapolated beyond the extremal points. On the basis of the curves thus determined for the attenuation S_A and the reduced attenuation $S_{A,s}$ relative to the points corresponding to the attenuation values of the ear protectors for the 454 noise spectra investigated, it was considered that these curves represent well the dependence of the mean attenuation of the ear protectors on the noise spectrum index Δ_{CA}. Instead of investigating the attenuations S_A and $S_{A,s}$ for a large range of spectra, it is sufficient to determine the curves for $S_A = f(\Delta_{CA})$ and $S_{A,s} = f(\Delta_{CA})$ on the basis of only five values: those obtained for the mean spectra in particular categories.

7. Determination of ear protector attenuation by the Botsford method (SLC)

For the seven types ear protector investigated, the value SLC was determined from formula (2) for the given mean noise spectra, as given in Table 4. Subsequently the mean value $\overline{\text{SLC}}$ was determined for the five categories, the calculations being made on the basis of the real-ear attenuation S_f and the reduced real-ear attenuation $S_{f,s}$ of the ear protectors. The mean values obtained are given in Table 9. Knowing the $\overline{\text{SLC}}$ values for each type of ear protectors, the values of the attenuation S_A and the reduced attenuation $S_{A,s}$ were calculated for the mean spectra. The values obtained are given in Tables 10 and 11.

Table 9. $\overline{\text{SLC}}$ **values for ear protectors** [dB]

Calculation basis	TD-1A	TD-5	Saturn II	E-A-R	Ear defender	3M Brand	Contraphon
S_f	16.7	21.2	19.3	27.8	21.7	24.5	16.3
$S_{f,S}$	11.7	17.7	11.7	22.0	14.3	20.0	12.6

8. Comparison of the different methods of determining ear protector attenuation

As an example, the values of the mean attenuation $\overline{S}_A$ and the reduced attenuation $\overline{S}_{A,s}$ of the E-A-R plugs obtained by different methods are shown together in Tables 10 and 11. Similar comparisons were made for all ear protectors investigated. The analysis led to the following conclusions:

Table 10. Mean attenuation $\bar{S}_A$ of the E-A-R plugs obtained by different methods (in dB (A))

Method	Spectral category				
	1	2	3	4	5
Exact	29.3	25.0	23.1	22.2	21.0
Linear regression	27.0	26.0	24.7	23.2	19.8
Square-law curvilinear regression	30.5	26.5	23.8	22.1	20.2
Mean spectrum	29.4	24.4	22.7	22.1	20.8
$\overline{\text{SLC}}$ from mean spectra	28.9	27.0	24.9	22.3	16.2

Table 11. Mean reduced attenuation $\bar{S}_{A,s}$ of the E-A-R plugs obtained by different methods (in dB (A))

Method	Spectral category				
	1	2	3	4	5
Exact	23.1	19.0	17.3	16.6	15.8
Linear regression	22.5	20.0	16.9	16.6	15.8
Square-law curvilinear regression	24.7	19.5	17.2	16.6	15.8
Mean spectrum	23.2	18.4	16.9	16.5	15.6
$\overline{\text{SLC}}$ from mean spectra	23.1	21.2	19.1	16.8	10.4

1. The linear regression method gives lower values of $\bar{S}_A$ and $\bar{S}_{A,s}$ in the spectral categories 1, 4 and 5 and higher values in categories 2 and 3, compared to the values obtained by exact calculation.

2. The curvilinear regression method gives values of $\bar{S}_A$ and $\bar{S}_{A,s}$ close to the values obtained by exact calculation for the spectral categories 2 and 3, while in some cases in category 4 it gives lower values, and higher values for category 1. Comparison of the curvilinear regression curves of the attenuation $\hat{S}_A$ and $\hat{S}_{A,s}$ shows that the curves for the set of sepctra in category 1 ($\Delta_{CA} \leqslant 0$) represent well the nature of the dependence of the attenuation on the difference Δ_{CA}, with the square-law curve giving better representation of the dependence than the exponential one.

3. The mean spectrum method gives values of $\bar{S}_A$ and $\bar{S}_{A,s}$ slightly lower in categories 2, 3, 4 and 5 and slightly higher in category 1, compared to the values of $\bar{S}_A$ and $\bar{S}_{A,s}$ obtained by exact calculation.

4. The Botsford method (SLC) for mean noise spectra always gives lower values of $\bar{S}_A$ and $\bar{S}_{A,s}$ in category 5, often gives higher values in categories 2, 3 and 4, while in category 1 it gives values equal to or lower than the values of $\bar{S}_A$ and $\bar{S}_{A,s}$ obtained by exact calculation, within the range of 0.1 - 6.7 dB(A).

5. In view of its precision and the simplicity of rapid determination of ear protector performance and their matching to noises with different spectral distributions, the mean spectrum method appears to be the most suitable.

6. The mean attenuation curves $\bar{S}_A = f(\Delta_{CA})$ and $S_{A,s} = f(\Delta_{CA})$ are characteristic of a given type of ear protector and the mean values of the reduced attenuation $S_{A,s}$ for each of the five noise spectral categories should be given as the data characterizing the protective properties of the ear protectors.

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