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A METHOD OF PREDICTING NOISE EQUIVALENT LEVEL VALUE IN URBAN STRUCTURE

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The paper presents a method of predicting the noise equivalent level value in urban structure. Unlike the methods used thus far, the presented method consists in determination of a parameter a which is a measure of the energy reaching the observation point during motion of a single source. The method is very laborious and, therefore, the paper presents a solution of the problem of determination of the minimum number of the measurements of the parameter a, necessary to determine the noise equivalent level value with a preset accuracy.

1. Introduction

The pooling investigations performed among the inhabitants of towns [13, 23] have revealed that they rate the traffic noise as the most nuisant type of noise. Within the already existing urban structure, where it is impossible to change the localization of buildings and transportation routes, the noise can be minimized by an appropriate "programming" of the structure and intensity of transportation traffic. In such a case it is necessary to know the relation between the parameters describing acoustic field (noise evaluation indicators, e.g. noise equivalent level L_{eq}) [1] and the value of "traffic intensity" (n_i) of the noise sources, i.e. transportation vehicles. Provided the relation $L_{eq} = f(n_i)$ is available, it is feasible to determine the permissible values of traffic intensity which correspond to a predetermined (e.g. given by a standard) value of L_{eq}.

Determination of the function $f(n_i)$ in an urban area is much more difficult than in the case of an open area, e.g. in the vicinity of a motor way where the noise sources move at a constant speed (an extensive reference list ot this problem is given in [16]).

[1] Other noise evaluation indicators are discussed in [16].

The configuration of acoustic field in an urban area complicates as a result of reflections from many planes and non-uniform motion of noise sources (rounda-bouts, crossings, traffic lights etc). Only if urban structure is highly symmetric (e.g. "tunnel" development), it is possible to determine the function $f(n_i)$ by mathematical analysis. In other cases this function is being obtained by regression analysis. The results of investigations in the form of plots, nomograms, tables, corrections etc. are presented in [1, 3, 6, 7, 8, 24].

This paper presents the principle (Section 3) and experimental verification (Section 4) of a new method of predicting the noise equivalent level value in an urban area. The theoretical background of this method was discussed in [16].

The essential difference between this method and the presently used method based on regression analysis is that the parameters α_i appearing in function

$$L_{eq} = 10 \log\Big(\sum_i n_i \alpha_i + C\Big)$$

are determined from the measurement of the signal emitted by a single source (Section 3.2) rather than from the set of values L_{eq} for the resultant signal (being the sum of signals coming from individual sources).

The problem of minimization of the number of measurements, necessary to achieve the required degree of consistency of theoretical and experimental results, is discussed in Section 5.

The basic concept of the new method of noise equivalent level determination results from equation (13) derived in [16] from the definition (1) of noise equivalent level. The consistency of the proposed method with other measurement methods is demonstrated in Section 2 by deriving from the same definition equations (9) and (12) encountered in the literature and thus proving their equivalence.

2. Methods of equivalent level measurement

The noise equivalent level L_{eq} is defined [20] as

$$L_{eq} = 10 \log \frac{1}{T} \int_{-T/2}^{T/2} 10^{0,1L(t)}\, dt, \tag{1}$$

where $L(t)$ is the noise level measurement in dB(A) and T – measurement duration.

There exist instruments like Brüel-Kjaer, type 4426, or RFT, type 00005, which measure L_{eq} directly.

The value of noise equivalent level L_{eq} can also be determined by using a noise level meter and a recording voltmeter to register the course of $L(t)$.

By dividing the noise level into classes of constant width $(L_i, L_i+\Delta L)$

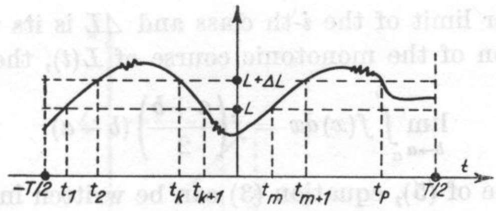

Fig. 1. Changes of sound level vs. time $L(t)$ [dB(A)]

(cf. Fig. 1), the integral in definition (1) can be presented in the form of a sum,

$$\int_{-T/2}^{T/2} 10^{0,1L(t)}\,dt = \sum_{j=1}^{N} \int_{t_j}^{t_{j+1}} 10^{0,1L(t)}\,dt, \tag{2}$$

where $t_1 = -T/2$, $t_{N+1} = T/2$ are the instants of the beginning and the end of the measurement, respectively.

By approximating each integral by the product of the mean value of the integral function in the interval (t_j, t_{j+1}) and the length $t_{j+1} - t_j$ of this interval, we obtain

$$\int_{-T/2}^{T/2} 10^{0,1L(t)}\,dt = \sum_{j=1}^{N} 10^{0,1L_j}(t_{j+1} - t_j), \tag{3}$$

where

$$10^{0,1L_j} = \frac{1}{t_{j+1} - t_j} \int_{t_j}^{t_{j+1}} 10^{0,1L(t)}\,dt. \tag{4}$$

When the width of the class tends to zero ($\Delta L \to 0$), the length $t_{j+1} - t_j$ of the integration interval tends also to zero and thus equation (4) can be written in the form

$$10^{0,1L_j} \approx 10^{0,1(L_i + \frac{1}{2}\Delta L)}, \tag{5}$$

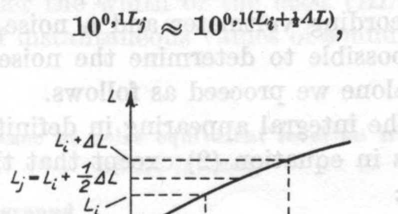

Fig. 2. Noise level L_j (equation (3)) as the mean value of values L_i, $L_i + \Delta L$ defining the lower and the upper limit of a "class"

where L_i is the lower limit of the i-th class and ΔL is its width (Fig. 2) since, under the assumption of the monotonic course of $L(t)$, the relation

$$\lim_{b\to a}\int_a^b f(x)\,dx = f\left(\frac{a+b}{2}\right)(b-a) \tag{6}$$

is satisfied. By virtue of (5), equation (3) can be written in the following form:

$$\int_{-T/2}^{T/2} 10^{0,1L(t)}\,dt = \sum_{j=1}^{N} 10^{0,1(L_i+\Delta L/2)}(t_{j+1}-t_j). \tag{7}$$

It may happen that the course of $L(t)$ is within the same class $(L_i, L_i+\Delta L)$ for several time intervals (t_j, t_{j+1}), as for the intervals (t_1, t_2), (t_k, t_{k+1}), (t_m, t_{m+1}) in Fig. 1. This means that the sum (7) may contain several terms with identical factor $10^{0,1(L_i+\Delta L/2)}$. By grouping such terms and next summing with respect to all classes we obtain

$$\int_{-T/2}^{T/2} 10^{0.1L(t)}\,dt = \sum_i t_i\cdot 10^{0.1(L_i+\Delta L/2)}, \tag{8}$$

where

$$t_i = \sum_i (t_{j+1}^{(i)} - t_j^{(i)})$$

is the total time interval in which the temporary value of noise level $L(t)$ satisfies the unequality $L_i < L(t) < L_i+\Delta L$.

By using equation (8) in definition (1), we obtain an expression determining the value of noise equivalent level L_{eq} in terms of instantaneous values of sound level $L(t)$ measured in A decibels:

$$L_{eq} = 10\log\frac{1}{T}\sum_i t_i\cdot 10^{0.1(L_i+\Delta L/2)}. \tag{9}$$

As it was mentioned, this formula can be applied only if the measurement is performed using a recording voltmeter and a noise level meter. To derive the formula making it possible to determine the noise equivalent level value using noise level meter alone we proceed as follows.

Let us assume that the integral appearing in definition (1) can be replaced by a sum of integrals as in equation (2) except that the integration intervals are equal to each other:

$$t_{j+1}-t_j = \Delta t, \quad j = 1, 2, \ldots$$

Under the assumption of a sufficiently short integration interval Δt and monotonic course of $L(t)$ in the interval (t_j, t_{j+1}), equation (2) can be written in the form

$$\int_{-T/2}^{T/2} 10^{0.1L(t)}\,dt = \Delta t\sum_{j=1}^{N} 10^{0.1L_j}, \tag{10}$$

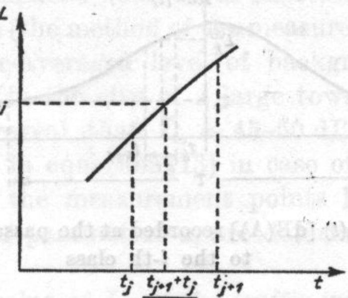

Fig. 3. Noise level L_j (equation (10)) corresponding to the moment $t = \frac{1}{2}(t_j + t_{j+1})$.

where $L_j = L\left((t_{j+1}+t_j)/2\right)$ is the value of the sound level at the instant $\frac{1}{2}(t_{j+1}+t_j)$ (cf. Fig. 3).

Since $T = N\Delta t$, by virtue of equation (10) we obtain from definition (1) another expression for calculating the noise equivalent level value:

$$L_{\mathrm{eq}} = 10 \log \frac{1}{N} \sum_{j=1}^{N} 10^{0.1L_j}. \tag{11}$$

If the successive readings of level L are repeated in such a way that values L_j correspond to numbers n_j, then

$$L_{\mathrm{eq}} = 10 \log \frac{1}{N} \sum_{j} n_j \cdot 10^{0.1L_j}. \tag{12}$$

This formula makes it possible to determine the noise equivalent level value by reading instantaneous values of sound level (expressed in dB(A)) in equal time intervals.

It follows from formulae (9) and (12) that the accuracy of L_{eq} determination is the higher the smaller the width of the class ($\Delta L \to 0$) is and the more frequently the readings of instantaneous values of sound level are taken, i.e. when $\Delta t \to 0$.

3. Dependence of noise equivalent level on transportation traffic intensity

3.1. Theoretical background

Let us consider several sources of the same j-th type (e.g. 7 vehicles of the same type). Under the assumption that they move with the same speed $V_k(t)$ along the same l-th path, we obtain the set of signals $L^{(i)}(t)$ very similar to each other (cf. Fig. 4).

To simplify the notation, we introduce an index i for each possible combination $(j\,k\,l)$ which will identify the "class" of the source [16].

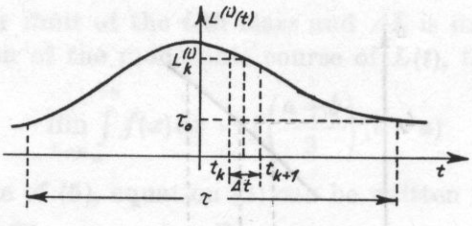

Fig. 4. Noise level changes $L^{(i)}(t)$ [dB(A)] recorded at the passage of a single source belonging to the i-th class

If we have, for instance, two types of sources — two types of vehicles ($j = 1, 2$) which move at the same speed $V_k(t)(k = 1)$ along two different paths ($l = 1, 2$), we shall register four different signals $L^{(i)}(t)(i = 1, 2, 3, 4)$ since this is just the number of possible combinations among the indices ($j\,k\,l$).

The urban noise is a result of the superposition of signals produced by individual sources. As it has been demonstrated [16] the noise equivalent level L_{eq} can be determined by means of the formula

$$L_{eq} = 10 \log \frac{1}{I_0}\Big[\sum_{i=1}^{M} n_i \int_{-\infty}^{+\infty} I_i(t)\,dt + \bar{I}^0\Big],$$

where $I_i(t)$ is the time-dependent intensity of noise generated by a moving source of i-th class, $\bar{I}^0$ — the average background intensity, I_0 — the reference intensity, n_i — the number of sources of i-th class passing the observation point per unit time (traffic intensity), M — the number of classes of noise sources.

Actually it is the pressure level which is the measurable quantity

$$L(t) = 10 \log p^2(t)/p_0^2,$$

where $p_0 = 2\cdot 10^{-5}\,N/\mathrm{m}^2$. As it was demonstrated by Beranek [2], it can by assumed that the pressure level equals to intensity level with an accuracy much better than 1 dB,

$$L(t) = 10 \log \frac{I(t)}{I_0},$$

where $I_0 = 10^{12}\,\mathrm{W/m}^2$.

Hence

$$L_{eq} = 10 \log\Big[\sum_{i=1}^{M} n_i a_i + 10^{0.1\bar{L}_0}\Big], \tag{13}$$

where

$$a_i = \int_{-\infty}^{+\infty} 10^{0.1 L_i(t)}\,dt \tag{14}$$

and $L_i(t)$ is the time-dependent noise level expressed in dB(A), produced by a single source of i-th class (the method of the measurement of a_i will be discussed later on); $\bar{L}_0$ is the time-averaged level of background intensity — $\bar{I}^0$. The measurements performed in the city of a large town at a large distance from the stream of vehicles reveal that $\bar{L}_0 \approx 45$–50 dB(A). This allows to omit the last term of the sum in equation (13) in case of the high traffic intensity (large values of n_i) and the measurement points located close to the road.

Provided the values of parameters a_i are determined in advance, equation (13) makes it possible:

(a) to determine the value of L_{eq} if the traffic intensity n_i is known;

(b) to modify the value of L_{eq} by imposing appropriate limitations upon the traffic structure: $n_i \leqslant n_i^*$.

These problems will be treated in more detail later on.

3.2. Method of calculating the values of a_i

Equation (14) provides a way of calculating the values of a_i. As it was already mentioned, the quantity $L_i(t)$ appearing in this equation is the noise level generated by a single source of the i-th class. To obtain the course of $L_i(t)$, the measurement should be performed under the conditions when only a single source is actually moving in the vicinity of observation point. It is thus convenient to perform such measurements in the night (preliminary investigations indicate that the method of model measurements can also be applied for this purpose).

However, such measurement yields the signal $L_j^{(i)}(t)$ (noise level produced by the source and the background) rather than "pure" signal $L_i(t)$, and the former is different for each j-th source belonging to the same i-th class:

$$L_j^{(i)}(t) = 10\log\left(\frac{I_j^{(i)}(t)}{I_0} + \frac{\tilde{I}^{(0)}}{I_0}\right).$$

Introducing the notation

$$L_j^{(i)}(t) = 10\log\frac{I_j^{(i)}(t)}{I_0}, \qquad \tilde{L}_0 = 10\log\frac{\tilde{I}^{(0)}}{I_0}$$

($L_j^{(i)}$ is the noise level produced by the source only, $\bar{L}_0$ — the noise level associated with the acoustic background present during the measurement), from (14) we obtain

$$a_{ij} = \int_{-\tau/2}^{\tau/2} [10^{0.1L_j^{(i)}(t)} - 10^{0.1\tilde{L}_0}]\,dt, \tag{15}$$

where τ is the signal duration (cf. Fig. 4), i.e. the time of source passage, $L_j^{(i)}(t)$ — the registered change of intensity level with time, $\tilde{L}_0$ — the background level during the measurement. The quantity $\tilde{L}_0$ has, as a rule, a value different to that of $\bar{L}_0$ (equation (13)) (for instance, the acoustic background in the night, when the measurements of $L^{(i)}(t)$ are performed, is different than during the day).

To determine the values of parameters a_{ij} we divide, in agreement with equation (15), the interval $(-\tau/2, \tau/2)$ into equal intervals Δt and obtain the formula

$$a_{ij} = \Delta t \sum_{k=1}^{M} 10^{0.1 L_{jk}^{(i)}} - \tau \cdot 10^{0.1 \bar{L}_0}, \tag{16}$$

where $L_{jk}^{(i)}$ is, in agreement with Fig. 4, the value of the sound level at the instant $t^{(k)} = \frac{1}{2}(t_{k+1} + t_k)$, i.e. in the middle of the interval (t_{k+1}, t_k).

4. Measurement results

4.1. Classification of noise sources

The parameters a_{ij} were determined for vehicles moving along a two-way street. The measurement point was placed at a height of the third floor at a distance of 30 m from the nearest street crossing. Fig. 5a presents a cross-section of the street and Fig. 5b – its view from the top with the marked measurement point A.

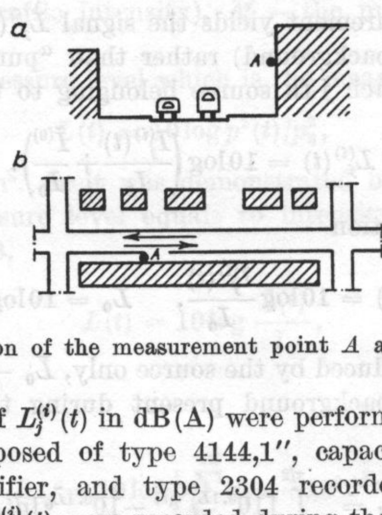

Fig. 5. Localization of the measurement point A at a two-way street

The measurements of $L_j^{(i)}(t)$ in dB(A) were performed using a set of Brüel-Kjaer equipment composed of type 4144,1″, capacitance microphone type, 2602 microphone amplifier, and type 2304 recorder with 50 dB potentiometer. The courses of $L_j^{(i)}(t)$ were recorded during the night between 23h and 3h since undisturbed signals produced by a single vehicle were possible to obtain only during that time. Typical courses of the noise level $L_j^{(i)}(t)$ [dB(A)] produced by Fiat motor-cars and Jelcz buses moving to the right and to the left are shown in Fig. 6.

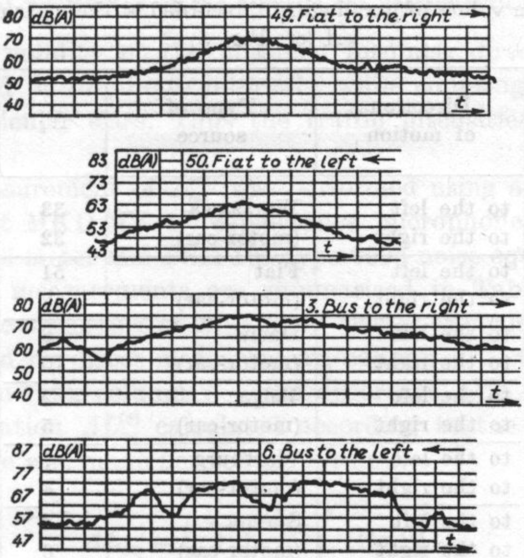

Fig. 6. Noise level changes $L_j^{(i)}(t)$ [dB(A)] for several single vehicles

The values of parameters a_{ij} for each course of $L_j^{(i)}(t)$ were calculated using equation (16) and next mean values a_i were determined from the formula

$$a_i = \frac{1}{N_i} \sum_{j=1}^{N_i} a_{ij}, \tag{17}$$

where N_i is the number of registered signals produced by the sources of the i-th class.

The values of a_i and the numbers N_i for 22 classes of sources are given in Table 1. It follows from this Table that the values a_i corresponding to buses are higher by an order of magnitude from the remaining values. One can also see a marked difference between the values of a_i corresponding to different directions of the vehicle movement. This difference is associated with a different distance from the measurement point. Therefore, for further calculations, we accept a 4-class classification of the noise sources:

1. motor-cars moving to the right,
2. motor-cars moving to the left,
3. buses moving to the right,
4. buses moving to the left.

The mean values of a_i calculated from equation (17) for these classes of noise sources amount in hour/veh., respectively, to:

$$a_1 = 2\,359, \quad a_2 = 1\,072, \quad a_3 = 49\,049, \quad a_4 = 28\,397.$$

Table 1. Mean values of parameters a_i recorded at the measurement point A (cf. Fig. 5)

No. of source class	Direction of motion	Type of source	N_i	a_i $\left[\frac{\text{hour}}{\text{veh.}}\right]$
1	to the left	Warszawa	33	1 091
2	to the right	(motor-car)	32	2 004
3	to the left	Fiat	51	1 166
4	to the right	(motor-car)	52	2 607
5	to the left	Dacia	8	942
6	to the right	(motor-car)	10	2 159
7	to the left	Volga	2	1 281
8	to the right	(motor-car)	5	1 755
9	to the left	Wartburg	7	783
10	to the right	(motor-car)	4	1 392
11	to the left	Syrena	4	900
12	to the right	(motor-car)	6	3 546
13	to the left	Moskvich	2	379
14	to the right	(motor-car)	5	3 257
15	to the left	Trabant	1	708
16	to the right	(motor-car)	3	2 883
17	to the left	Skoda	3	1 554
18	to the right	(motor-car)	2	1 402
19	to the left	Nysa	6	776
20	to the right	(pick-up)	2	422
21	to the left	Jelcz	13	28 397
22	to the right	(bus)	10	49 049

The standard deviations Δa_i calculated from equation

$$\Delta a_i = \left\{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}(a_{ij} - a_i)^2\right\}^{1/2} \tag{18}$$

amount to:

$$\Delta a_1 = \pm 1555, \quad \Delta a_2 = \pm 723, \quad \Delta a_3 = \pm 18732, \quad \Delta a_4 = \pm 10721.$$

Substituting the mean values of a_i to equation (13), we obtain the expected value of the noise equivalent level at measurement point A in the street of the cross-section shown in Fig. 5,

$$L_{\text{eq}} = 10\log(2359 n_1 + 1072 n_2 + 49049 n_3 + 28397 n_4 + 10^{0.1\bar{L}_0}), \tag{19}$$

where n_1 is the number of motor-cars moving to the right [veh./hour], n_2 – number of motor-cars moving to the left [veh./hour], n_3 – number of buses moving to the right [veh./hour], n_4 – number of buses moving to the left [veh./hour], $\bar{L}_0$ – acoustic background.

At high traffic intensity the last term accounting for acoustic background can be disregarded in calculations.

4.2. Experimental verification of the formula for determination of L_{eq}

To verify the validity of the obtained formula, direct measurements of L_{eq} were performed in 10-minute intervals, while counting simultaneously the vehicles of a particular class. Thus the traffic intensities n_1, n_2, n_3, n_4 were determined.

The direct measurement of $L_{eq}^{(m)}$ was performed using a set of RFT equipment consisting of MKD MV 1″ capacitance microphone No 3103, PSI 202 precision noise level meter and PSM 101 type 0005 noise equivalent level meter.

The results of measurements are summarized in Table 2. Columns 1 to 4 present the traffic intensities of individual classes of vehicles, column 5 — the value $L_{eq}^{(m)}$ obtained by direct measurement, column 6 — the value $L_{eq}^{(c)}$ obtained from equation (19), column 7 — the difference $L_{eq}^{(m)} - L_{eq}^{(c)}$, column 8 — the standard deviation $\Delta L_{eq}^{(c)}$ calculated according to the law of "error propagation" [10]. Use was made here of the formula

$$\Delta L_{eq} = \left\{ \sum_{i=1}^{4} \left(\frac{\partial L_{eq}}{\partial \alpha_i} \right)^2 (\Delta \alpha_i)^2 \right\}^{1/2},$$

i.e.

$$\Delta L_{eq}^{(c)} = \frac{10 \log e}{\sum_{i=1}^{4} n_i \alpha_i + 10^{0,1 \bar{L}_0}} \left\{ \sum_{i=1}^{4} n_i^2 (\Delta \alpha_i)^2 \right\}. \tag{20}$$

Table 2. Summary of the values of L_{eg} calculated and measured at the measurement point A (cf. Fig. 5) at known traffic intensities n_i

No	n_1 [veh./hour]	n_2 [veh./hour]	n_3 [veh./hour]	n_4 [veh./hour]	$L_{eq}^{(m)}$ [dB(A)]	$L_{eq}^{(c)}$ [dB(A)]	$L_{eq}^{(m)} - L_{eq}^{(c)}$ [dB(A)]	$\Delta L_{eq}^{(c)}$ [dB(A)]
	1	2	3	4	5	6	7	8
1	174	210	6	12	61.3	61.0	0.3	1.2
2	144	156	18	12	62.8	62.4	0.4	1.1
3	174	120	12	6	61.5	61.1	0.4	1.2
4	132	84	6	12	60.5	60.2	0.3	1.1
5	126	216	18	6	62.5	62.0	0.5	1.2
6	168	174	18	12	63.0	62.6	0.4	1.1
7	108	120	6	12	60.5	60.1	0.4	1.3
8	162	144	12	12	62.1	61.7	0.4	1.6
9	120	102	6	6	59.7	59.0	0.7	1.3
10	162	84	12	12	61.9	61.5	0.4	1.1
11	162	180	12	18	62.6	62.2	0.4	1.1
12	198	156	6	—	59.9	59.7	0.2	1.6
13	186	198	6	12	61.3	61.1	0.2	0.9
14	150	222	12	12	62.2	61.8	0.4	1.1
15	114	138	6	6	59.8	59.5	0.3	1.2
16	150	120	12	18	62.4	62.0	0.4	1.1
17	174	138	6	6	60.4	60.1	0.3	1.3

It follows from Table 2 that the difference $L_{eq}^{(m)} - L_{eq}^{(c)}$ between the directly measured value and the value obtained from equation (19) for given traffic intensities n_1, n_2, n_3, n_4 is smaller than 0.7 dB(A). The average value of this difference equals to 0.4 dB(A).

It may be thus concluded that the method of predicting the noise equivalent level L_{eq} in urban structures, based on equation (13), is fully justified.

5. Optimization of the measurement process

The spectacular agreement between the values L_{eq} obtained by calculation and by direct measurement can be explained as due to very small differences between the values $a_i (i = 1, 2, 3, 4)$ appearing in (19) and the values

$$\bar{a}_i = \lim_{N_i \to \infty} a_i$$

which apply to the whole population of noise sources passing the observation point. Let us denote these differences by δa_i. The value of δa_i is the smaller the more accurately the value of a_i in (17) is calculated, i.e. the larger is the number of measurements N_i.

The question arises how large should be the number N_i to make the values of δa_i small enough to determine the value of L_{eq} from equation (13) with an error δL_{eq} smaller than k dB(A) with a probability p.

Replacing the standard deviations Δa_i in (20) by the quantities δa_i, we obtain a general expression defining the error δL_{eq},

$$\delta L_{eq} = \frac{10 \log e}{\sum_{i=1}^{M} n_i a_i + 10^{0.1 \bar{L}_0}} \left\{ \sum_{i=1}^{M} n_i^2 (\delta a_i)^2 \right\}^{1/2},$$

where M is the number of classes of noise sources.

From the requirement $\delta L_{eq} < k$ dB and under the assumption that every class provides the same "contribution" to the value δL_{eq}, we obtain

$$\delta L_{eq} < \frac{k}{\sqrt{M}} \frac{\sum_{i=1}^{M} n_i a_i + 10^{0.1 \bar{L}_0}}{n_i 10 \log e}. \tag{21}$$

The parameters a_i in (17) are random values.

If a_{ij} $(j = 1, 2, \ldots, N_i)$ have a normal distribution [10], then

$$\delta a_i = \frac{t_p^{(i)} \Delta a_i}{\sqrt{N_i}}, \tag{22}$$

where $t_p^{(i)}$ is the value obtained from Student's distribution for the probability p at $N_i - 1$ degrees of freedom, Δa_i – standard deviation given by (18), N_i – the number of measurements of $a_{ij} (j = 1, 2, \ldots, N_i)$.

From equations (21) and (22) we find N_i^* — the number of measurements of parameters $a_{ij}(j = 1, 2, \ldots, N_i)$, necessary to reduce the error δL_{eq} of the disscussed method below k dB with a probability p:

$$N_i^* = M\left(\frac{10\log e\, t_p^{(i)} n_i \Delta a_i}{k\sum_{i=1}^{M} n_i a_i + 10^{0.1\bar{L}_0}}\right)^2. \quad (23)$$

To find the value of N_i^* from this formula a "pilot" series of measurements of $a_{ij}(i = 1, 2, \ldots, M; j = 1, 2, \ldots, N_i)$ should be performed and the values of a_i (17) Δa_i(18), and $t_p^{(i)}$ should be determined. If the inequality $N_i^* < N_i$ is satisfied, there is no need to perform additional measurements since the power of the set $\{a_{ij}\}$ is adequate.

It follows that the number of measurements N_i^*, necessary to determine the value of L_{eq} from (13) with an error less than k dB (with probability p), tends to zero if the intensity of the motion of noise sources tends to zero.

Equation (23) has been derived under the assumption that the partition of noise sources into individual classes has been executed "a priori". Practically it happens that the values corresponding e.g. to various types of noise sources do not differ much from each other and the need to form separate classes for these sources becomes questionable.

Table 1 presents mean values of a for various types of motor-cars. In comparison with the values of a for buses the differences between these values are small and, therefore, we have decided to form a single common class for all motor-cars regardless their types and taking into consideration only their direction of motion.

In general case this problem can be formulated as follows: how to perform a partition of all sources into classes in such a way that

(a) The error δL_{eq} of determining the value of equivalent level L_{eq} from (13) is less than k dB with a probability p.

(b) The total number of the measurements of parameters $a_{ij}(j = 1, 2, \ldots, N_i,\ i = 1, 2, \ldots, M)$ is minimum, i.e.

$$\sum_{i=1}^{M} N_i^* = \text{minimum}. \quad (24)$$

Condition (b) can be regarded as the aim of the optimization of the measurement process.

Similarly to the case of determination of the "necessary" number of measurements N_i^*, let us assume that we have at our disposal a "pilot" series of measurements $\{a\}$. As a first step to solving the above problem we introduce a partition into "unquestionable" classes, i.e. the classes with markedly different values of a. Let the number of these classes be M_1. It follows from the example discussed in Section 4 that $M_1 = 2$ if the noise sources have to be divided into at least two classes: motor-cars and buses. It is less evident whether it is necessary to split these classes with respect to different motion directions "to the left" and "to the right".

Next, we check, using equation (23), whether the number of measurements $N_{i,1}$ in each class is sufficient (at the assumed value of probability p and error k), i.e. whether the relation $N_{i1} > N^*_{i,1}$ is satisfied.

In turn, we perform a new partition of the set of parameters $\{a_{ij}\}$ into M_2 classes ($M_2 > M_1$), check the validity of relation $N_{i,2} > N^*_{i,2}$, repeat the same for M_3 classes etc.

At each q-th partition into various classes, i.e. when the set $\{a_{ij}\}$ (of power N) is divided into subsets of power $N_{i,q}$, use can be made of the papers of Christie, Hillquist and Scott, Jonasson, Lewis, Olson, Nelson and Piner, Priede, Rathe, Ulrich, Waters [4, 5, 9, 11, 15, 17, 19, 21, 22, 25, 26, 27] which give values of the noise level as functions of velocity and acceleration.

Further on we consider only those partitions into classes (among all $q = 1, 2, \ldots$) for which the inequalities

$$N_{i,q} > N^*_{i,q}, \quad i = 1, 2, \ldots, M_q, \tag{25}$$

equivalent to condition (a), are satisfied. (If none of the partitions into classes satisfies these inequalities, then the set $\{a_{ij}\}$ has to be supplemented with additional measurements of parameter a.)

Out of all partitions into classes, which satisfy inequalities (25), we choose that one for which the sum of necessary measurements in each class $N^*_{i,q}$ ($i = 1, 2, \ldots, M_q$) satisfies condition (24).

This partition into classes in the optimum one, since it permits the value of equivalent level (13) to be determined with an error less than k dB (with the probability p) from the minimum number of measurements.

Example. Let us assume that measurements of the parameter a (Table 1) are the "pilot" series with the power of individual classes ($M = 4$) $N_1 = 121$, $N_2 = 117$ (classes of motor-cars moving "to the right" and "to the left") and $N_3 = 10$, $N_4 = 13$ (classes of buses moving "to the right" and "to the left").

Let us assume the probability $p = 0.99$ and the value of acceptable error $k = 0.5$ dB (it means that the values L_{eq} obtained from (13) will bear an error less than 0.5 dB with the above probability). From Student's distribution for the numbers of freedom degrees $N_1 - 1 = 120$, $N_2 - 1 = 116$, $N_3 - 1 = 9$, $N_4 - 1 = 12$) we obtain that $t^{(1)}_{0.99} = 2.58$, $t^{(2)}_{0.99} = 2.58$, $t^{(3)}_{0.99} = 3.25$, $t^{(4)}_{0.99} = 3.05$. The values of standard deviations Δa_i are given in Section 4.1. It follows from (13) that the sum in the nominator of expression (23) can be presented in the form

$$\sum n_i a_i + 10^{0.1\bar{L}_0} = 10^{0.1L_{\text{eq}}}.$$

Assuming the mean traffic intensities, obtained from the measurements, presented in Table 2: $n_1 = 153$, $n_2 = 151$, $n_3 = 10$, $n_4 = 10$, and the corresponding value $L_{eq} = 61$ dB(A), we have $N_1 = 70$, $N_2 = 15$, $N_3 = 69$, $N_4 = 20$.

The results obtained indicate that to use formula (19) for the determination of the value of L_{eq} with the accuracy 0.5 dB (with the probability $p = 0.99$) the number of measurements a_{ij} in classes 1 and 2 was too large ($N_i^* < N_i$) and in classes 3 and 4 – too small ($N_i^* > N_i$). The two latter classes should be complemented with additional measurements to satisfy condition $N_i^* \leqslant N_i$.

6. Conclusions

The work is primarily aimed at verification of the method of predicting the value of noise equivalent level L_{eq} outlined in [16]. Good agreement of the experimental data and the results obtained from formula (13) confirms the validity of the method (Section 4.2.).

To demonstrate consistency of the new method with other measurement methods, definition (1), which is also the starting point to derive equation (13), is used in Section 1 to derive expressions enabling L_{eq} to be determined either from the record of noise level changes in time (equation (9)) or from a set of instantaneous values of noise level, recorded at equal time intervals (equation (12)).

The method of determining the value of L_{eq} in urban structure follows from equation (13). An application of this formula requires a partition of all sources into appropriate classes. This partition is made basing on the value of parameter a (equations (14) and (15)) which is a measure of the energy reaching the observation point during motion of an individual source. Equation (13) contains the quantities a_i – mean values for particular classes. The error introduced by calculating L_{eq} from (13) is the smaller the more accurately is the value a_i of (17) calculated and the larger is the number of measurements of a_{ij} ($j = 1, 2, \ldots, N_i$). Equation (19) is the form of (13) specified for a particular case.

The problem of minimizing this error is linked to the problem of optimizing the measurements. It was demonstrated in Section 5 that if the value of the error is assumed to be k dB with the probability p, then – after performing a pilot series of measurements of $\{a\}$ for randomly chosen noise sources – the whole population of sources can be divided into classes (after eventual complementing the number of measurements to satisfy the inequality $N_i^* < N_i$) in such a way that the assumed requirements of the accuracy of the method will be satisfied.

The values of parameters a_i depend on the power of acoustic sources (e.g. on the types of cars), the trajectory, the way of operation and the type of urban structure and, therefore, equation (19) is valid only for measurement point A, as indicated in Fig. 5. Therefore the general form of equation (19) is as follows:

$$L_{eq}^{(m)} = 10\log\Big(\sum_{i=1}^{M^{(m)}} n_i^{(m)}\alpha_i^{(m)} + 10^{0.1\bar{L}_0^{(m)}}\Big), \quad m = 1, 2, \ldots, \tag{26}$$

where $n_i^{(m)}$ is the traffic intensity of noise sources passing the m-th observation point, $M_i^{(m)}$ — number of classes of sources in the vicinity of the m-th point, $\bar{L}_0^{(m)}$ — mean background level measured at the m-th point.

If we assume that the condition of favourable acoustic climate in the vicinity of each of these points is given by inequality

$$L_{eq}^{(m)} < \tilde{L}_{eq}^{(m)}, \quad m = 1, 2, \ldots, \tag{27}$$

where $\bar{L}_{eq}^{(m)}$ can be considered as values resulting from various standard values for residential areas, hospitals, schools etc., then equation (26) yields information on the requirements which should be imposed on the values of traffic intensities $\{n_i^{(m)}\}$ along particular streets (Fig. 7) to satisfy inequalities (27).

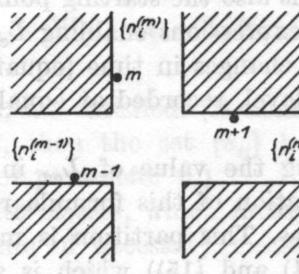

Fig. 7. Localization of measurement points in a typical urban structure

Thus the acoustic climate in urban areas can be formed by suitable "programming" the structure of transportation traffic.

Let us consider for example the case discussed in Section 4. Let us assume that the standard requires that $L_{eq} \leqslant 60$ dB(A) at point A. Assuming the mean background level $\bar{L}_0 = 40$ dB(A), from (19) we obtain

$$2359n_1 + 1072n_2 + 49049n_3 + 28397n_4 < 99\cdot 10^4.$$

This is a particular case of inequality (27) with equation (26) taken into account. This inequality provides information on the maximum intensity of the traffic of motor-cars (n_1 and n_2) and buses (n_3 and n_4) for which the condition of good acoustic climate at point A is still satisfied, i.e. $L_{eq} < 60$ dB(A).

The method of predicting the value of noise equivalent level (L_{eq}), presented in this paper, is fairly laborious but the error of L_{eq} determination is very small.

The theoretical and experimental investigations carried out presently at the Chair of Acoustics of the Adam Mickiewicz University are aimed at such development of the presented method which will make it applicable over a possibly widest range of problems. In particular, this method may become a starting point for development of a new methodology of preparing acoustic maps of towns since it permits us not only to determine the acoustic climate (the value of L_{eq}) at various points of the town but also to "program" the structure and intensity (n_i) of traffic in such a way that this climate will satisfy the given requirements, i.e. the values of L_{eq} will be e.g. less than the values directly related to the existing obligatory standards.

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