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METHODOLOGY FOR UNCERTAINTY ESTIMATION OF SHORT-TERM TOTAL ENVIRONMENTAL NOISE MEASUREMENTS

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Abstract. *The third edition of the ISO 1996 series describes the methods for measuring and assessing environmental noise from different noise source types (road, rail and air traffic, and industrial plants). Additionally, these standards provide guidelines for assessing the uncertainty of short-term and long-term environmental noise measurements, considering the impact of various sources of uncertainty. The procedure described for assessing measurement uncertainty refers to the specific noise of individual noise sources (road, rail and air traffic, and industrial plants) and cannot be directly applied when considering the total noise contributed by multiple, diverse, near and far sources in each situation at a specific time, along with the corresponding measurement uncertainty. The limit values of the noise indicators specified by the Serbian regulations refer to the total noise, so it is necessary to determine the noise indicators for the total noise to assess environmental noise in each situation and at a given time. Although Serbian legislation does not require the use of measurement uncertainty in environmental noise assessments, the uncertainty must be determined and reported in the measurement report according to the requirements of the third edition of the ISO 1996 series. This paper aims to provide a detailed procedure for assessing the uncertainty of total environmental noise measurements for individual noise in the context of Serbian legislation and the third edition of the ISO 1996 series. The presented procedure can also be applied in other countries where noise limit values refer to total noise.*

Key words: *environmental noise measurement, short-term measurement, measurement uncertainty*

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1. Introduction

The law on environmental noise protection [1] establishes the obligation to monitor environmental noise (long-term measurements) and periodically measure individual noise sources (short-term measurements). According to the by-law [2], long-term and short-term noise measurements must be conducted in accordance with the requirements of ISO 1996 [3, 4]. Environmental noise is assessed using noise indicators for long-term measurements (L_{day}, L_{evening}, and L_{night}), and the rating level for short-term measurements (L_{Req}). All assessment values must be determined for total noise, as the regulation specifies [5] the limit values that refer to total noise. Total noise is illustrated in Fig. 1, including specific and residual noise.

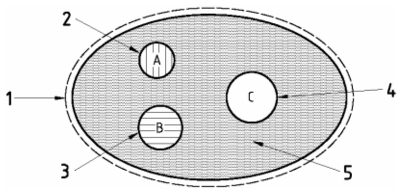

Fig. 1 Total (1), specific (2, 3, 4), and residual noise (5) [3]

Generally, measurement uncertainty is a quantitative indicator of the reliability of any measurement results. Determining the measurement uncertainty is particularly important in environmental noise measurement because environmental noise can fluctuate significantly due to variations in the operation of noise sources and changes that occur during noise propagation.

In recent years, there has been considerable interest in investigating the uncertainty of environmental noise measurements. Many papers [6-15] address environmental noise measurement uncertainty, possible sources of uncertainty, and approaches for determining environmental noise measurement uncertainty, which comply with ISO/IEC Guide 98-3 (GUM) [16]. Most of these studies focus on the uncertainty of short-term measurements, with some papers [13-15] addressing the uncertainty of long-term measurements, but not according to the ISO 1996-2 guidelines [4].

Although Serbian legislation does not require the use of measurement uncertainty in environmental noise assessments, accredited laboratories must determine and report measurement uncertainty in their measurement reports. In practice, accredited laboratories apply different approaches for determining measurement uncertainty.

Therefore, the measurement uncertainty of short-term environmental noise measurements according to the ISO 1996-2 guidelines is considered to specify a unique methodology for estimating the uncertainty of short-term environmental noise measurements.

2. Determination of the Rating Total Noise Level Determined by Short-term Measurements

Short-term measurements are conducted during a measurement time interval with well-defined sound emission and meteorological conditions. The measurement time interval must cover all relevant variations in noise emission and typically ranges between 10 minutes and a few hours. For periodic noise, the measurement time interval should cover an integer number of several periods or cycles. If continuous measurements during the selected period are not possible, the measurement time intervals should be chosen so that each represents a part of the cycle, and all intervals collectively represent the complete cycle. For single-event noise, the measurement time intervals should be chosen so that the sound exposure level of the single event can be determined.

Short-term measurements are usually attended and conducted with instrumentation that includes a sound level meter, filters and a sound calibrator, all of which must meet the requirements for a class 1 instrument according to the appropriate standards. The sound level meter, filters and sound calibrator should be verified according to the relevant test methods at intervals not exceeding two years. Additionally, the entire measuring system should be checked by the sound calibrator at the start and end of every measurement series. A windscreen should always be used during outdoor measurements.

Short-term measurements should be conducted during favorable ($3 \leq v \leq 6$ m/s) and very favorable conditions ($v > 6$ m/s (day), $v \geq -1$ m/s (night), , where v is the wind speed (with a negative sign indicating wind direction from receiver to source), “day” refers to the time between sunrise and sunset and “night” refers to the time between sunset and sunrise or when Eq. (1) is applied [4]:

$$\frac{h_{\mathrm{s}} + h_{\mathrm{r}}}{D} \geq 0.1\,, \tag{1}$$

where h_{s} and h_{r} are the source and the receiver heights and D is the horizontal distance between the source and receiver.

If the ground is hard, larger distances may be acceptable, although no studies have specifically addressed this topic. In practice, the authors of this paper apply distances three times larger for hard ground.

A minimum time of 10 minutes is usually sufficient to average meteorological variations under favorable and very favorable conditions, or when eq. (1) is applied. For short-term measurements under unfavorable ($v < 1$ m/s (day), $v < -1$ m/s (night)) and neutral ($1 \leq v \leq 3$ m/s) conditions, measurements should be taken for at least 30 minutes [4]. These minimum times should be increased to achieve sufficient averaging of source conditions. The increase in the measurement time interval depends on the type of noise source.

The ISO 1996 [4] guidelines can be applied to road and rail traffic, aircraft noise and industrial noise. For road and rail traffic and aircraft noise, increasing the measurement time interval reduces measurement uncertainty, and the selection of the measurement time interval depends on the required measurement uncertainty. For industrial noise, the selection of the measurement time interval depends on the source operating conditions.

The source operating conditions should be divided into classes where variations in sound emission are stationary and less significant than the variation in transmission path attenuation due to meteorological conditions. The operating conditions should be defined by the activity as well as its location. To categorize the operating conditions, the equivalent continuous sound pressure level should be measured over 5 to 10 minutes at a distance long enough to include noise contributions from all major sources, yet short enough to minimize meteorological effects. If the equivalent-continuous sound pressure levels vary considerably, a new categorization of the operating conditions should be made. Guidelines for selecting the measurement time interval for industrial noise can be found in ISO 9612, clause 9.2

[17]. These guidelines are illustrated in Fig. 2, which presents noise situations with three different source operating conditions (classes), where *t* is the selected measurement time interval and *T* is the duration of the classes.

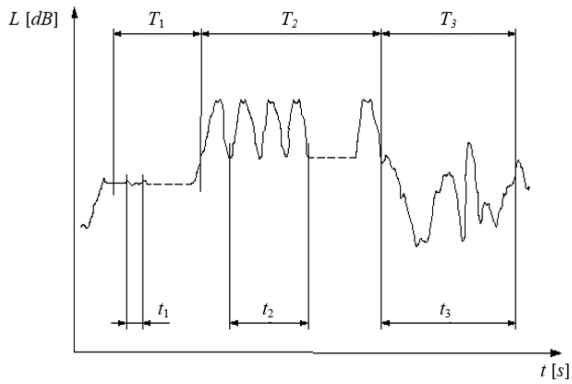

Fig. 2 An example of three cycles with different noise situations (adopted from [17])

To assess the total environmental noise at the assessment point, one or more short-term measurements of the total noise level (at least 3, preferably 5) should be conducted, each lasting at least 10 minutes. These measurements should be taken for each operating condition of the observed source(s) within each reference time interval (day, evening and night), under favorable or very favorable conditions, or when applicable, using a formula for moderate changes in sound pressure due to meteorological conditions (1).

Afterward, the average value of the measured levels is determined for each reference time interval, adding adjustments for noise source rating levels made for the noise character during periods when the noise is tonal and/or impulsive. Additionally, the duration of each class of operating conditions is taken into account. The determined value represents the rating equivalent-continuous level for total noise (abbreviated rating total noise level):

$$L_{\mathrm{Req},\,T} = 10\log\frac{1}{M}\sum_{j=1}^{M}10^{L_{\mathrm{Req},j}/10}, \tag{2}$$

where

- M is the number of the classes of operating conditions,
- T_0 is the duration of the reference time interval (12 h for day, 4 h for evening and 8 h for night),
- $L_{\mathrm{Req},j}$ is the rating level for the class of operating conditions *j,*

$$L_{\mathrm{Req},j} = 10\log\frac{1}{n_j}\sum_{i=1}^{n_j}10^{L_{\mathrm{eq},i}/10} + K_j + 10\log\frac{T_j}{T_0}, \tag{3}$$

- n_j is the number of the measurements for the class of operating conditions *j,*
- $L_{\mathrm{eq},i}$ is the equivalent-continuous sound pressure level for measurement *i,* at the assessment point for the class of operating conditions *j,*
- T_j is the duration of the class of operating conditions *j*,
- K_j is the adjustment for noise character for the class of operating conditions *j.*

Adjustments for tonal or impulsive character of noise are suggested in Table A.1 of ISO 1996 [3]. These adjustments are added only to levels of total noise, not to levels of residual sound. Adjustments are made only to specific sound sources, not to residual sound levels.

If the duration of specific noise source(s) activities T_{ss} is not equal to the duration of the reference time interval T_0, the residual noise is considered as one of the classes of source operating conditions within the reference time interval. The rating total noise level is then determined by combining the total noise level calculated according to (2) and the residual noise level determined by averaging the short-term measurements conducted when the observed specific sound source(s) is (are) off (at least 3 measurements):

$$L_{\mathrm{Req},T} = 10 \log\left(\frac{T_{ss}}{T_0} 10^{L_{\mathrm{Req},T_{ss}}/10} + \frac{T_0 - T_{ss}}{T_0} 10^{L_{\mathrm{res}}/10}\right). \quad (4)$$

3. Determination of Measurement Uncertainty

When determining the measurement uncertainty of the rating total noise level from short-term measurements, two scenarios must be considered. The first scenario is when the duration of the operating conditions of the observed noise source(s) is equal to the reference time interval. The second scenario occurs when the duration is not equal, and the residual noise is considered as one of the classes of operating conditions within the reference time interval.

The measurement uncertainty should be determined in compliance with the ISO Guide to Uncertainty in Measurements (GUM) [16].

According to GUM, each significant source of error must be identified and corrected. If the quantity to be measured is L', which is a function of quantities x_j the equation becomes:

$$L' = f(x_j)\,. \quad (5)$$

If each quantity has a standard uncertainty u_j, the combined uncertainty u is given by:

$$u(L_{Aeq,m}) = \sqrt{\sum_{j=1}^{n} (c_j u_j)^2}\,, \quad (6)$$

where the sensitivity coefficients c_j are given by:

$$c_j = \frac{\partial f}{\partial x_j}\,. \quad (7)$$

The estimated (true) value of the rating total noise level at the assessment point is defined as follows:

$$L = L' + \delta_{\mathrm{slm}} + \delta_{\mathrm{sou}} + \delta_{\mathrm{met}} + \delta_{\mathrm{loc1}} + \delta_{\mathrm{loc2}}\,, \quad (8)$$

where

- L' is the calculated value of the rating total noise level according to Eq. (2) or (4),
- δ_{slm} is an error due to the selection of the measurement chain (sound level meter) [4],
- δ_{sou} is an error due to the deviations from the expected operating conditions of the source [4],

δ_{met} is an error due to meteorological conditions deviating from the assumed conditions [4],
δ_{loc1} is an error due to the selection of receiver location relative to reflective surfaces [4],
δ_{loc2} is an error due to the selection of microphone location representative of the assessment point (choice of microphone position, height above ground level, orientation) [17,18].

An error due to the selection of microphone location, δ_{loc2}, is added to the uncertainty budget recommended by ISO 1996-2 [4] according to the guidelines in [17,18].

The combined standard measurement uncertainty of the estimated value of rating total noise level is given by:

$$u_L^2 = c_{L'}^2 u_{L'}^2 + c_{\text{slm}}^2 u_{\text{slm}}^2 + c_{\text{sou}}^2 u_{\text{sou}}^2 + c_{\text{met}}^2 u_{\text{met}}^2 + c_{\text{loc1}}^2 u_{\text{loc1}}^2 + c_{\text{loc2}}^2 u_{\text{loc2}}^2 , \tag{9}$$

where

$c(L')$ is the sensitivity coefficient for L',
c_{slm} is the sensitivity coefficient for the sound level meter,
c_{sou} is the sensitivity coefficient for the source operating conditions,
c_{met} is the sensitivity coefficient for the meteorological conditions,
c_{loc1} is the sensitivity coefficient for selecting the receiver location relative to the reflective surfaces,
c_{loc2} is the sensitivity coefficient for selecting the receiver location relative to the assessment point,
$u(L')$ is the standard uncertainty for L' in dB,
u_{slm} is the standard uncertainty for the sound level meter in dB (u_{slm} = 0,5 dB for a class 1 sound level meter and u_{slm} = 1,5 dB for a class 2 sound level meter [4]),
u_{sou} is the standard uncertainty for the source operating conditions,
u_{met} is the standard uncertainty for the meteorological conditions,
u_{loc1} is the standard uncertainty due to selection of the receiver location relative to reflective surfaces in dB (estimated according to Annex B of ISO 1996-2 [4]),
u_{loc2} is the standard uncertainty due to selection of the receiver location relative to the assessment point in dB (u_{loc2} = 1 dB [17] or can be determined as the standard deviation of the measurement repeatability).

All the sensitive coefficients in (9) have been estimated as 1.

The standard uncertainty for the source operating conditions is considered only for single measurements of the equivalent-continuous sound pressure level at the assessment point. In this case, the standard uncertainty for L' is equal to 0.

The standard uncertainty for the source operating conditions is determined from at least 3, and preferably 5 measurements under repeatability conditions (the same measurement procedure, the same instruments, the same operator and the same place) at a position where variations in meteorological conditions have little influence on the results, using the following equation:

$$u_{sou} = \sqrt{\sum_{i=1}^{n} \frac{(L_i' - \overline{L'})^2}{n-1}} , \tag{10}$$

where

L'_i is the measured value for measurement *i,*

$\overline{L'}$ is the arithmetic average of all measurements,

n is the total number of all measurements.

Additionally, the standard uncertainty for the source operating conditions for the road, rail, and air traffic can be determined based on the number of vehicle pass-by (for road and rail traffic) and the number of sound events during the measurement time interval, using Eqs. 7-9 in ISO 1996-2 [17].

If short-term measurements are conducted under favorable and very favorable conditions or when eq. (1) is applied, then the standard uncertainty for meteorological conditions is 2 dB for distances $D \leq 400$ m. For longer distances:

$$u_{met} = 1 + \frac{D}{400}, \tag{11}$$

The standard uncertainty for meteorological conditions can be neglected when the sound source and the assessment point are in the same building.

The standard uncertainty for meteorological and the source operating conditions cannot be calculated as the combined uncertainty directly from the short-term measurements because these measurements cannot be concerned as independent measurements (see Table 4 in ISO 1996-2 [4] for the minimum time between two measurements to be independent).

If the reference time interval consists of a mixture of source operating conditions, including the residual noise, repeated measurements of the equivalent-continuous sound pressure level at the assessment point are recommended (at least 3, and preferably 5). Then, the total noise level can be calculated as [4]:

$$L' = 10 \cdot \log\left(p_1 10^{\overline{L'_1}/10} + p_2 10^{\overline{L'_2}/10} + ... + p_M 10^{\overline{L'_M}/10} \right), \tag{12}$$

where

$\overline{L'_j}$ is the energy averaged equivalent-continuous sound pressure level for repeated measurements for the class of source operating conditions *j,*

p_j is the duration of the class of source operating conditions *j* relative to the duration of the reference time interval, T_0,

$$p_i = \frac{T_i}{T_0}, \quad \sum_i p_i = 1, \tag{13}$$

where

T_j is the duration of the class of source operating conditions *j,*

M is the number of classes of operating conditions.

The combined standard uncertainty for L' is then [4]:

$$u_{L'} = \sqrt{\sum_{j=1}^{M} c_{L'_j}^2 u_{L'_j}^2 + \sum_{j=1}^{M-1} c_{p_j}^2 u_{p_j}^2}. \tag{14}$$

To avoid underestimating the error, p_M is the period with the highest average sound level and this period has been omitted in (14).

The sensitivity coefficients in (12) can be calculated as [4]:

$$c_{L'_j} = \frac{\partial L'}{\partial \overline{L'}_j} = \frac{p_j \, 10^{\overline{L'}_j/10}}{\sum_{j=1}^{M} p_j \cdot 10^{\overline{L'}_j/10}}, \tag{15}$$

$$c_{p_j} = \frac{\partial L'}{\partial p_j} = 10 \cdot \log(e) \frac{10^{\overline{L'}_j/10} - 10^{\overline{L'}_M/10}}{\sum_{j=1}^{M} p_j \, 10^{\overline{L'}_j/10}} \; . \tag{16}$$

For n repeated measurements, the standard uncertainty is the standard deviation of the mean value; otherwise, it is equal to 0:

$$u_{L'_j} = \sqrt{\sum_{i=1}^{n_j} \frac{(L'_i - \overline{L'})^2}{n_j (n_j - 1)}} \; \text{dB} = \frac{\sigma_{L'}}{\sqrt{n_j}} \; . \tag{17}$$

Repeated measurements carried out using the same equipment are not independent with respect to the uncertainty due to sound level meter.

The standard uncertainty of observations of the duration of the class of source operating conditions is determined as the standard deviation of observations (estimation and/or measurement):

$$u_{p_j} = \sqrt{\sum_{k=1}^{m_j} \frac{(p_{jk} - \overline{p_j})^2}{(m_j - 1)}} \; . \tag{18}$$

Finally, the expanded measurement uncertainty with a coverage probability of 95% and an associated coverage factor of 2 is:

$$U = \pm 2 u_L \, . \tag{18}$$

The estimated (true) value of the rating total noise level at the assessment point then becomes:

$$L = L' \; \pm 2U \; . \tag{19}$$

4. Conclusion

Serbian regulations in the field of environmental noise require the measurement and assessment of total environmental noise at the assessment point. Although these regulations do not mandate the use of measurement uncertainty in the assessment of environmental noise at the assessment point, accredited laboratories must determine and report measurement uncertainty in accordance with the requirements of ISO 1996-1 and ISO 1996-2.

In practice, accredited laboratories interpret and apply the guidelines for determining measurement uncertainty provided in ISO 1996-2 in various ways. To unify procedures, this paper describes in detail the methodology for determining the rating total noise level based on short-term measurements and corresponding measurement uncertainty. Although the methodology is consistent with the guidelines provided in the ISO 1996 series, there are some differences:

- the methodology in the ISO 1996 series refers to determining the rating noise level and corresponding measurement for specific noise;
- the guidelines for determining the measurement time interval depending on the operating conditions of the noise source are presented as described in ISO 9612;
- the acceptable distances for hard surfaces in (1) are recommended;
- the number of short-term measurements of the total noise level for repeated measurements is recommended;
- it is recommended that if the duration of specific noise source(s) activities is not equal to the duration of the reference time interval, the residual noise should be considered as one of the classes of source operating conditions within the reference time interval;
- a new contribution to measurement uncertainty related to the selection of microphone location representative of the assessment point (choice of microphone position, microphone height above ground level, microphone orientation) is also added according to the guidelines in ISO 9612;
- it is recommended that the standard uncertainty for meteorological conditions and the source operating conditions is not calculated as the combined uncertainty directly from the short-term measurements;
- special attention is given to the case of a mixture of source operating conditions and repeated short-term measurements are recommended in order to determine the combined standard uncertainty of the calculated value of the rating total noise level according to Eq. (2) or Eq. (4).

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