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DETERMINATION OF THE UNCERTAINTIES OF NOISE MEASUREMENTS

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Abstract: Identification of the noise measuring uncertainties by declared measured values is unconditionally necessary and required by legislative. Uncertainty of the measurements expresses all errors that accrue during the measuring. By indication of uncertainties the measurer documents that the objective value is with certain probability found in the interval that is bounded by the measurement uncertainty. The paper deals with the methodology of the uncertainty calculation by noise measurements in living and working environments.

1. INTRODUCTION

The measurement results uncertainty is a result of casual errors as well as identifiable and quantifiable errors that affect the measurement's result. For this reason, when determining the measurement results´ uncertainty, the subject matter of the balance is all the sources of errors of certain kind (model) of measurement. Upon balancing of the types of errors of individual kinds of measurements, a series of uncertainties appear and these result from a diversity of the sources of errors affecting measurement's result and from the description of their probabilistic character.

2. TYPES OF UNCERTAINTIES

Two types of uncertainties have an impact on the result:

- A type uncertainty (identification u_A) – method of evaluation of uncertainty stemming from the statistical analysis of the series of observations (measurement's results) is characterised by the selection dispersion s_i^2 or by the standard deviation si and the number of degrees of freedom n_i,
- B type uncertainty (identification u_B) – method of evaluation of uncertainty based on other than statistical analysis of the series of observations, the B type uncertainties come from various sources and they are characterised by specific dispersion u_j^2 or by the standard deviation u_j, if among the components of correlation, co-variance is included within calculation.

Assumed is certain distribution of the probability that describes in what way can indicated value estimate actual value or the probability that uncertainty (given by interval) covers actual value. The survey of the most frequent distributions of probabilities is given on the Figure 1.

The standard uncertainties of the A and B types are united in the combined uncertainty according to the following relation:

$$u = \sqrt{u_A^2 + u_B^2} \tag{1}$$

The A type uncertainties are determined from the measurements series of the same quantity under the same conditions. The B type uncertainties are connected with known or identified and quantified sources of errors. Identification and basic evaluation of the B type uncertainties has to be carried out by the experimenter that executes measurements. The characteristic features of the A type uncertainties is that their values decrease with the increasing number of repeated measurements while the values of the B type uncertainties are not dependant on the amount of repeated measurements. The standard uncertainties of the B type coming from various sources of errors are combined in the resultant standard B type uncertainty according to the following relation:

$$u = \sqrt{\sum_{i=1}^{n} u_i^2} \tag{2}$$

Since, upon measurement of noise in the field, it is not possible to execute repeated measurement of the same quantity, it is impossible to evaluate the A type uncertainty and all the sources of possible errors are assessed by the B type uncertainties; then $u = u_B$.

If high reliability (probability) connected with the value of the measured quantity being present within certain interval is required, the extended uncertainty is determined according to the following relation:

$$U = k_u \,.\, u \tag{3}$$

where k_u is extension coefficient.

When evaluating the measurements in terms of the health protection of person, k_u is given as $k_u = 2$. Probability that the actual value is within the interval given by the extended uncertainty is thus 95 %.

3. MEASUREMENT PRECISENESS

The measurement preciseness is a qualitative notion that characterizes measurement from the point of possibility of acquiring a result that is close to the precise value of the measured quantity. The measurement preciseness is quantified by the measurement uncertainty. According to the value of uncertainty and method of determining it, measurements can be divided into regular, precise and informative measurements.

Regular measurement (measuring regular preciseness) is such a measurement the extended uncertainty of which is the same or lower than uncertainty of the same measurement determined on the basis of simple model situations and the uncertainty may be determined by means of direct reading from the table.

Precise measurement is such a measurement the extended uncertainty of which is lower than the uncertainty of regular measurement determined by standard methodology based on a simple model situation under the identical conditions would be. It is used mainly in those instances when the hygienic limit is within the interval around the measured value given by the extended uncertainty of the regular preciseness measurement.

Informative measurement is any measurement the extended uncertainty of which is higher than the uncertainty of regular measurement determined by standard methodology based on simple model situations under the identical conditions would be. Generally these are the measurements with measuring devices that meet the requirements of the sound-level meters of the 2nd class. The result of the informative measurement may serve the purposes of assessing observation or exceeding of the hygienic limits exclusively in the cases when the hygienic limit is outside the interval around measured value given by the extended uncertainty of the information measurement. [3]

4. MEASUREMENT ERRORS

4.1 The measuring device errors dependant on frequency

Frequency weight characteristic error

Develops as a result of the deviations of measuring device (sound-level meter) from the ideal frequency weight characteristic measured in the sound field comprising of the plane sound waves transmitted towards microphone in the reference direction of incidence. The precise development of the ideal frequency weight characteristic is specified by the specific standard for sound-level meters. Deviations from the ideal development are caused by imperfection of the whole measuring chain (microphone, pre-amplifier, weight filter, detector etc.). The highest share in the frequency weight characteristic error during measurement can be generally attributed to the measuring microphone itself. Lower share can be attributed to the impact of the electronic circuits of sound-level meter.

Error caused by the direction characteristic

Ideal measuring microphone captures sound waves from all directions of the measured area with the same sensitivity like in the sound field comprising of the plane sound waves transmitted towards microphone in the reference direction of incidence. The error caused by the direction characteristic develops as a result of the deviation of the characteristics of the actual measuring microphone (in connection with other parts of the measuring device that affect, with their placement, a sound field in the direct proximity of microphone e.g. sound-level meter body, measuring device's stand etc.) from the characteristics of the ideal measuring microphone. This error is generally higher the higher are the deviations of the characteristics of the measured sound waves from the characteristics in the sound field comprising of the plane sound waves transmitted towards microphone in the reference direction of incidence. The electric properties of the measuring device do not have any impact on the magnitude of this error.

4.2 Frequency-independent errors of measuring device

Calibration overall error during measurement

It is a difference between the response of the ideally precise sound-level meter to the ideal calibration signal under the ideal reference conditions and the response of the actual sound-level meter calibrated under specific measurement conditions. This error includes the errors caused by the changes in static pressure, temperature and relative humidity, calibration error under reference conditions, amplitude characteristic linearity error and the error caused by the changed properties under constant test conditions.

Calibration error under reference conditions

It is a difference between the response of the ideally precise sound-level meter to the ideal calibration signal under the ideal reference conditions and the response of the actual sound-level meter calibrated by actual calibrator under the ideal reference conditions. [1]

5. CALCULATION OF THE MEASUREMENT UNCERTAINTY – PRECISE PROCEDURE

This procedure is used for determining the measurement uncertainty when the highest preciseness of determination of the measurement uncertainty is required.

5.1 Determination of the frequency-independent biggest permissible errors of measuring device

This group includes:

- calibration error under reference conditions,
- error caused by the changed properties under constant test conditions,
- amplitude characteristic linearity error,
- time averaging error,
- error caused by the changed range,
- error caused by the changed static pressure,
- error caused by the changed temperature,
- error caused by the changed relative humidity,
- error caused by the resolution of display (for the devices with the standard numerical display with the resolution of 0,1 dB is z_{max} = 0,05 dB and can be ignored during calculations),
- error of the individual calibration of specific measuring device performed by respective metrology shop. [1]

5.2 Calculation of the frequency-dependent biggest permissible errors of measuring device

This group includes:

- error of the frequency weight characteristic,
- error caused by direction characteristic.

Upon calculations, the following steps are followed:

a) Determined (measured) are individual elements of the measured signal in the thirdoctave frequency bands L_f for f = 20Hz, 25Hz, 31,5Hz, ..., 12,5kHz, 16kHz, 20kHz.

Determined are individual biggest permissible errors in the thirdoctave frequency bands:

$z_{max(+)f}$ = ... [dB] f = 20Hz, 25Hz, 31,5Hz, ... 12,5kHz, 16kHz, 20kHz
$z_{max(-)f}$ = ... [dB] f = 20Hz, 25Hz, 31,5Hz, ... 12,5kHz, 16kHz, 20kHz

b) When determining and calculating specific values the case of asymmetric tolerance (e.g. +3 dB /-6 dB) can occur (in conflict with the assumptions given in TPM 0051-93) i.e. $|zmax(+)| \neq |zmax(-)|$. Therefor, the values of the biggest permissible errors have to be determined separately for positive and negative tolerances.

c) Calculated is total weighted level of measured signal from the individual the thirdoctave bands:

$$L = 10\log \sum_{f=20Hz}^{20kHz} 10^{\frac{L_f + X_f}{10}} \tag{4}$$

X_f - value of the frequency weight function in specific frequency band.

Developments of the frequency weight functions (weighing A and C) are given in STN EN 60651.

d) Calculated is the total weighted level of the measured signal from the levels in the individual thirdoctave bands increased by the biggest permissible error of measuring device:

$$L_{(+)} = 10\log \sum_{f=20Hz}^{20kHz} 10^{\frac{L_f + X_f + z_{max(+)f}}{10}} \tag{5}$$

e) Calculated is the total weighted level of the measured signal from the levels in the individual thirdoctave bands reduced by the biggest permissible error of measuring device:

$$L_{(-)} = 10\log \sum_{f=20Hz}^{20kHz} 10^{\frac{L_f + X_f - z_{max(-)f}}{10}} \tag{6}$$

f) The biggest permissible error of measuring device for the whole frequency band of measurement then will be as follows:

$$z_{max(+)} = L_{(+)} - L \tag{7}$$

$$z_{max(-)} = L - L_{(-)} \tag{8}$$

g) For further calculation, the value numerically higher will be used as the biggest permissible error of measuring device (for the whole frequency band of measurement):

$$z_{max} = MAX\,(z_{max(+)}, z_{max(-)}) \tag{9}$$

5.3 Calculation of relative standard uncertainties

With the relations (2), (3) and (11) used for the calculation of uncertainties, the values in decibels cannot be calculated with. Each value z_{max} expressed in decibels has to be, firstly, calculated as relative error of the acoustic pressure quadrate according to the relation (10):

$$z_{max} = 10^{\frac{|z_{max}|}{10}} - 1 \tag{10}$$

Relative standard uncertainty (for individual errors) is calculated from the relative error of the acoustic pressure quadrate:

$$u = \frac{z_{max}}{\chi} \qquad (11)$$

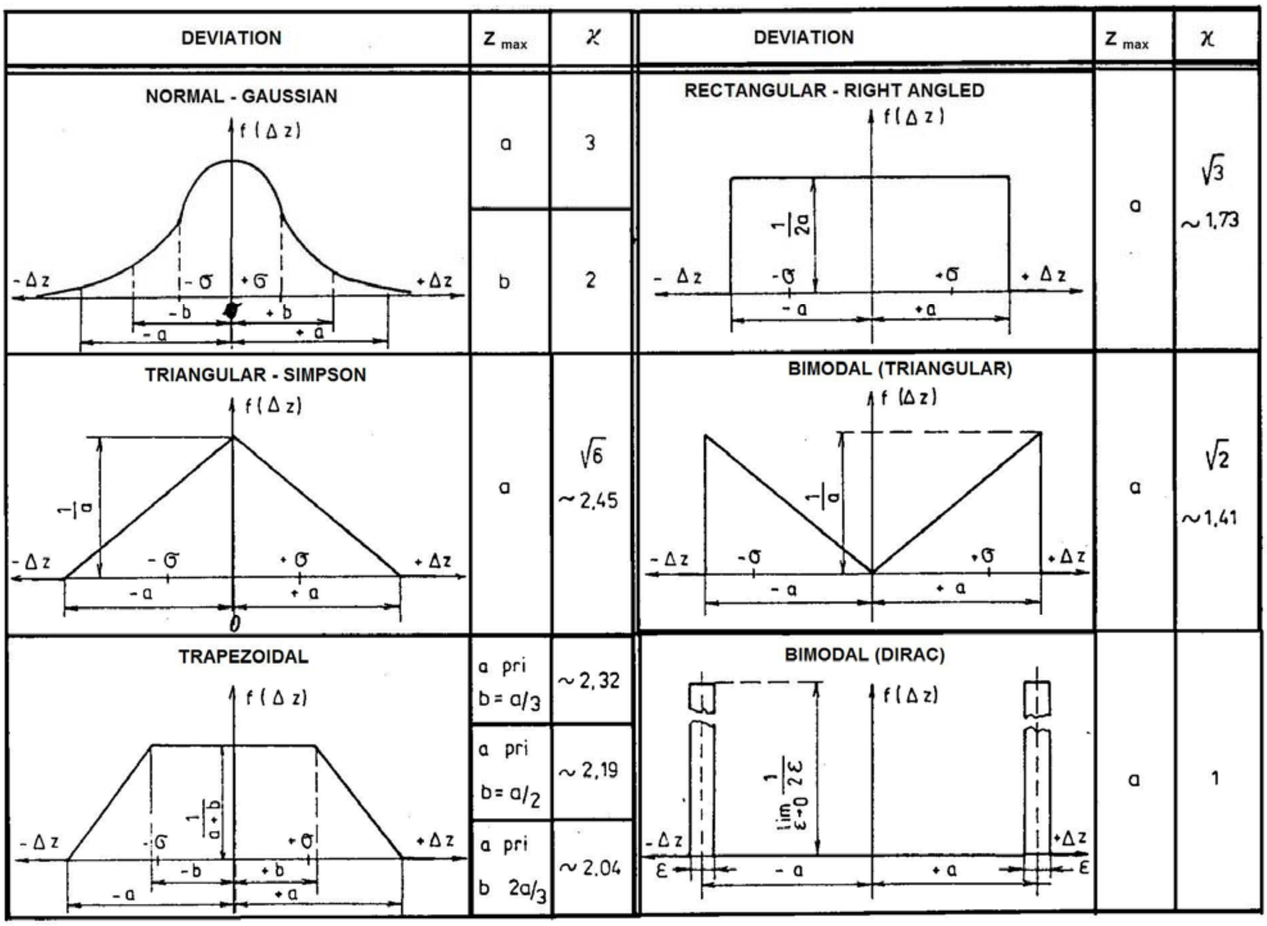
χ – depends on development of probability of deviations within the interval $[-z_{max}; +z_{max}]$ see Figure1.

$\chi = 1{,}73$ – for z_{max} with the uniform distribution of the probability's development (e.g.: error caused by display's resolution, amplitude characteristic linearity error ...)

$\chi = 2$ – for z_{max} that is a superposition of several non-correlated tolerances of measuring device (e.g.: calibration under reference conditions)

$\chi = 3$ – for z_{max} frequency-dependant, determined from the values $z_{max(f)}$ for f = 20Hz, ...20kHz (e.g. error of frequency weight characteristic), if the value z_{max} is practically unexceedable.

Resultant relative standard uncertainty is calculated according to the relation (2).



DEVIATION	Z_{max}	χ	DEVIATION	Z_{max}	χ
NORMAL - GAUSSIAN	a	3	RECTANGULAR - RIGHT ANGLED	a	$\sqrt{3}$ ~ 1,73
	b	2			
TRIANGULAR - SIMPSON	a	$\sqrt{6}$ ~ 2,45	BIMODAL (TRIANGULAR)	a	$\sqrt{2}$ ~ 1,41
TRAPEZOIDAL	a pri b = a/3	~ 2,32	BIMODAL (DIRAC)	a	1
	a pri b = a/2	~ 2,19			
	a pri b 2a/3	~ 2,04			

Legend: σ *- middle quadratic deviation*

$\chi = z_{max} / \sigma$

Fig. 1 Distribution of probability

5.4 Balance of errors from the standardised tolerances and deviations

Table 1 gives the balance of the uncertainties sources from the standardised tolerances of the frequency-dependent parameters within the corresponding frequency band and from the standardised deviations of the frequency-independent parameters for the Class 1 sound-level meters with the connected measuring microphone.

5.5 Calculation of extended uncertainty

Extended uncertainty is calculated from the relative standard uncertainty according to the relation (3) and is converted to decibels according to the relation (12):

$$U = 10 \log (U + 1) \qquad (12)$$

Table 1 Balance of the uncertainties sources from the standardised tolerances and deviations of the individual parameters of the Class 1 sound-level meters

Uncertainty source - parameter		**Tolerance/deviation**			**Share u_{Bpi} (dB)**
		$\lvert z_{\max} \rvert$ **(dB)**	**Probability development**	χ **(-)**	
Frequency weight function A, C and Z	31,5 Hz up to 4 kHz	1,6	uniform	1,73	0,925
	> 4 kHz up to 8 kHz	2,6			1,503
	> 8 kHz up to 12,5 kHz	4,5			2,601
	> 12,5 kHz up to 16 kHz	10,2			5,896
Direction characteristic ±30° from reference direction	250 Hz up to 1 kHz	1,3	uniform	1,73	0,751
	> 1 kHz up to 2 kHz	1,5			0,867
	> 2 kHz up to 4 kHz	2,0			1,156
	> 4 kHz up to 8 kHz	3,5			2,023
	> 8 kHz up to 12,5 kHz	5,5			3,179
Direction characteristic ±90° from reference direction	250 Hz up to 1 kHz	1,8	uniform	1,73	1,040
	> 1 kHz up to 2 kHz	2,5			1,445
	> 2 kHz up to 4 kHz	4,5			2,601
	> 4 kHz up to 8 kHz	8,0			4,624
	> 8 kHz up to 12,5 kHz	11,5			6,647
Error in amplitude characteristic linearity		1,1	uniform	1,73	0,636
Changed level of the input signal from 1 dB up to 10 dB		0,6	uniform	1,73	0,347
Time weight characteristics F and S		0,3	uniform	1,73	0,173
Change of the static pressure from 85 kPa up to 108 kPa		0,7	uniform	1,73	0,405
Changed air temperature from -10°C up to + 50 °C		0,8	uniform	1,73	0,462
Changed relative humidity of air from 25% up to 90%		0,8	uniform	1,73	0,462
Changed power source voltage		0,3	uniform	1,75	0,173

6 CALCULATION OF THE UNCERTAINTY OF THE EVALUATIVE NOISE LEVEL (SIMPLIFIED PROCEDURE – REGULAR MEASUREMENT)

This procedure enables determination of uncertainty of evaluated level of noise in the working environment. Such uncertainty is defined by the following relation:

$$L_{Ar,To} = 10\log\frac{1}{T_0}\left(\sum_{j=1}^{n} T_j \cdot 10^{0.1(L_{Aeq,Tj}+K_j)}\right) \qquad (13)$$

T_0 - is nominal time (T_0 = 8 h per working shift or night time; T_0 = 16 h for day time),
$L_{Aeq,Tj}$ - is equivalent level sounding during time interval T_j,
$K_j = K_i + K_t$ - is a sum of tone and impulse correction.

Calculation procedure is as follows:

Extended uncertainties U are determined for individual levels $L_{Aeq,Tj}$ (j = 1,... n). Based on these values respective relative standard uncertainties u_j are then read from the Table 2.

Tab. 2

U [dB]	1,8	2,0	2,3	2,6	2,8	3,3	3,6	4,5
u_j [–]	0,257	0,292	0,349	0,410	0,453	0,569	0,645	0,909

The biggest permissible error for individual time intervals T_j (j = 1,... n) is calculated according to the following relation:

$$z_{\max,Tj} = \frac{\Delta T_j}{T_j} = \frac{T_{j\max} - T_{j\min}}{T_{j\max} + T_{j\min}} \tag{14}$$

T_j – time interval nominal value,
ΔT_j – max. tolerance of time interval T_j,
T_{jmax} – max. value of time interval T_j,
T_{jmin} – minimum value of time interval T_j.

Uncertainty caused by the error of time interval T_j (j = 1,... n) is calculated according to the following relation:

$$u_{Tj} = \frac{z_{\max,Tj}}{1{,}73} \tag{15}$$

If the value u_{Tj} is lower than 0,05, it may be ignored with the next calculation.

Calculated are measurement uncertainties of individual sound exposures used with the calculation of evaluative level:

$$u_{Ej} = \sqrt{u_j^2 + u_{Tj}^2} \tag{16}$$

Relative standard uncertainty of the evaluative noise level is calculated as follows:

$$u = \frac{\sum_{j=1}^{n} T_j \cdot 10^{0,1\left(L_{AeqTj} + K_j\right)} \cdot u_{Ej}}{\sum_{j=1}^{n} T_j \cdot 10^{0,1\left(L_{AeqTj} + K_j\right)}} \tag{17}$$

Resultant extended standard uncertainty of the evaluative level converted to decibels:

$$U = 10 \log\left(2\,u + 1\right) \tag{18}$$

7 CONCLUSION

The scope of provided information when submitting the measurements results and their uncertainties should stem from the requirements of customer specification. The methods used for calculation of the result and its uncertainty should be stated in the measurement protocol and should include:

- sufficient documentation of the steps and calculations during the analysis of data (results) enabling repetition of calculations if necessary,
- all the corrections used upon the data analysis,
- sufficiency of feedback documentation proving the uncertainty calculation method.

In case customer requires assessment of correspondence with specification (limit value of quantity), there are several possibilities when considering the value of extended uncertainty of measurement:

Example 1: Measured (calculated) value of quantity increased by the value of extended uncertainty is lower or equals the limit value of quantity

$$\left(L_{nam} + U\right) \leq L_{prip.} \tag{19}$$

Example 2: Measured (calculated) value of quantity reduced by the value of extended uncertainty is lower or equals the limit value, yet, at the same time, this value increased by the uncertainty value is higher than the limit value of quantity

$$\left(L_{nam} - U\right) \leq L_{prip.} < \left(L_{nam} + U\right) \tag{20}$$

Example 3: Measured (calculated) value of quantity reduced by the value of extended uncertainty is higher than the limit value of quantity

$$\left(L_{nam} - U\right) > L_{prip.} \tag{21}$$

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