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INVESTIGATIONS OF UNCERTAINTY OF ACOUSTICAL MEASURING INSTRUMENTS APPLIED TO NOISE CONTROL

G. WSZOŁEK and Z. ENGEL

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Mickiewicza 30, 30-059 Kraków, Poland
e-mail: wszolek@uci.agh.edu.pl
engel@uci.agh.edu.pl

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In view of regulations harmonised with the European Union legislation, being presently introduced in Poland, it is required that the presentation of the measured sound level values is accompanied by the uncertainty study. It is especially important in cases concerning an acoustical environment of human life and work.

The uncertainty study comprises, among others, accuracy of the measuring instrument itself and its calibration prior to the measurements as well as uncertainty of the measuring method and the way of the test performance. The first element of this estimate is uncertainty of testing measuring microphones and sound level meters in order to verify whether they conform to the requirements being set for the newly manufactured instruments at the stage when they are subjects to the type approving procedure.

1. Introduction

Acoustical properties describing an environment are related to the acoustical pressure measurements. The basic instruments for measuring acoustical pressure are microphones and sound level meters. When a new device is being designed and manufactured it has to undergo several tests and their results will decide of the so-called "Type approval". This type approval of the instrument is the necessary condition for the permission for its production and use in the particular country. Requirements, which are to be met by microphones and sound level meters are given in standards and in metrological regulations.

In connection with regulations harmonised with the European Union legislation, being presently introduced in Poland, several new requirements concerning the conformity assessment system were developed. New standards and regulations related both to instruments and to noise measurements in the environment require that the presentation of the measured sound level values is accompanied by the uncertainty study. However they neither supply nor recommend methods of the uncertainty estimation.

Polish manufacturers of microphones and sound level meters who would like to enter the foreign markets have to be ensured that their instruments fulfil requirements of international standards. Tests performed in Poland should be recognised or confirmed in other countries. Thus the results of measurements along with the estimation of uncertainty performed in the specified laboratory should be within the permissible limits.

Uncertainty estimation is not an exact physical theory, but rather an approximate description of imperfections of experiments. The theory of uncertainty of measurement utilises the principles of probability mathematics and mathematical statistics [1].

According to [2], the definition of uncertainty is as follows:

Uncertainty of measurement – a parameter related to the measured result, characterising the scatter of results, which can be reasonably attributed to the measured value.

Uncertainty estimation procedures are based on the detailed specification of sources of errors and their qualification into A or B group. This is the most difficult and challenging task. If an error randomly changes from one measurement to another it belongs to A group. The error statistics of A group is known *a priori*, which means that the variance σ_{A}^2 decreases proportionally to the number of measurements, N, in the series. If, for several consecutive measurements the error is constant, it is qualified into B group. Uncertainties of measurements caused by B group errors are not estimated from the random distribution of results in the measuring series as in the case of A[(1)] group.

The estimation of uncertainty related to B type errors is based on a scientific judgement of an experimentator utilising all available information (other than statistic ones) concerning measurements and sources of their uncertainty. Therefore in the uncertainty estimation procedure of an error from B group the proper probability distribution of the set, from which the error originated should be chosen.

Components of sources of A type errors concern uncertainty classified previously as random errors. Estimation of B group errors concern sources classified previously as systematic ones (or when there was a random error but only single result was available), however understood quite differently than before [3] (systematic error as a random phenomenon [4]). The new approach [2, 5] thus changes irreversibly the traditional differentiation between random and statistical errors. Furthermore it is recommended that all components of the uncertainty of measurements are presented as variances and covariance of random variables influencing the result and adding them in accordance with the general principle of the determination of random variables functions. Thus the total value of the uncertainty variance is obtained by summing contributing variances (and covariance) together with their relevant sensitivity coefficients, regardless whether they were statistically estimated from the measuring series or were expressed as variances, when utilising available information, e.g. from the assumed probability distributions [3].

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(1) Quite often the uncertainty calculated on the basis of B group method were previously estimated by the statistical analysis of a series of single observations [2].

Certain general unification of the uncertainty expression in measurements can be found in [2, 5], however, the methodology given there is not sufficient. While in simple measurements, which can be presented by not complicated and easy models, one can use standard procedures for calculating uncertainty, in measurements described by relatively complex models, procedures of uncertainty estimations should be to large extent modified, what requires understanding the notion of uncertainty of measurements as well as probability mathematics and statistics.

The final result of an individual estimation of the uncertainty of measurement always depends on the person performing the measurement, his/her knowledge and experience concerning both the measurements and the uncertainty estimation. Presented hereby estimation of uncertainty is an assessment of measurement accuracy performed on the basis of the authors' many years of research experience. The given experimental methods concern mainly acoustical estimation of instruments at the stage of their construction and the type approving procedure. However, some elements of this estimation can be utilised for the assessment of uncertainty of acoustical measurements performed by means of those instruments.

2. Investigations of sound level meters

Acoustical investigations of instruments in a free-field encompass the determination of frequency response and directional characteristics. They allow to estimate the disturbance of an acoustic field caused by an introduction of an obstacle, which constitute the measuring instrument (either a microphone itself or a sound level meter).

Electrostatic microphones (often electret microphones of a stable polarised membrane or stable electrode) and sound level meters – measuring and analysing devices – are nowadays the most commonly used instruments for acoustic measurements. Application of an electret eliminates the necessity of using DC source and facilitates the construction of other equipment elements but for acoustical investigations of instruments themselves in the free-field type of a microphone is of no importance. Similarly multifunctionality of a meter does not matter. The results of acoustical investigations of instruments are highly influenced by their dimensions, shape and stability of parameters. In case of determining the characteristics concerning the type of instrument the scatter of results obtained for individual instruments belonging to the same type is extremely important. The quality of a microphone used is a decisive factor in such cases.

Determinations of frequency and directional responses in the free-field allow to check whether the particular instrument meets requirements and to assess the corrective coefficients. When corrections being the difference between the frequency response in the free-field and the pressure response are already known, then certain indirect methods (mostly electrical) can be applied at the calibration and legislation procedure of those instruments. This allows performing several control tests in laboratories, which do not have very sophisticated, highly specialised equipment.

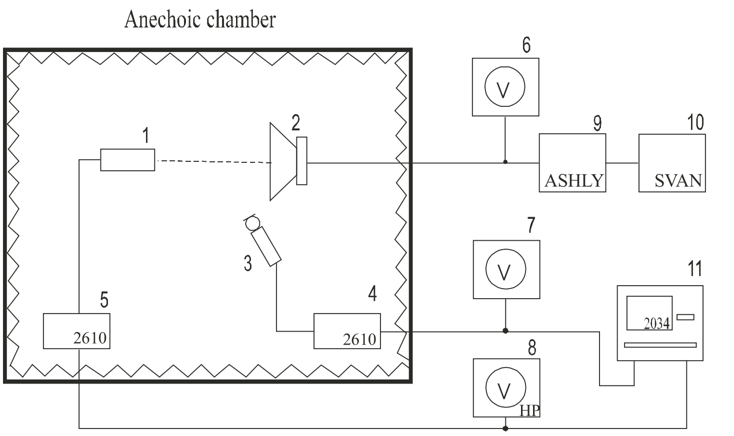
The presented paper outlines only the research program. More details concerning the methodology and obtained results can be found in bibliography [1, 6–8].

Values of the frequency characteristics in the acoustical free-field are determined by comparing the response of the instrument under test with the response of the reference microphone – at the same sound signal, same measuring set-up and in the same environmental conditions.

The basic requirements for this method, called substitution method, are a very precise positioning of microphones and the measuring conditions control.

Microphones, first the reference one and then the microphone from the meter, must be placed exactly at the same point of the acoustical field and in such a way that the angle of incidence of an acoustic wave on the reference microphone plane will be 0° (against the main axis of the microphone).

Investigations of the frequency characteristics of microphones and sound level meters are being done by means of the measuring se-up presented in Fig. 1. The frequency response is determined by the point-by-point method by a sinusoidal signal at the acoustical pressure level of 94 dB in the frequency range from 250 Hz to 20 kHz. In the range from 250 Hz to 2 kHz those are midband frequencies of 1/3 octave, from 2 kHz to 8 kHz – 1/6 octave and from 8 to 20 kHz – 1/12 octave.



1- Object under testing, reference microphone or microphone/meter
2- Loudspeaker
3- Control microphone
4,5- Measuring amplifiers
6,7,8- Digital voltmeters
9- Power amplifier
10- Generator of sinusoidal signals
11- Narrow band frequency analyser

Fig. 1. Layout of the measuring set-up for the determination of frequency response of microphones and sound level meters.

Measurements should be done for at least three various measuring distances: *source – microphone*. At each point the measurements are repeated twice for the reference microphone as well as for the microphone being tested. The measurement result is an average value of all measurements.

Results of the frequency response LIN of the MP7B meter (meter only and meter with a wind-shield) are exemplified in Fig. 2.

Frequency	Relative values of frequency response LIN of the MP7B meter in the free-field (0°), microphone M024, in dB	
Hz	Meter	Meter with wind-shield,
250	0.0	0.1
–	–	–
9500	–	–
10000	– 0.4	– 0.6
10700	– 0.2	–
12000	– 1.2	–
12500	– 1.0	– 1.3
13500	– 1.1	–
15100	– 0.8	–
16000	– 0.9	– 1.6
19000	– 2.4	–
20000	– 3.0	– 3.8

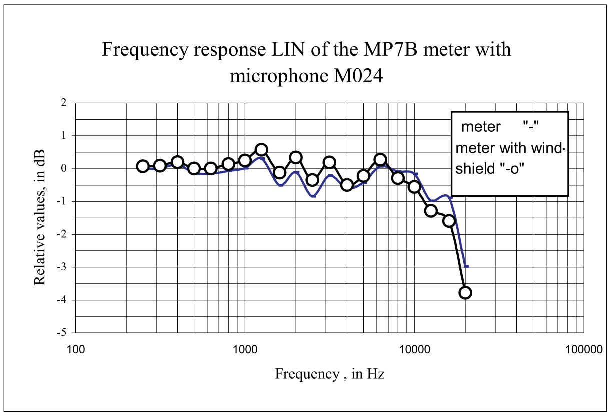


Fig. 2. Frequency response LIN of the MP7B sound level meter.

Directional characteristics of instruments are determined for the frequency range from 250 Hz to 12.5 kHz and the reference acoustic pressure level of 94 dB. They are determined either in a continuous or point-by-point way. Those responses for the sound level meters are being estimated in two mutually perpendicular planes and for two ways of the meter placement in an acoustic field:

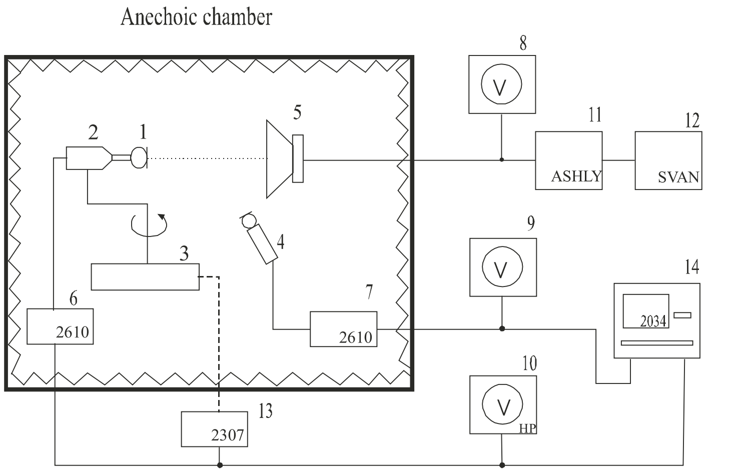
- Position "h" – faceplate of the meter in upward position,
- Position "v" – meter turned by 90° (around the main axis of a microphone) vs. position "h".

The measuring set-up used by the authors for the determination of directional responses of microphones and sound level meters is presented in Fig. 3.

Due to an application of electrical and acoustical control of generated signal and the accurate reading of the output signal of the instrument under test the presented measuring set-up allows more accurate determinations than the standard ones. Characteristics are most frequently shown in polar or in rectangular coordinates. When it is required the results are read from the digital voltmeter and changes of the acoustical pressure level are presented in tables.

An example of results obtained for MP7B meter investigations are presented as graphs – in polar coordinates – in Fig. 4 and in Table 1.

Measurements are being done at one measuring distance. The proper positioning of the instrument vs. the sound source and vs. the axis of the table rotation is very essential. The axis of symmetry of the meter microphone and the axis of symmetry



1,2 - Object under testing,
3 - Turntable,
4 - Control microphone,
5 - Sound source,
6, 7- Measuring amplifiers,
8, 9, 10 - Digital voltmeters,
11 - Power amplifier,
12 - Generator of sinusoidal sign,
13 - Level recorder,
14 - Narrow band frequency analyser

Fig. 3. Schematic presentation of the measuring set-up for the determination of the directional response.

of the sound source have to be in the same plane. Simultaneously the meter must be placed on the rotating table in such a way that its rotation will be vs. the axis, which is perpendicular to the main axis of the meter microphone and crosses the reference plane of that microphone.

a) b)

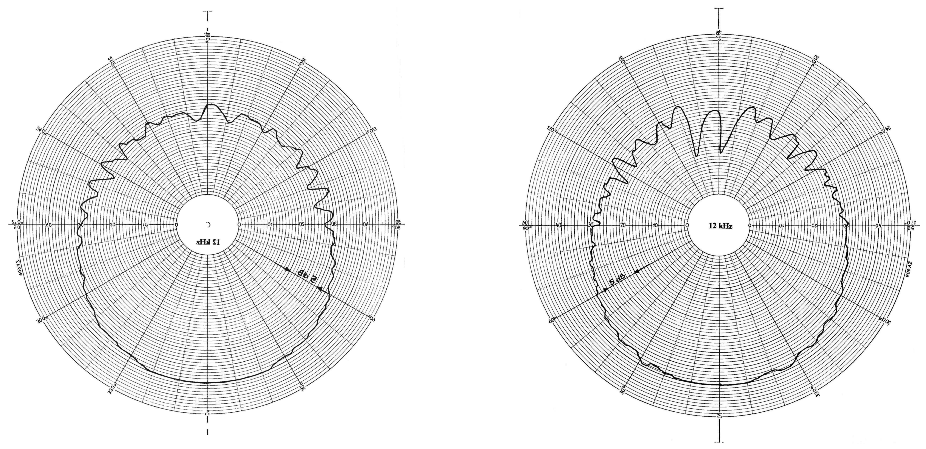


Fig. 4. Directional characteristics of the MP7B sound level meter determined for frequency 12 kHz and two positions: “h” (a) and “v” (b).

Table 1. Deviations from the omnidirectional characteristics of the MP7B meter.

Position	Frequency Hz	Maximum absolute difference in displayed sound levels at any two sound-incidence angles within $\pm\theta$ degrees from the reference direction dB				
		$\pm 30°$	$\pm 60°$	$\pm 90°$	$\pm 120°$	$\pm 150°$
1	2	3	4	5	6	7
"v"	250	0.0	0.1	0.1	0.1	0.1
	–	–	–	–	–	
	10000	1.3	2.6	5.1	7.0	7.2
	10700	1.3	2.7	5.4	7.5	7.5
	11300	0.9	4.7	5.4	7.6	7.8
	12000	0.4	2.9	6.3	8.8	8.8
	12500	1.2	3.8	6.8	11.3	11.3

3. Mathematical models of measurements

Mathematical models for the estimation of uncertainty of the obtained results were formulated for the measurements performed according to the presented above methods, experimental set-up and conditions in the anechoic chamber located at the Chair of Mechanics and Vibroacoustics, University of Science and Technology, Kraków.

Formulation of equation for the result of the measurement is a mathematically expressed relation between the measured values and input values – when factors influencing this result are accounted for [9].

The accuracy of measurements of the frequency response of instruments tested in the free-field depends on several factors. These factors can be divided into four groups:

- Factors connected with the experimental stand and the room – anechoic chamber (reflections, interference phenomena, positioning), positioning),
- Factors related to equipment and the measuring set-up:
  - Stability of measuring paths and their calibration, errors in a frequency response, linearity of paths, spacing between the useful signal and noises in the experimental set-up, spacing between the measuring signal and the anechoic chamber background,
  - Stability of the generated signal level, stability of frequency, nonlinear distortions,
  - Errors related to the voltage level measurement,
- Factors related to the reference microphone,
- Factors related to the influence of environmental conditions.

In order to present the general procedure of the uncertainty estimation all components should be accounted for. Prior to the formulation of mathematical models – due to a large number of components and their various weights – their influence on the result of measurement was discussed.

Influence and the related uncertainty were assessed on the basis of measurement data, standardisation certificates of equipment and experimental investigation aimed at the estimation of the given component and the uncertainty of its measurements.

The discussion and the estimation of the contribution of each component to the combined uncertainty of measurements allowed to reject factors not essential for this particular measurement and to formulate the mathematical models.

The mathematical model of the frequency response is presented below by the expression (1):

$$L_{p,b} = \delta L_{\text{cal}} + \delta L_{s,\acute{z}} + 20\log\left(\frac{V_b}{V_{bo}}\right) - 20\log\left(\frac{V_w}{V_{wo}}\right) - \delta L_W - \left[20\log\left(\frac{V_{\text{AC}}}{V_{94}}\right) - \Delta L_m\right] + \delta L_{m,r} + \delta L_{p,r}, \tag{1}$$

where:

- $L_{p,b}$ relative value (vs 1000 Hz) of the acoustical pressure level of the tested microphone (meter), in dB, at reference sound pressure level 20 μPa,
- L_{cal} stability of the calibration of measuring paths – done by an acoustic calibrator,
- $\delta L_{s,\acute{z}}$ stability of the acoustic signal level generated by the sound source,
- V_b/V_{bo} voltage value at the output of the measuring path – microphone (meter) being tested, in relation to the voltage value adequate for the calibration level, in dB,
- V_w/V_{wo} voltage value at the output of the reference path – reference microphone, in relation to the voltage value adequate for the calibration level, in dB,
- δL_W correction of the free-field of the reference microphone, being the difference between the response of the microphone in the AC free-field and the pressure response. It is being determined for microphones of the type corresponding to the reference microphone type. This correction is added to the pressure response of the microphone – individually determined – in dB,
- δL_m measurement error when the sound level meter was used for measuring (concerns only functions, which have been used). Not applied at testing microphones,
- $\delta L_{p,r}$ scatter of the results. Related to various measuring distances and positioning of the tested instrument vs the reference microphone,
- $\delta L_{m,r}$ error related to the resolution of the sound level meter,
- $\left[20 \cdot \log\left(\frac{V_{\text{AC}}}{V_{94}}\right) - \Delta L_m\right]$ correction used only at the determination of the sound level meters, related to the voltage difference at the AC voltage output of the tested meter and its indication L_m.

The mathematical model of the determination of the directional response of the sound level meters is presented as Eq. (2):

$$\Delta L = \delta L_{\mathrm{cal}} + \delta L_{s,\acute{z}} + 20\log\left(\frac{V_b}{V_{bo}}\right) - \left[20\cdot\log\left(\frac{V_{\mathrm{AC}}}{V_{94}}\right) - \Delta L_m\right] + \delta L_{p,r} + \delta L_{\mathrm{pos}}\,, \tag{2}$$

where:

ΔL difference between the acoustical pressure level of ideal and of actual directional characteristics of the tested meter, in dB, at the reference sound pressure level 20 μPa,

V_{bo} voltage value at the output of the measuring path of the tested meter for the reference direction of the incidence of the sound wave,

V_b voltage value at the output of the measuring path for the selected direction of the sound wave incidence – from 0° to $\pm 150°$,

δL_{pos} error related to the accuracy of positioning of the meter's main axis in the reference direction and the reference plane of the meter's microphone on the axis of rotation estimated experimentally.

Models presented above concern sound level meters. However, when factors related solely to the meters are omitted, these models become mathematical models for microphone measurements.

Each of the components appearing in Eqs. (1) and (2) is characterised with the standard uncertainty, which should be determined from the statistical assessment of type A or B method in order to determine the combined standard uncertainty.

4. Uncertainty of investigations

Both characteristics – frequency and directional – are determined by indirect measurements. In indirect measurements uncertainties of directly measured values are transferred onto the calculated value in accordance with the principle of uncertainty transfer. The combined uncertainty standard, u_c, of the result y is obtained as addition of standard uncertainties of input quantities x_i according to Eq. (3):

$$u_c(y) = \sqrt{\sum_{i=1}^{N}\left[\frac{\partial y}{\partial x_i}u(x_i)\right]^2}\,. \tag{3}$$

Equation (3) is a true one at the assumption that input variables are not correlated. Although one must admit that values measured directly are correlated (the same reference standard, same measuring instruments), nevertheless an influence of correlated but negligibly small values, was deemed irrelevant.

On the basis of Eq. (1) and further by applying dependence (3) one can create the expression defining the combined uncertainty in the evaluation of response:

$$u_c^2(L_{p,b}) = u^2(\delta L_{\mathrm{cal}}) + u^2(\delta L_{s,z}) + \left[20\log\left(\frac{u(V_b)}{V_{bo}}\right)+1\right]^2 + \left[20\log\left(\frac{u(V_w)}{V_{wo}}\right)+1\right]^2 + u^2(\delta L_W) + \left[20\log\left(\frac{u(V_{\mathrm{AC}})}{V_{94}}\right)+1\right]^2 + u^2(L_m) + u^2(\delta L_{m,r}) + u^2(\delta L_{p,r}). \tag{4}$$

On the basis of expression (4) defining the combined uncertainty the uncertainty budget was estimated for the MP7B meter – used as an example. Due to the fact that uncertainties for certain frequency ranges are of a very similar value, the uncertainty of evaluation of the response is being done in the following frequency sub-ranges: $>$ 200 Hz to 1.25 kHz, $>$ 1.25 kHz to 10 kHz, $>$ 10 kHz to 20 kHz.

Data concerning standard uncertainty of individual components and the combined standard uncertainty for the first sub-range are presented in Table 2.

Table 2. Uncertainty budget of the estimation of the frequency response for the MP7B meter – in the frequency range $>$ 200 Hz to 1.25 kHz.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Contribution to the standard uncertainty $u_i(y)$
		dB			dB
δL_{cal}	0 dB	0.0057	rectangular	1	0.0057
$\delta L_{s,\acute{z}}$	0 dB	0.028	rectangular	1	0.028
V_w	0.55 V	0.0015	trapezoidal	-1	0.0015
V_b	0.8 V	0.0015	trapezoidal	1	0.0015
δL_W	0 dB	0.05	normal	-1	0.05
V_{AC}	0.05V	0.0048	trapezoidal	-1	0.0048
$\delta L_{m,r}$	0 dB	0.029	rectangular	1	0.029
$\delta L_{p,r}$	0 dB	0.05	normal	1	0.05
$L_{p,b}$	0 dB	Combined standard uncertainty u_c =			0.082

The combined standard uncertainty u_c for the consecutive frequency ranges equals: $u_c = 0.082$, 0.16 and 0.30 dB.

The analysis of the contribution of individual components to the combined standard uncertainty revealed that the following factors influence the uncertainty in the most noticeable way:

- uncertainty of estimation of the free-field response of the reference microphone,
- nonstability of a signal generated by the sound source,

- scatter of results (related mainly to the instrument positioning and measurements performed in various points within the space of the chamber).

Expanded uncertainty of an estimation of frequency response for the MP7B sound level meter – for the coverage factor $k = 2$ and the coverage probability of approximately 95%, $U_{95} = 0.2$, 0.3, 0.6 dB, in the consecutive frequency sub-ranges – respectively. Permissible values of expanded uncertainty for this type of measurements given in the International Standards [10] are: $U_{95} = 0.4$, 0.6 and 1.0 dB, respectively.

On the basis of the mathematical model of the directional characteristics (2) and by applying the dependence (3) the expression for the combined uncertainty can be given:

$$\begin{aligned} u_c^2(L_p) &= u^2(\delta L_{\mathrm{cal}}) + u^2(\delta L_{z,s}) + \left[20 \cdot \log\left(\frac{u(V_b)}{V_{bo}} + 1\right)\right]^2 \\ &+ \left[20 \log\left(\frac{u(V_{\mathrm{AC}})}{V_{94}} + 1\right)\right]^2 + u^2(\delta L_m) + u^2(\delta L_{m,r}) + u^2(\delta L_{\mathrm{pos}}), \end{aligned} \tag{5}$$

Uncertainty of measurements is estimated in 4 sub-ranges: $>$ 250 Hz to 1 kHz, $>$ 1.25 kHz to 4 kHz, $>$ 4 kHz to 8 kHz and $>$ 8 kHz to 12.5 kHz.

Data concerning the first frequency sub-range are presented in Table 3.

Table 3. Uncertainty budget of the estimation of the directional characteristics for the MP7B meter – in the frequency range $>$ 250 Hz to 1 kHz.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Contribution to the standard uncertainty $u_i(y)$
		dB			dB
δL_{cal}	0 dB	0.0057	rectangular	1	0.0057
$\delta L_{s,\acute{z}}$	0 dB	0.028	rectangular	1	0.028
V_{bo}	0.8 V	0.0015	trapezoidal	1	0.0015
V_b	0.8 V	0.0015	trapezoidal	1	0.0015
V_{AC}	0.05V	0.048	trapezoidal	-1	0.0048
δL_m	0 dB	0.02	rectangular	1	0.02
$\delta L_{m,r}$	0 dB	0.05	rectangular	1	0.05
δL_{pos}	0 dB	0.065	normal	1	0.065
ΔL	0 dB	Combined standard uncertainty u_c =			0.089

Some of the data presented in Table 3 data are the same as in Table 2 because the experimental set-up used for both types of tests had the same input, control and measuring scheme.

Analysing the results contained in Table 3 we can find that the largest contributions to the combined uncertainty are coming from:

- uncertainty related to the positioning of the sound level meter,
- nonstability of a signal generated by the sound source.

Expanded uncertainty of an estimation of the directional characteristics of the tested sound level meter for the coverage factor $k = 2$ and the coverage probability of approximately 95% equals: $U_{95} = 0.2$, 0.3, 0.5 and 0.8 dB in the consecutive frequency sub-ranges – respectively.

Permissible values of expanded uncertainty for this type of measurements given in the International Standards [10] are: 0.3, 0.5, 1 and 1.5 dB, respectively.

Unfortunately no data concerning the uncertainty of the directional characteristics measurements are known to the authors, since in [11] only the data concerning uncertainty of the response of the sound level meters (vs. the reference microphone) declared by the leading calibration laboratories can be found.

Values reported by: Physicalische Technische Bundesanstallt (PTB), Danish Primary Laboratory of Acoustics (DPLA), National Physical Laboratory (NPL) along with the data estimated in this paper are presented in Fig. 5.

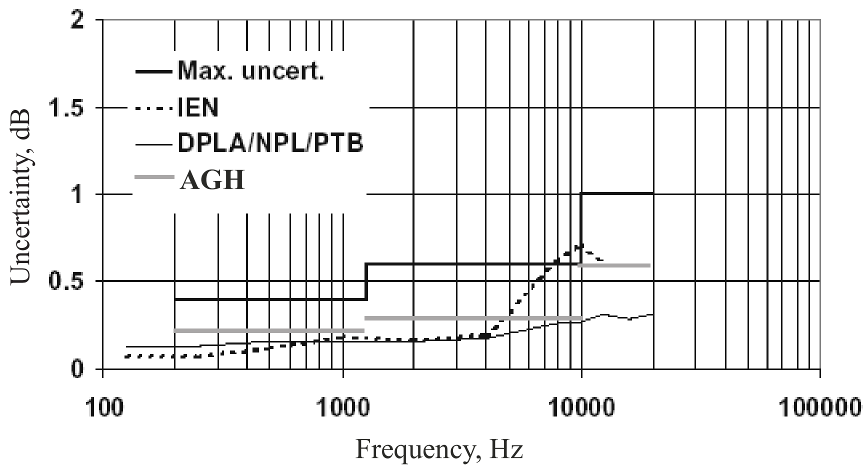


Fig. 5. Values of uncertainty of measurements in a free-field – declared by several primary calibration laboratories together along with the value estimated in [1] (– AGH line).

As can be seen from Fig. 5 the results obtained in [1] are – in the first two frequency ranges – similar to the results from the leading European laboratories. In the third range the obtained result is higher than the results reported by the mentioned above laboratories (the reason for this discrepancy is a high uncertainty related to the reference microphone). However this value is still much lower than the one permissible by the Standards.

5. Conclusions

A method of uncertainty estimation in acoustical investigations of microphones and sound level meters in a free-field was discussed in the paper. The results of such experiments are decisive for the type approving procedure of those instruments and their further application to the noise hazard assessment.

As shown in the analysis the results obtained in our laboratory are much better than the ones required by the International Standards (10).

High precision and accuracy of our measurements is the result of several years of experience and gradual elimination of factors affected by errors.

The obtained results of acoustical investigations of sound level meters assure that when a specified meter fulfils the standard requirements in our acoustical laboratory it will also succeed in meeting the acoustical requirements in primary calibration laboratories abroad. Such fact has already occurred, which additionally confirms the high quality of investigations described in the paper.

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