Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Measurement uncertainty of the sound absorption coefficient

Anna Izewska

Building Research Institute, Filtrowa Str.1, 00-611 Warsaw, Poland
a.izewska@itb.pl

The standard ISO/IEC 17025:2005 on the competence of testing and calibration laboratories requires that these laboratories shall apply procedures for estimating the uncertainty of their measurement results. One of the possibility is to evaluate the budget of uncertainty, taking into account all components that contribute significant uncertainty to the final result. In case of the sound absorption coefficient measurement, carried out according to the standard EN ISO 354:2003, the overall uncertainty is first of all influenced by the reverberation times T_1, T_2 and the power attenuation coefficients m_1 and m_2, calculated according to the ISO 9613-1 standard and representing the climatic conditions in the reverberation room. In spite of very little difference between the values m_1 and m_2 representing the change of climatic conditions (usually, it is the case in laboratory), exponential form of the coefficient's function causes that the uncertainty of measurement results increase with frequency very fast. Particularly for the high frequencies, the values of uncertainty are so important that the evaluation of the sound absorption coefficient is practically not possible.

1 Introduction

Because of lack of uncertainty evaluation based on inter-laboratory validation approach, it has to be carried out by the laboratory itself. Using the general methods specified in GUM[1], first of all we need to establish a relationship between the mesurand Y and other quantities $X_1, X_2,...X_n$ (input values) through a function f, called the measurement equation

$$Y = f(X_1, X_2,....X_n) \tag{1}$$

Such equation must express not only the physical relation from which we can obtain the value of mesurand Y but also it should be accompanied by a quantitative statement of its uncertainty which arises from the uncertainties of the input values of directly measured quantities x_1, x_2 ...x_n being the estimates of X_1, X_2, ...X_n.

In general, uncertainty components (each of them - represented by estimated standard deviation, termed standard uncertainty and noted u(xi) or, shortly, ui) are categorized according to the method used to evaluate them. There are two methods of evaluating standard uncertainty:

- type A is based on any valid statistical method, for example the standard deviation of the mean of a series of independent observations s(xi); in such case the standard uncertainty u(xi) = s(xi),

- type B takes advantage of an outside source (for example, data provided in calibration) and/or of an assumed distribution.

The standard deviation of the estimated measurement result y, called combined standard uncertainty $u_c(y)$, is obtained by combining the individual standard uncertainties $u(x_i)$ using the usual statistic method of combining standard deviations "root – sum – squares" according to the formula:

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \tag{2}$$

and calculating the positive root square of the result.

Equation (2) is called the law of propagation of uncertainty and the partial derivatives $\delta f/\delta x_i$ are referred to sensitivity coefficients. The products of module $\delta f/\delta x_i$ and $u(x_i)$ are usually presented in a table, as "uncertainty budget". This practice is very useful to identify the dominant terms that contribute significant uncertainty to the result.

The measure of uncertainty, that defines an interval in which the value of the quantity subject to measurement (the mesurand Y) can be confidently asserted to lie, is named expanded uncertainty U (it means that one can confidently believe that the value of Y, estimated by y, lies within the limits $y - U \leq Y \leq y + U$).

The expanded uncertainty is obtained by multiplying a combined standard uncertainty by a coverage factor k depending on the desired level of confidence and the type of statistical distribution.

$$U(Y) = ku_c(y) \tag{3}$$

2 Uncertainty components occurring in measurements of sound absorption coefficient

2.1 Reverberation time

The reverberation time is measured in n points for each frequency band. The mean value T_f calculated from n measurements is taken as the estimated measurement result. In this case, the standard uncertainty of T_f is equal to the experimental standard deviation $s(T_f)$ of the mean of a series of independent observations $T_{f,i=1,....n}$.

$$u(T_f) = s(T_f) = \frac{s(T_{f,i})}{\sqrt{n}} \text{ , s} \tag{4}$$

Student's – t distribution with n freedom degrees is assumed.

2.2 Area of sample

Assuming the rectangular distribution of estimated measurement result, with the boundary of ±0,005 m^2, the standard uncertainty of sample's area amounts to

$$u(S) = \frac{0{,}005m^2}{\sqrt{3}} = 0{,}0029m^2 \tag{5}$$

2.3 Volume of room

Assuming the rectangular distribution of estimated measurement result, with the boundary of resolution ±0,5 m^3, the standard uncertainty of room volume amounts to

$$u(V) = \frac{0{,}5m^3}{\sqrt{3}} = 0{,}2887m^3 \quad (6)$$

2.4 Environment factors

The measurement equations for the environmental factors like temperature, atmospheric pressure and relative humidity assume the form:

$$e = e_0 + \delta e_1 + \delta e_2 + \delta e_3 + \delta e_4 \quad (7)$$

where

e_0 - the reading value of the environmental factor in a room,

δe_1 - the dispersion of sensor indications,

δe_2 - the resolution of sensor indications,

δe_3 - the error of sensor indications,

δe_4 - the uncertainty of indications error.

The standard uncertainty of dispersion δe_1 is calculated on the basis of the estimated standard deviation of *m* series of *n* measurements.

$$u(\partial e_1) = \frac{S_i(e_1)}{\sqrt{n}} \quad (8)$$

where $S_i(e_1)$ – the experimental standard deviation of i^{th} series equal to

$$S_i(e_1) = \sqrt{\frac{\sum_{i=1}^{m} S_i(e_{1,i})}{m}} \quad (9)$$

The standard uncertainty of resolution δe_2 is evaluated with the assumption of rectangular distribution with the boundary of resolution supposed, respectively, as $b = \pm 0.05\ ^oC$, ± 0.05 kPa or ±0.05%.

$$u(\delta e_2) = \frac{b}{\sqrt{3}} \quad (10)$$

Contribution in uncertainty of δe_3 and δe_4 are calculated from the expanded uncertainty *U* evaluated for normal distribution with confidence level 95% and stated in the calibration certificate of the device.

$$u(\delta e_3) = \frac{U(\delta e_3)}{k_{N,95\%}} = \frac{U(\delta e_3)}{2} \quad (11)$$

$$u(\delta e_4) = \frac{U(\delta e_4)}{k_{N,95\%}} = \frac{U(\delta e_4)}{2} \quad (12)$$

The equation of propagation law of uncertainty has the form:

$$u^2(e) = u^2(\delta e_1) + u^2(\delta e_2) + u^2(\delta e_3) + u^2(\delta e_4) \quad (13)$$

3 Uncertainty of the sound absorption coefficient measurement

The sound absorption coefficient α_s of a plane absorber or a specified array of test objects is calculated using the formula

$$\alpha_s = \frac{A_T}{S} \quad (14)$$

where

A_T - the equivalent sound absorption area of the test specimen, m^2

S - the area covered by the test specimen, m^2

The equivalent sound absorption area of the test specimen, A_T, according to ISO 354:2003 [3] is given as follows

$$A_T = A_2 - A_1 = 55{,}3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1) \quad (15)$$

where

V - the volume of the empty reverberation room, m^3

T_1 - the reverberation time of the empty reverberation room, s

T_2 - the reverberation time of the reverberation room after the test specimen has been introduced, s

c_1, c_2 - the propagation speed of sound in air at the temperature t_1 and t_2 (respectively), m/s

m_1,m_2 - the power attenuation coefficients, calculated according to ISO 9613-1[4] using the climatic conditions that have been present in the empty reverberation room and after the test specimen has been introduced, m^{-1}
The value of *m* is calculated from the attenuation coefficient α dependent on temperature *t*, atmospheric pressure p_a and relative humidity h_r, according to the formula

$$m = \frac{\alpha}{10\lg(e)}$$

The detailed analyse of the uncertainty budget leads to a conclusion that the standard uncertainty of sound absorption depends very strongly on the sensitivity coefficients of humidity, particularly at the high frequencies (see Table 1).

In the previous version of standard ISO 354:1985 [2] a possible change of climatic conditions was not taken into consideration ($m_1 = m_2 = 0$). Table 2 presents the calculation results of the sound absorption coefficient α_s and its standard and expanded uncertainties carried out with respect to environment factors and without them. It can be observed that in spite of very little difference between the values m_1 and m_2 (representing the change of climatic conditions), the values of α_s calculated according to [3] in the frequency bands $f \geq 3150$ Hz are considerably greater. Also, the uncertainties of measurement results increase with frequency very fast. Particularly for the high frequencies, the values of uncertainties are so important that the evaluation of α_s is practically not possible.

f, Hz	α_S	$u_c(\alpha_S)$	$U(\alpha_S)$	Sensitivity coefficients of environment factors					
				$\delta\alpha_S/\delta pa_1$	$\delta\alpha_S/\delta pa_2$	$\delta\alpha_S/\delta hr_1$	$\delta\alpha_S/\delta hr_2$	$\delta\alpha_S/\delta t_1$	$\delta\alpha_S/\delta t_2$
100	**0,14**	0,009	0,018	0,00000	0,00000	-0,00023	0,00018	0,00062	0,00085
125	**0,31**	0,014	0,029	0,00000	0,00000	-0,00035	0,00027	0,00061	0,00116
160	**0,54**	0,017	0,035	0,00000	0,00000	-0,00056	0,00045	0,00072	0,00181
200	**0,64**	0,020	0,041	0,00000	0,00000	-0,00082	0,00070	0,00072	0,00227
250	**0,82**	0,023	0,048	0,00000	0,00000	-0,00120	0,00109	0,00059	0,00301
315	**0,92**	0,025	0,052	0,00000	0,00000	-0,00177	0,00174	0,00020	0,00382
400	**0,94**	0,027	0,056	0,00000	0,00000	-0,00267	0,00280	-0,00064	0,00468
500	**1,02**	0,020	0,041	0,00000	0,00000	-0,00398	0,00437	-0,00182	0,00571
630	**0,99**	0,019	0,040	0,00001	-0,00001	-0,00617	0,00694	-0,00312	0,00680
800	**1,00**	0,024	0,049	0,00001	-0,00001	-0,00994	0,01119	-0,00448	0,00811
1000	**0,96**	0,019	0,039	0,00001	-0,00002	-0,01568	0,01748	-0,00568	0,00929
1250	**0,98**	0,026	0,053	0,00002	-0,00002	-0,02478	0,02729	-0,00692	0,01062
1600	**0,98**	0,023	0,047	0,00002	-0,00003	-0,04105	0,04464	-0,00852	0,01224
2000	**0,96**	0,030	0,060	0,00003	-0,00004	-0,06455	0,06960	-0,01033	0,01418
2500	**0,99**	0,045	0,093	0,00004	-0,00005	-0,10116	0,10837	-0,01285	0,01702
3150	**1,03**	0,068	0,139	0,00005	-0,00007	-0,16047	0,17109	-0,01665	0,02146
4000	**1,01**	0,106	0,217	0,00007	-0,00011	-0,25730	0,27334	-0,02279	0,02829
5000	**1,02**	0,163	0,332	0,00009	-0,00015	-0,39768	0,42128	-0,03153	0,03816
6300	**0,98**	0,253	0,516	0,00011	-0,00020	-0,61920	0,65403	-0,04515	0,05338
8000	**0,95**	0,394	0,804	0,00011	-0,00023	-0,96576	1,01642	-0,06626	0,07662

Table 1. Sound absorption α_S with its uncertainties and sensitivity coefficients

f, Hz	Acc. to ISO 354:2003 [3]			Acc. to ISO 354:1985 [2]			m_2-m_1	Difference α_S
	α_S	$u_c(\alpha_S)$	$U(\alpha_S)$	α_S	$u_c(\alpha_S)$	$U(\alpha_S)$		
100	**0,14**	0,009	0,018	**0,14**	0,009	0,018	0,000	-0,001
125	**0,31**	0,014	0,029	**0,31**	0,014	0,029	0,000	-0,004
160	**0,54**	0,017	0,035	**0,54**	0,017	0,035	0,000	0,000
200	**0,64**	0,020	0,041	**0,64**	0,020	0,041	0,000	0,005
250	**0,82**	0,023	0,048	**0,82**	0,023	0,048	0,000	0,004
315	**0,92**	0,025	0,052	**0,92**	0,025	0,052	0,000	0,000
400	**0,94**	0,027	0,056	**0,94**	0,027	0,056	0,000	0,001
500	**1,02**	0,020	0,041	**1,02**	0,020	0,041	0,000	0,004
630	**0,99**	0,019	0,040	**0,98**	0,019	0,039	0,000	0,006
800	**1,00**	0,024	0,049	**1,00**	0,024	0,048	0,000	0,005
1000	**0,96**	0,019	0,039	**0,96**	0,018	0,037	0,000	0,000
1250	**0,98**	0,026	0,053	**0,97**	0,024	0,048	0,000	0,008
1600	**0,98**	0,023	0,047	**0,97**	0,015	0,031	0,000	0,005
2000	**0,96**	0,030	0,060	**0,96**	0,013	0,026	0,000	0,003
2500	**0,99**	0,045	0,093	**0,98**	0,018	0,038	0,000	0,008
3150	**1,03**	0,068	0,139	**1,02**	0,017	0,035	0,000	0,007
4000	**1,01**	0,106	0,217	**1,00**	0,014	0,029	0,000	0,006
5000	**1,02**	0,163	0,332	**1,02**	0,013	0,027	0,000	0,001
6300	**0,98**	0,253	0,516	**0,99**	0,017	0,035	0,000	-0,010
8000	**0,95**	0,394	0,804	**0,97**	0,026	0,054	0,000	-0,016

Table 2. Set of calculation results of sound absorption coefficient α_s and its uncertainties conducted according to both versions of standard ISO 354 [2,3]

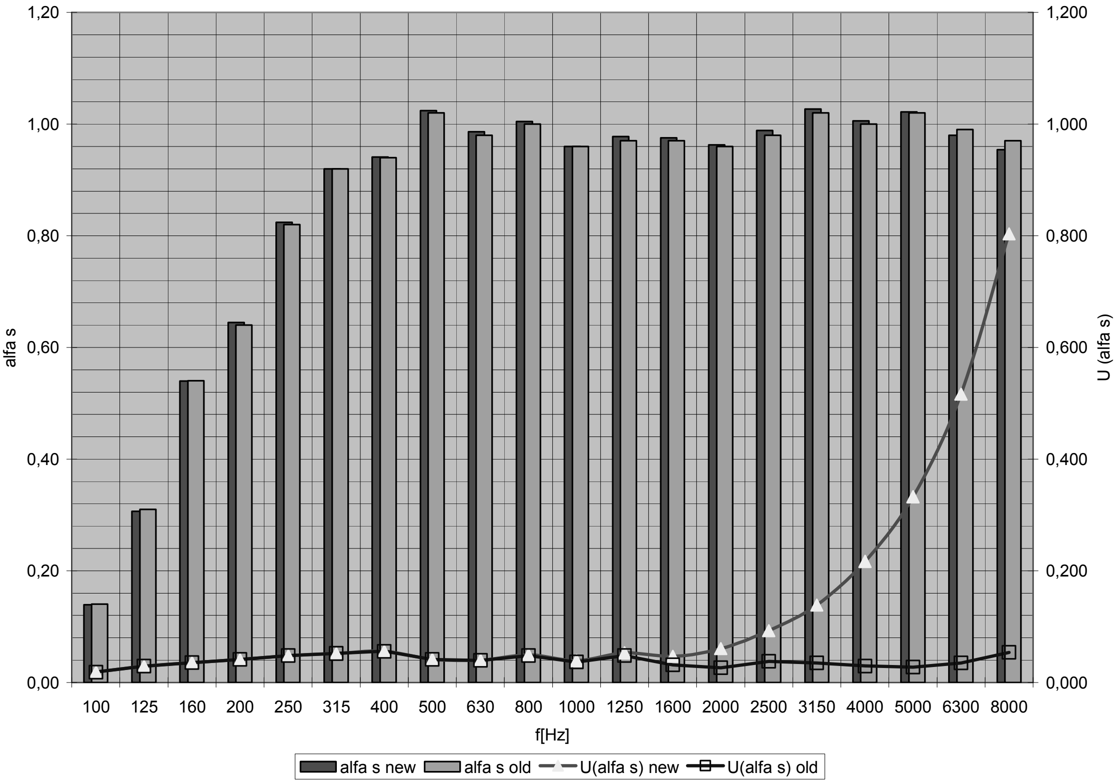

Fig 1.Comparison the calculation results of the sound absorption coefficient and its expanded uncertainty carried out according to both version of ISO 9613-1 standard

4 Conclusion

The evaluation of the uncertainty is very important because it testifies to the quality of measurements.

Observing the uncertainty budget for each band of frequency allows to find the deciding factors. In case of sound absorption measurements, it could be very difficult to obtain accurate results due to the important uncertainty at high frequencies bands. The function circumscribing the power attenuation coefficient *m* calculated according to ISO 9613-1, thanks to the non-linear shape, influences the uncertainty of measurement results in spite of very small changes in environmental conditions in laboratory.

References

[1] Guide to the Expression of Uncertainty in Measurement. International Organization for Standardization, Geneva, First Edition, 1993. Corrected and reprinted 1995

[2] EN ISO 354:1985, Acoustics – Measurement of sound absorption in a reverberation room

[3] EN ISO 354:2003, Acoustics – Measurement of sound absorption in a reverberation room

[4] ISO 9613-1:1993, Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere