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Maximum Expanded Measurement Uncertainty: Hearing Aids

Zemar M. DEFILIPPO SOARES; Isabella FLORÊNCIO C. DA SILVA; Nelson M. ESPIRITO SANTO

Electroacoustic Lab. - INMETRO, Brazil

ABSTRACT

For the study of measurement uncertainty estimation it is necessary to understand the model used to perform the measurements. In acoustic performance measurements of Hearing Aids the IEC 60118 part 0 and part 7 present the method used for the measurements achievements. However, these standards present two possible acoustic environments where acoustic performance measurements of Hearing Aids can be achieved: Anechoic Chamber and Test Box. This work will estimate the maximum expanded measurement uncertainty in acoustic performance measurements of Hearing Aids in Anechoic Chamber and Test Box. For the estimation of the maximum expanded measurement uncertainty will be studied the main sources of uncertainties that lead to the greatest impact in the model used. A strong emphasis will be given to the source of uncertainty regarding the sound field where Hearing Aids are positioned for acoustic performance measurements. This investigation is based on results of experimental measurements. This work shows the differences found in the estimation of maximum expanded measurement uncertainty in the Anechoic Chamber and in the Test Box.

Keywords: Hearing Aids, Uncertainty, Sound Field

1. INTRODUCTION

For the study of expanded measurement uncertainty estimation it is necessary to understand the model used to perform the measurements. In acoustic performance measurements of Hearing Aids the IEC 60118 part 0 and part 7 present the model used for the measurements achievements. However, these standards present two possible acoustic environments where acoustic performance measurements of Hearing Aids can be performed.

- Anechoic Chamber
- Test Box

The expanded measurement uncertainty can be managed to estimate the lowest expanded measurement uncertainty and also the maximum admissible expanded measurement uncertainty for a model used. The lowest expanded measurement uncertainty is estimated when the Laboratory performing Hearing Aids acoustic performance measurements calibrates its measurement instrumentation and then applies the deviation values described in the calibration certificates to correct the systematic errors those measuring instruments are introducing into the measurement result.

The maximum expanded measurement uncertainty is estimated when the Laboratory calibrates its measuring instruments but does not apply the values of deviations reported in the calibration certificates. The action taken by the Laboratory summarizes the understanding that the measuring instruments conform to the requirements of the standard applied during the calibration and therefore will not apply any correction due to systematic errors caused by the measuring instruments in the measurement results.

IEC 60118-7 (2005) describes in Table 4 of clause 9 that the maximum permitted expanded measurement uncertainty ($\boldsymbol{U_{Max}}$) must not be greater than 1 dB (for frequencies in the range 200 Hz to 4000 Hz) and must also not be greater than 1.5 dB (for frequencies greater than 4 kHz). IEC 60118-0 (2015) describes in Table 3 of clause 10 that $\boldsymbol{U_{Max}}$ must not be greater than 2 dB (for frequencies in the range 200 Hz to 4000 Hz) and must not be greater than 2.5 dB (for frequencies greater than 4 kHz).

From the above, it is noticed that the method using test box (IEC 60118-7) has a lower $\boldsymbol{U_{Max}}$ than the method using anechoic chamber (IEC 60118-0).

This work will present examples of expanded measurement uncertainty budget where one of the laboratories has a good quality system. It will also present a expanded measurement uncertainty budget where the measuring instruments of the second laboratory operate very close to limit of the allowed tolerances. With the results of these two examples it will be shown how one can reach an U_{Max}, both in Anechoic Chamber and in Test Box.

2. EXPANDED MEASUREMENT UNCERTAINTY BUDGET

2.1 Laboratory with a good quality system

It is assumed here that a laboratory with a good quality system is one that has its measurement standards calibrated in an Accredited Laboratory linked to the ILAC and then applies the deviation values described in the calibration certificates to correct the systematic errors those measuring instruments are introducing into the measurement result.

All significant sources of uncertainties must be identified in the model adopted. Since the standards IEC 60118-0 and IEC 60118-7 use a free-field sound propagation model, then one of the main sources of uncertainty must be related to the law of the inverse distance ($1/r$, where r is the distance in meters). This implicate in the decay of the sound pressure level of 6 dB when the distance "r" is doubled.

2.1.1 Anechoic Chamber

The first source of uncertainty to be investigated in this subsection is that related to free-field sound propagation. The anechoic chamber of the Electroacoustic Laboratory of INMETRO has dimensions of Height (4.10 m), Length (5.32 m) and Width (4.30 m), totaling approximately 94 m^3. The SPL measurements for the determination of *deviation rms* (*rmsd*) [3] in the anechoic chamber have taken the reference measurement point which is one meter away from the loudspeaker. The SPL measurements started 0,85 meter distant from the Loudspeaker in steps of 2 mm until the last point 1,15 meter distant from the loudspeaker. After these SPL measurements, all the SPL measured were normalized to the SPL related to the reference point (one meter). A linear regression was taken and differences between this linear regression and $1/r$ Law was computed (see Equation 1). Equation (1) to determine the value of the "*deviation rms* (*rmsd*)" of the ideal free sound field:

$$\boldsymbol{rmsd} = \left[\frac{\Sigma_{i=1}^{N} \left| Linear\,\mathrm{Re}_i - 1/r_i \right|^2}{N} \right]^{1/2} \tag{1}$$

where:

$\boldsymbol{N}$: is the number of measured points;

$\boldsymbol{r}$: is the distance from the loudspeaker;

$\boldsymbol{1/r_i}$: is the SPL calculated for the i-th point of the straight line that represents the Law of the inverse of the distance;

$\boldsymbol{LinearRe_i}$: is the SPL calculated for the i-th point of the straight line that fits the measured points.

Table 1 shows the *rmsd* values determined inside the Anechoic Chamber; also it shows the estimated *standard measurement uncertainty* ($\boldsymbol{u}_{s\,field}$) values of the non-uniformity of the sound field assuming a rectangular probability distribution.

Table 1 - Non-uniformity of the free field in terms of *rmsd* and *standard measurement uncertainty* ($\boldsymbol{u}_{s\,field}$)

Freq (Hz)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
rmsd (dB)	0,042	0,037	0,033	0,035	0,032	0,042	0,043	0,087	0,072	0,053	0,040	0,032	0,128	0,073	0,122	0,043	0,083	0,090
$\boldsymbol{u}_{S\,field}$ (dB)	0,024	0,021	0,019	0,020	0,018	0,024	0,025	0,050	0,042	0,031	0,023	0,018	0,074	0,042	0,070	0,025	0,048	0,052

The other sources of standard uncertainties (Type B) considered relevant in this work are: Reference microphone ($\boldsymbol{u}_{Mic}$), Coupler + microphone ($\boldsymbol{u}_{Coupl+Mic}$), Pistonphone ($\boldsymbol{u}_{Piston}$), Hearing aids positioning ($\boldsymbol{u}_{Posit}$), Coupling of the Tube of hearing aids to the coupler ($\boldsymbol{u}_{Tube}$), linearity of the A/D converter ($\boldsymbol{u}_{Lin\,AD}$) and rounding ($\boldsymbol{u}_{Round}$). Finally, the standard uncertainty of type A related to repeatability ($\boldsymbol{u}_{Repeat}$) is also considered. Figure 1 shows the model of the measured method used here to estimate the sources of uncertainties.

2.1.1.1 Reference microphone, u_{Mic}

It is assumed that the ½" reference microphone meets the requirements (allowable tolerances) of Table 6 of IEC 61094-4 [4]. It is also assumed that the microphone was calibrated and its systematic deviations were corrected during the measurement. Therefore, $\boldsymbol{u}_{Mic}$ is the expanded measured uncertainty stated in the calibration certificate (coverage factor k = 2) divided by two.

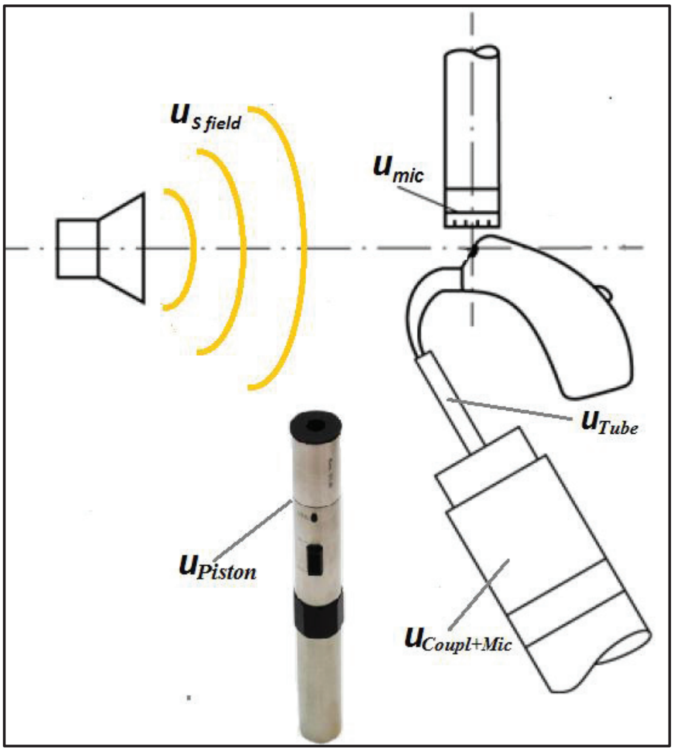

Figure 1 – Model of the measured method used to estimate the sources of uncertainties.

2.1.1.2 Coupler+ microphone, $u_{Coupl+Mic}$

IEC 60318-5 [4] does not refer to tolerances acceptable to the acoustic impedance of the acoustic coupler 2cm^3. Already IEC 60318-4 [5] informs the allowable tolerances to the acoustic impedance of the artificial ear. Table 1 of IEC 60318-4: 2010 informs these tolerances from 100 Hz to 10kHz. Then it is assumed that an artificial ear meets the requirements (allowable tolerances) of Table 1 of IEC 60318-4. It is also assumed that the "artificial ear + microphone" was calibrated and its systematic deviations were corrected during the measurement. Therefore, $u_{Coupl+Mic}$ is the expanded measured uncertainty stated in the calibration certificate (coverage factor k = 2) divided by two.

2.1.1.3 Pistonphone, u_{Piston}

The pistonphone is used to adjust the gain of both the reference microphone channel and the microphone channel of the coupler. It has been calibrated and the systematic deviation value determined complies with the requirement of Table 5 of IEC 60942: 2017 [7]. This deviation is corrected during the gain adjustment procedure. u_{Piston} is the expanded measured uncertainty stated in the calibration certificate (coverage factor k = 2) divided by two.

2.1.1.4 Coupling of the Tube of hearing aids to the coupler, u_{Tube}

A study was performed with variations in the length of the tube. The variations were of 3 mm on the nominal value of 25 mm (22 mm, 25 mm and 28 mm). SPL measurements on the output coupler were performed with these different tube lengths. The maximum deviation on the SPL compared to the SPL with the nominal tube length of 25 mm was divided by $\sqrt{3}$ (rectangular distribution) and the value of u_{Tube} was determined.

2.1.1.5 Linearity of the A/D converter, $u_{Lin\ AD}$

The data acquisition system used is based on an A/D converter which may have some non-linearity problem when SPL signals have differences greater than 10 dB. In the calibration of this data acquisition system the greatest deviations were observed when signals with differences of up to 40 dB were injected to the A/D converter. These maximum values of deviations obtained divided by $\sqrt{3}$ (rectangular distribution) are the $u_{Lin\ AD}$ determined.

2.1.1.6 Rounding, u_{Round}

Considering that the results obtained are rounded to a decimal digit in dB, then the contribution due to rounding is $u_{Round} = 0{,}05/\sqrt{3}$.

2.1.1.7 Repeatability, u_{Repeat}

The u_{Repeat} of the hearing aids under test characterizes the quality in the execution of the measurement procedure. Three replicates of a BTE Hearing Aid were performed and the standard deviation was calculated. The u_{Repeat} was determined by dividing the standard deviation by √2 (number of replicates minus 1).

The expanded measurement uncertainty budget is shown in dB (Table 2), however before calculating the combined standard measurement uncertainty (u_C) and also the expanded measurement uncertainty ($u_{95\%}$), all values were converted to percentages and only after determination of the expanded measurement uncertainty in % did this value converted to dB. Table 2 shows the expanded measurement uncertainty budget in anechoic chamber.

Table 2 – Expanded measurement uncertainty budget ($u_{95\%}$) in anechoic chamber

S Uncert/Freq. (Hz)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
$u_{s\,field}$ (dB)	0,024	0,021	0,019	0,020	0,018	0,024	0,025	0,050	0,042	0,031	0,023	0,018	0,074	0,042	0,070	0,025	0,048	0,052
u_{Piston} (dB)	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035
u_{Piston} (dB)	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035
u_{Mic} (dB)	0,040	0,040	0,040	0,040	0,040	0,040	0,040	0,040	0,040	0,045	0,045	0,045	0,050	0,050	0,055	0,055	0,060	0,065
u_{Tube} (dB)	0,006	0,006	0,006	0,006	0,014	0,017	0,043	0,087	0,115	0,058	0,069	0,087	0,087	0,087	0,173	0,231	0,121	0,144
u_{Posit} (dB)	0,075	0,070	0,070	0,060	0,060	0,040	0,060	0,075	0,050	0,050	0,060	0,100	0,100	0,125	0,170	0,210	0,250	0,162
$u_{Lin\,AD}$ (dB)	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
u_{Round} (dB)	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029
$u_{Coupl+Mic}$ (dB)	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,125	0,150
u_{Repeat} (dB)	0,015	0,015	0,015	0,015	0,015	0,015	0,015	0,025	0,015	0,015	0,015	0,015	0,022	0,015	0,015	0,015	0,100	0,100
u_C (%)	1,67	1,64	1,64	1,58	1,59	1,51	1,66	1,96	2,04	1,69	1,79	2,10	2,13	2,29	3,19	3,93	3,86	3,42
$u_{95\%}$ (%)	3,33	3,27	3,27	3,17	3,18	3,02	3,32	3,91	4,07	3,38	3,58	4,21	4,25	4,58	6,38	7,86	7,71	6,84
$U_{95\%}$ (dB)	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4	0,5	0,7	0,6	0,6

2.1.2 Test Box

As described in 2.1.1, it is understood that one of the main sources of uncertainty is the sound field. Therefore the idea is to verify the non-uniformity of the sound field around the position where the reference microphone and the hearing aid should stay during the measurement procedure. The interval of points where SPL should be measured has beginning 0,057 meter from the loudspeaker and, in steps of 4 millimeters, extended until the point 0,121 meter from the loudspeaker, where the average measuring point is 0.089 meters and corresponds to the circular marking center (see Figure 2) of the *FONIX 8120* (by *Frye Electronics*). Figure 1 shows the positioning of these measurement points within the *FONIX 8120* (test box).

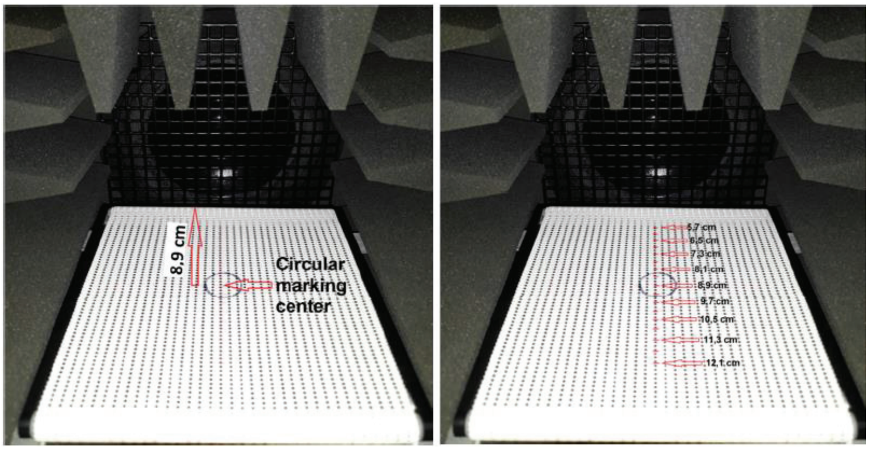

Figure 2 - Positioning of the SPL measurement points inside the FONIX 8120

After obtaining all SPL representing each distant point of the loudspeaker *rmsd* was determined like in 2.1.1. and consequently the value of $u_{s\,field}$. Table 3 shows the *rmsd* values determined inside the FONIX 8120, also it shows the estimated *standard measurement uncertainty* ($u_{s\,field}$) values of the non-uniformity of the sound field assuming a rectangular probability distribution.

Table 3 – *rmsd* values determined inside the FONIX 8120 and $u_{s\,field}$ related to the non-uniformity of the sound field in Test Box

Freq (Hz)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
rmsd **(dB)**	2,099	1,674	1,250	0,668	0,554	0,303	0,214	0,414	0,529	0,398	0,327	0,874	0,775	0,973	1,191
$u_{S\,field}$ (dB)	1,212	0,967	0,722	0,386	0,320	0,175	0,123	0,239	0,305	0,230	0,189	0,505	0,448	0,562	0,687

The u_{mic} was evaluated differently from 2.1.1.1, because the microphone that accompanies the

FONIX it is not in accordance with IEC 61094-4, so it could not be calibrated. Even without being able to calibrate the microphone it has been assumed that it meets at least the permitted tolerances of IEC 61094-4. Then the u_{mic} equals the tolerance of IEC 61094-4 divided by √3 (rectangular distribution).

The $u_{Coupl+Mic}$ was assumed differently than 2.1.1.2, because the coupler that accompanied FONIX could not be calibrated, since the microphone accompanying it cannot be calibrated. It was assumed that the coupler complies with IEC 60318-4. Then the tolerances of this standard were divided by √3 and $u_{Coupl+Mic}$ was determined.

The u_{piston} was assumed equal to 2.1.1.3, however it is computed only once, since the FONIX 8000 measuring system has only one measuring channel. The u_{Tube} was assumed to be identical to 2.1.1.4. The $u_{Lin\ AD}$ could not be evaluated because the FONIX 8000 measuring system is a closed system that did not allow to be calibrated electrically, so a typical value of good quality acquisition boards was assumed. The u_{Round} was assumed identical to 2.1.1.6. Finally, the u_{repeat} was determined by performing three replicates of a BTE Hearing aids measurement and the values obtained were treated as in 2.1.1.7.

The method used by FONIX is a sequential method, unlike the method used in 2.1.1 which is a simultaneous method. Since the FONIX 8000 measuring system has only one measurement channel, then it is possible that the transfer function between the loudspeaker / microphone / Hearing aids may change over a period of time, not so long, but for example, during the measurement with control microphone (reference) and then with the BTE Hearing aids (temperature, humidity, barometric pressure and heating of the loudspeaker coil may occur). To deal with this problem, a new standard measurement uncertainty was assumed. It tries to estimate this variation of the transfer function and will be called u_{TF}. Measurements were performed and the detected variations of SPL were assumed with rectangular probability distribution.

The expanded measurement uncertainty budget is shown in dB (Table 4), however before calculating the combined standard measurement uncertainty (u_C) and also the expanded measurement uncertainty ($u_{95\%}$), all values were converted to percentages and only after determination of the expanded measurement uncertainty in % did this value converted to dB. Table 4 shows the expanded measurement uncertainty budget in Test Box (FONIX).

Table 4 – Expanded measurement uncertainty budget ($u_{95\%}$) in Test Box (FONIX)

S Uncert/Freq. (Hz)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
$u_{s\ field}$ (dB)	1,212	0,967	0,722	0,386	0,320	0,175	0,123	0,239	0,305	0,230	0,189	0,505	0,448	0,562	0,687
u_{Piston} (dB)	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035	0,035
u_{TF} (dB)	0,055	0,058	0,068	0,167	0,196	0,364	0,393	0,398	0,358	0,404	0,352	0,294	0,248	0,144	0,121
u_{Mic} (dB)	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,433
u_{Tube} (dB)	0,006	0,006	0,006	0,006	0,014	0,017	0,043	0,087	0,115	0,058	0,069	0,087	0,087	0,087	0,173
u_{Posit} (dB)	0,095	0,090	0,090	0,085	0,085	0,080	0,085	0,095	0,075	0,075	0,090	0,135	0,138	0,152	0,195
$u_{Lin\ AD}$ (dB)	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005
u_{Round} (dB)	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029
$u_{Coupl+Mic}$ (dB)	0,346	0,346	0,346	0,346	0,346	0,346	0,346	0,404	0,404	0,404	0,462	0,462	0,520	0,577	0,693
u_{Repeat} (dB)	0,230	0,160	0,080	0,075	0,025	0,034	0,130	0,062	0,180	0,022	0,250	0,027	0,023	0,026	0,029
u_C (%)	16,2	13,1	10,3	7,4	7,0	7,2	7,4	8,2	8,5	8,1	8,6	9,6	9,5	10,5	13,2
$u_{95\%}$ (%)	32,3	26,2	20,6	14,7	13,9	14,4	14,9	16,4	16,9	16,2	17,2	19,3	18,9	21,0	26,4
$U_{95\%}$ (dB)	2,4	2,0	1,6	1,2	1,1	1,2	1,2	1,3	1,4	1,3	1,4	1,5	1,5	1,7	2,0

2.2 Laboratory operate very close to limit of the allowed tolerances

In this subsection it is assumed that a Laboratory does not have a very efficient quality system and performs its activities without applying systematic corrections to the measurement results. In subsection 2.1 the most important measuring instruments have calibration certificates and the systematic deviations described therein are taken into account on the measurement result. In this subsection instruments such as Reference Microphone, Coupler and Sound Calibrator are assumed to have only the information that are operating very close to the tolerance limit allowed. Another difference from subsection 2.1 is that the Pistonphone (class LS) is not used but a Class 2 Sound Calibrator. Subsections 2.2.1 and 2.2.2 show the final impacts that this new approach leads to the expanded measurement uncertainty budget.

2.2.1 Anechoic Chamber

The standard uncertainty related to nonuniformity of the sound field $u_{S\ Field}$ is considered the same, since the anechoic chamber used by the Laboratory is the same. As with the standard uncertainty related to nonuniformity of the sound field, the standard uncertainties u_{Tube}, u_{Posit}, u_{Round} and u_{Repeat} are identical to those in subsection 2.1.

2.2.1.1 Reference microphone, u_{Mic}

It is assumed that the ½" reference microphone meets very close to limit of the allowed tolerances described in Table 6 of IEC 61094-4. It is also assumed that the microphone was not calibrated and its systematic deviations were not corrected during the measurement. Then the u_{mic} equals the tolerance of IEC 61094-4 divided by $\sqrt{3}$ (rectangular distribution).

2.2.1.2 Coupler + microphone, $u_{Coupl+Mic}$

It is assumed that the occluded ear simulator meets very close to limit of the allowed tolerances described in Table 1 of IEC 60318-4:2010. It is also assumed that the occluded ear simulator was not calibrated and its systematic deviations were not corrected during the measurement. Then the $u_{Coupl+Mic}$ equals the tolerance of IEC 60318-4 divided by $\sqrt{3}$ (rectangular distribution).

2.2.1.3 Sound Calibrator, u_{SCal2}

Sound Calibrator class 2 is used to adjust the gain of both the reference microphone channel and the microphone channel of the coupler. It is assumed that the Sound Calibrator class 2 was not calibrated and its systematic deviations were not corrected during the measurement. Then the u_{SCal2} equals the tolerance described in Table 5 of IEC 60942: 2017 by $\sqrt{3}$ (rectangular distribution).

The expanded measurement uncertainty budget is shown in dB (Table 5), however before calculating the combined standard measurement uncertainty (u_C) and also the expanded measurement uncertainty ($u_{95\%}$), all values were converted to percentages and only after determination of the expanded measurement uncertainty in % did this value converted to dB. Table 5 shows the expanded measurement uncertainty budget in Anechoic Chamber.

Table 5 – Expanded measurement uncertainty budget ($u_{95\%}$) in anechoic chamber for Laboratory that operate very close to limit of the allowed tolerances

S Uncert/Freq. (Hz)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
$u_{s\ field}$ (dB)	0,024	0,021	0,019	0,020	0,018	0,024	0,025	0,050	0,042	0,031	0,023	0,018	0,074	0,042	0,070	0,025	0,048	0,052
u_{SCal2} (dB)	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433
u_{SCal2} (dB)	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433
u_{Mic} (dB)	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,433	0,577	0,722	0,866
u_{Tube} (dB)	0,006	0,006	0,006	0,006	0,014	0,017	0,043	0,087	0,115	0,058	0,069	0,087	0,087	0,087	0,173	0,231	0,121	0,144
u_{Posit} (dB)	0,075	0,070	0,070	0,060	0,060	0,040	0,060	0,075	0,050	0,050	0,060	0,100	0,100	0,125	0,170	0,210	0,250	0,162
$u_{Lin\ AD}$ (dB)	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052
u_{Round} (dB)	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029
$u_{Coupl+Mic}$ (dB)	0,346	0,346	0,346	0,346	0,173	0,346	0,346	0,404	0,404	0,404	0,462	0,462	0,520	0,577	0,693	0,693	0,981	1,270
u_{Repeat} (dB)	0,015	0,015	0,015	0,015	0,015	0,015	0,015	0,025	0,015	0,015	0,015	0,015	0,022	0,015	0,015	0,015	0,100	0,100
u_C (%)	9,03	9,02	9,02	9,01	8,29	9,00	9,03	9,42	9,43	9,36	9,75	9,82	10,23	10,70	12,48	13,50	16,82	20,45
$u_{95\%}$ (%)	18,05	18,04	18,04	18,02	16,58	18,00	18,05	18,83	18,87	18,72	19,51	19,63	20,45	21,40	24,96	27,00	33,63	40,90
$U_{95\%}$ (dB)	1,4	1,4	1,4	1,4	1,3	1,4	1,4	1,5	1,5	1,5	1,5	1,6	1,6	1,7	1,9	2,1	2,5	3,0

2.2.2 Test Box

The standard uncertainties will be assumed identical to those in subsection 2.1.2, except for u_{SCal2} which replaces u_{Piston}, because it is assumed here that the Laboratory uses a Sound Calibrator (Class 2) of a lower accuracy class than the Pistonphone (class LS). Table 6 shows all the standard uncertainties assumed here, as well as the combined standard measurement uncertainty and the expanded measurement uncertainty.

Table 6 – Expanded measurement uncertainty budget ($U_{95\%}$) in Test Box (FONIX) for Laboratory that operate very close to limit of the allowed tolerances

S Uncert/Freq. (Hz)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
$u_{s\,field}$ (dB)	1,212	0,967	0,722	0,386	0,320	0,175	0,123	0,239	0,305	0,230	0,189	0,505	0,448	0,562	0,687
u_{SCal2} (dB)	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433	0,433
u_{TF} (dB)	0,055	0,058	0,068	0,167	0,196	0,364	0,393	0,398	0,358	0,404	0,352	0,294	0,248	0,144	0,121
u_{Mic} (dB)	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,289	0,433
u_{Tube} (dB)	0,006	0,006	0,006	0,006	0,014	0,017	0,043	0,087	0,115	0,058	0,069	0,087	0,087	0,087	0,173
u_{Posit} (dB)	0,095	0,090	0,090	0,085	0,085	0,080	0,085	0,095	0,075	0,075	0,090	0,135	0,138	0,152	0,195
$u_{Lin\,AD}$ (dB)	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052	0,052
u_{Round} (dB)	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029
$u_{Coupl+Mic}$ (dB)	0,346	0,346	0,346	0,346	0,346	0,346	0,346	0,404	0,404	0,404	0,462	0,462	0,520	0,577	0,693
u_{Repeat} (dB)	0,230	0,160	0,080	0,075	0,025	0,034	0,130	0,062	0,180	0,022	0,250	0,027	0,023	0,026	0,029
u_C (%)	17,0	14,1	11,5	9,0	8,7	8,8	9,0	9,7	9,9	9,6	10,0	10,9	10,8	11,7	14,2
$u_{95\%}$ (%)	33,9	28,2	23,0	18,0	17,3	17,7	18,1	19,3	19,8	19,2	20,0	21,8	21,5	23,4	28,3
$U_{95\%}$ (dB)	2,54	2,15	1,80	1,44	1,39	1,41	1,44	1,53	1,57	1,52	1,58	1,71	1,69	1,83	2,17

3. DISCUSSION

This work presents different frequencies range between the results in Anechoic Chamber and Test Box. IEC 60118-7 limits the measurements in the frequencies range 200 Hz to 5000 Hz. IEC 60118-0 limits the frequencies range according to the coupler that is used. As the coupler used in this work is the occluded ear simulator (IEC 60318-4), then the frequencies range used in Anechoic Chamber is from 200 Hz to 10000 Hz.

In the condition of the Laboratory having a good quality system two measurement results of expanded measurement uncertainty are presented, in Anechoic Chamber and in Test Box. Figure 3 shows different expanded measurement uncertainties.

When the Laboratory has a good quality system it is noticed that the $U_{95\%}$ are much better in Anechoic Chamber than in the Test Box. The Test Box used here is the most used commercial model in Brazil, so the effort to use it here. The problem with this model of FONIX is that its microphone does not meet the dimensional requirements of IEC 61094-4, making it impossible to calibrate it and consequently its coupler. This causes the uncertainty value to increase greatly, although another source of significant uncertainty is the nonuniformity of the sound field.

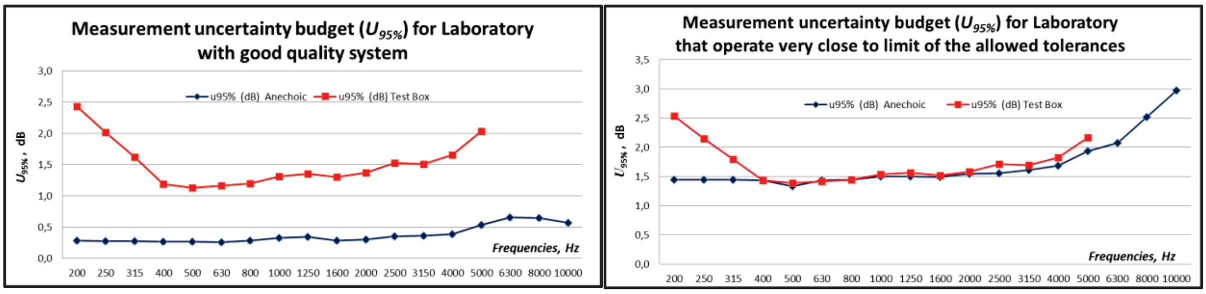

Figure 3 – Expanded measurement uncertainty ($U_{95\%}$) are presented in Anechoic Chamber and in Test Box

When it is assumed that the Laboratory operates very close to limit of the allowed tolerances, therefore, without much concern for the risk analysis of the results obtained in the measurements, the expanded measurement uncertainties in Anechoic Chamber and Test Box are very close (400 Hz to 2000 Hz). Out of this frequencies range the expanded measurement uncertainties related to Test Box increase compared to that presented in Anechoic Chamber.

The estimate of Expanded Measurement Uncertainty presented in Figure 3 may contribute to the members of WG 13 “Hearing Aids” of IEC (TC 29) reviewing the values of Maximum Uncertainty Permitted (U_{Max}) in the Anechoic Chamber and Test Box measurements. As described in Section 1 (Introduction), when the method used is the Test Box (IEC 60118-7) the U_{Max} is at least 1 dB lower than that of the method using Anechoic Chamber (IEC 60118-0).

This work used the "Occluded Ear simulator" coupler (IEC 60318-4) and not the 2 cm^3 coupler described in IEC 60318-5, because this standard does not specify requirements for conformity analysis. These requirements are indispensable in order to estimate the standard uncertainty related to $\boldsymbol{u}_{Coupl+Mic.}$

4. CONCLUSIONS

This work presented values of expanded measurement uncertainty ($\boldsymbol{U}_{95\%}$) for the acoustic performance measurement of hearing aids.

This work does not claim to establish the true value for expanded measurement uncertainty, but it presents the expanded measurement uncertainty of a laboratory that has a good quality system, which can be treated as the best calibration and measurement capability (CMC) for the measurement uncertainty. It also shows the expanded measurement uncertainty when the Laboratory operates close to the allowed tolerances of the measuring instruments, which can be assumed as a limiting condition for the permitted $\boldsymbol{U}_{Max}$ for a measurement method.

The authors recommend that further investigations into other models of Test Boxes be conducted with the purpose of having a more robust database to estimate $\boldsymbol{U}_{Max}$ for application in Hearing Aids normalization with greater accuracy.

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