BIPM Capacity Building & Knowledge Transfer Programme

2024 BIPM - TÜBİTAK UME Project Placement

REPORT

Project Name	Strengthening the Capacity of SNSU-BSN in the Fields of Acoustics, Ultrasound and Vibration (AUV) Topic: Sound Power Determination in Reverberation Room
Description	This project aims to determine sound power level using ISO 3741:2010, focusing on reference sound source calibration method in a reverberation room including evaluation of an uncertainty to assess measurement accuracy. The goal is to gain practical experience in sound power determination and evaluate the result by considering uncertainty.
Author, NMI	Nurvita Aji, Acoustics Laboratory, SNSU-BSN, Indonesia
Mentor at TÜBİTAK UME	1. Dr. Enver SADIKOĞLU, Acoustics Laboratory, TÜBİTAK UME, Türkiye 2. Dr. Cafer KIRBAŞ, Acoustics Laboratory, TÜBİTAK UME, Türkiye
Date	2 September 2024 – 29 November 2024

1. Motivation & Introduction

In Indonesia, the absence of regulations specifically targeting the Sound Power Level of household appliances leaves consumers vulnerable to potential health hazards and nuisance. Unlike other countries where stringent standards ensure the acoustic comfort of households, our regulatory framework lacks provisions to address excessive noise emissions. This regulatory gap not only compromises the well-being of citizens but also undermines the quality of life in our communities. The International Organization for Standardization (ISO) offers a potential solution amidst this gap. ISO standards provide comprehensive guidelines for measuring Sound Power Level, enabling objective and reliable assessments of appliance noise emissions. By aligning our efforts with these internationally recognized standards, Indonesia can establish a robust framework for evaluating and regulating Sound Power Level in household appliances, ensuring consumers' safety and comfort.

From a metrological perspective, measuring the Sound Power Level of products accurately is crucial. Precise measurements are directly linked to safer products and better protection for individuals against harmful noise levels. Therefore, determining the sound power of products with minimal uncertainty is paramount to ensure public health and well-being. Equipment manufacturers already use sound power levels to certify that their products meet noise emission standards set by national or international authorities. For example, appliances like refrigerators, vacuum cleaners, and power tools are often rated by their Sound Power Level to inform consumers of their potential noise impact. European countries governments, environmental agencies, and regulatory bodies use these measurements to ensure noise emissions do not exceed legally permissible thresholds.

Indonesia's primary responsibility for maintaining acoustics standards lies with the National Metrology Institute (NMI) under the SNSU-BSN. However, our department currently needs more personnel. Specifically, the acoustics team consists of only four members, three of whom have less than two years of experience in acoustics calibration. To address this shortcoming, it is essential to prioritize training and develop a deeper understanding of acoustics metrology within our department. The BIPM-TÜBİTAK UME Project Placements program presents an invaluable opportunity for me to learn how to determine sound power levels according to ISO standards. Participating in this program aims to gain practical experience and enhance my understanding of acoustics, which will help me acquire valuable skills. These skills will not only contribute to the improvement of acoustics metrology in Indonesia, but also have broader applications across various sectors.

2. Research

2.1. Purpose

Reference sound sources (RSS) are used extensively in comparison methods to determine the noise emissions of physically stationary sound sources. A reference sound source of known sound power output is used to establish the numerical relationship between the sound power level of a source in a given location in a given acoustic environment and the space- and time-averaged sound pressure level at a set of microphone positions. Once that relationship is established, measuring the average sound pressure level produced by an "unknown source" and determining the sound power level produced by that source is straightforward. This report aims to guide the calibration of reference sound sources to determine sound power level, as learned by participant in the Acoustics Laboratory of TÜBİTAK UME.

2.2. International Standards for Sound Power Level Determination

ISO 6926:2016 outlines the acoustic performance requirements for reference sound sources used for the determination of sound power levels of sound sources. It specifies the criteria for the sound power output's temporal steadiness (stability), spectral characteristics, and directivity. Based on ISO 6926:2016, there are three methods for the determination of Sound Power Level: ISO 3741:2010, ISO 3744:2010 and ISO 3745:2012. In this project, we used ISO 3741:2010 standard to determine the sound power level of RSS in the reverberation room with the following provisions.

2.3.1. Scope

This report explains the procedure of reference sound source calibration carried out in the acoustics laboratory of TÜBİTAK UME, Türkiye, based on ISO 6926:2016 and ISO 3741:2010 standards. The following is the scope of the calibration.

2.3.1.1. Reverberation room features

- A room within a room (double shell)
- There is a 30 cm gap between the outer room and inner room, and wall thickness is 30 cm
- The inner chamber is supported by 13 springs
- Room interior surfaces are hard concrete surfaces painted with epoxy
- Surface sound absorption coefficient <0.06
- Room effective dimensions 9.7 m x 6.6 m x 4.1 m and 262,51 m^3 volume of inner room
- Complies with ISO 3741 standard requirements
- Background noise is 13 dBA and Sound Transmission Loss of Door is 44 dB
- Reverberation Time is around 8 s depending on frequency

2.3.2. Sound Power Level Calculation

The following equation is used to calculate Sound Power Level of Noise Source Under Test in Each One-Third Octave based on ISO 3741:2010 (Using Reverberation Room).

$$L_w = \overline{L_{p(ST)}} + \left\{10\log\frac{A}{A_0}dB + 4{,}34\frac{A}{S}dB + 10\log\left(1+\frac{Sc}{8Vf}\right)dB + C_1 + C_2 - 6dB\right\} \quad (1)$$

where,

$$A = \frac{55{,}26}{c}\left(\frac{V}{T_{rev}}\right), \quad (2)$$

$$c = 20{,}05\sqrt{273+\theta}, \quad (3)$$

$$C_1 = -10\log\frac{p_s}{p_{s,0}}dB + 5\log\left(\frac{273{,}15+\theta}{\theta_0}\right)dB, \quad (4)$$

$$C_2 = -10 \log \frac{p_s}{p_{s,0}} dB + 15 \log \left(\frac{273{,}15 + \theta}{\theta_1} \right) dB \quad (5)$$

Formula Definitions:

L_w *sound power level of the noise source under test, in decibels;*

$\overline{L_{p(ST)}}$ *is the mean corrected one-third-octave band time-averaged sound pressure level in the test room with the noise source under test in operation, in decibels;* $\overline{L_{p(ST)}} = \overline{L'_{p(ST)}} - K_1$*, which* $\overline{L_{p(ST)}}$ *is the mean uncorrected one-third-octave band time-averaged sound pressure level an* K_1 *is background noise correction decibels*

T_{rev} *is the reverberation time, in seconds, of the reverberation test room at the mid-band frequency of the measurement(s);*

A *is the equivalent absorption area, in square meters, of the room*

A_0 *reference equivalent absorption area, set to 1* m^2*;*

c *is the speed, in meters per second, of sound at the temperature, ϑ, in degrees Celsius, of the air in the reverberation test room at the time of the test;*

V *is the volume, in cubic meters, of the reverberation test room;*

S *is the total surface area, in square meters, of the reverberation test room;*

f *is the mid-band frequency, in hertz, of the measurement(s);*

p_s *is the static pressure, in kilopascals, in the test room at the time of the test;*

$p_{s,0}$ *is the reference static pressure, 101,325 kPa;*

θ *is the air temperature, in degrees Celsius, in the test room at the time of the test;*

θ_0 *is given by standard, set to 314 K*;

θ_1 *is given by standard, set to 296 K.*

Explanation of the Additional Terms:

θ_0 and θ_1 are given by standard. These reference temperatures are part of the acoustic calibration process to standardize measurements, accounting for environmental factors that affect sound propagation and absorption.

C_1 and C_2 are correction factors for the temperature and atmospheric pressure during testing. These adjustments help compensate for changes in the speed of sound due to variations in temperature and pressure in the room.

2.3.3. Background Noise Correction (K_1)

The background noise correction, K_{1i}, at the *i*th microphone position in each one-third-octave band, shall be calculated using guidelines in Equation (6). If the difference between the averaged uncorrected Sound Pressure Level (SPL) of DUT and the averaged SPL of background noise equals or exceeds 15 dB, the correction for background noise will be zero.

$$K_1 = -10\, log\left(1 - 10^{-0,1\Delta L_p}\right) dB \tag{6}$$

where,

$$\Delta L_p = L'_{p(ST)} - L_{p(B)} \tag{7}$$

$$\overline{L_{p(ST)}} = \overline{L'_{p(ST)}} - K_1 \tag{8}$$

Formula Definitions:

K_1 *is background noise correction* (dB), ΔL_p *is the difference between* $L'_{p(ST)} - L_{p(B)}$, $L'_{p(ST)}$ *is averaged Uncorrected SPL of DUT* (dB), $L_{p(B)}$ *is averaged SPL of background noise* (dB), $L_{p(ST)}$ *is averaged corrected SPL of DUT* (dB).

2.3. Device Under Test and Calibration System

The DUT (Device Under Test) in the calibration is a reference sound source. In this calibration, we used 6 calibrated microphones as reference standards.

2.4.1. The unit under test information

Table 2.1. Unit Under Test Information

Device name	Reference Sound Source
Manufacturer	Brüel & Kjaer
Model/Type	4204
Produced L_w	91 dB re 1 pW

2.4.2. Reference(s) used in the calibration system

Table 2.2. Calibration system information

Device name	Manufacturer	Model/Type	Traceability
Diffused Field – Microphone and Preamplifier	G.R.A.S	40AR/ AA0012	UME
Diffused Field – Microphone and Preamplifier	G.R.A.S	40AR/ AA0012	
Diffused Field – Microphone and Preamplifier	G.R.A.S	40AR/ AA0012	
Diffused Field – Microphone and Preamplifier	G.R.A.S	40AR/ AA0012	
Diffused Field – Microphone and Pre-amplifier	G.R.A.S	40AR/ AA0012	
Diffused Field – Microphone and Pre-amplifier	G.R.A.S	40AR/ AA0012	
Acoustic Calibrator	Brüel & Kjaer	4231	

2.4.3. Support devices for reference sound source calibration system

Table 2.3. Support devices information

Device name	Manufacturer	Model/Type	Traceability
5/1 ch Input/Output Controller Module	Brüel & Kjaer	7537	UME
Power Supply	Brüel & Kjaer	2826	UME
6 ch Input Module	Brüel & Kjaer	3039	UME
4/2 ch Input/Output Module	Brüel & Kjaer	3109	UME
Thermohygrometer	UME	ESL1012	UME
Barometer	Brüel & Kjaer	UZ 0004	UME

2.4. Initial Condition

Based on Table 2.4, besides the meteorological conditions and the specifications of the reverberation room, the Sound Power Level determination requires the values of the SPL of the DUT, the SPL of the background noise (to calculate the background noise correction), and the reverberation time (to calculate the absorption area). These three parameters are obtained through measurements.

Table 2.4. The initial value for determining Sound Power Level

No	Symbol(s)	Quantity	Equation(s)	Value(s)	Unit
1	$\overline{L_{p(ST)}}$	corrected SPL of DUT	$\overline{L_{p(ST)}} = \overline{L'_{p(ST)}} - K_1$ $\overline{L'_{p(ST)}}$ uncorrected SPL of DUT K_1 is background noise correction	By measuring $\overline{\boldsymbol{L'_{p(ST)}}}$ **uncorrected SPL** of DUT By determining $\boldsymbol{K_1}$ **background noise correction** of measurement	dB
2	T_{rev}	reverberation time	at the mid-band frequency of the measurements	By measuring $\boldsymbol{T_{rev}}$ **reverberation time**	s
3	A	absorption area of the reverberation test room	$A = \frac{55{,}26}{c}\left(\frac{V}{T_{rev}}\right)$	V = 262,51 m^3 c depends on meteorological conditions	m^2
4	A_0	the reference absorption area	given by standard 3741:2010	1	m^2
5	c	speed of the air in the reverberation test room at the time of the test	$c = 20{,}05\sqrt{273 + \theta}$	c depends on meteorological conditions	m/s
6	V	volume of the reverberation test room	based on reverberation test room specifications	9,71 m x 6,61 m x 4,09 m = 262,51	m^3
7	S	total surface area	based on reverberation test room specifications	2 x ((9,71 x 6,61)+(6,61 x 4,09)+(9,71 x 4,09)) = 261,86	m^2
8	f	the mid-band frequency of the measurement(s)	given by standard 3741:2010	10 Hz – 10 kHz	Hz
9	p_s	the static pressure in the test room at the time of the test	p_s depends on meteorological conditions	measured by barometer	kPa
10	$p_{s,0}$	the reference static pressure	given by standard 3741:2010	101,325	kPa
11	θ	the air temperature in the test room at the time of the test	θ depends on meteorological conditions	measured by thermohygrometer	$°C$
12	θ_0	accounting for environmental factor C_1	given by standard 3741:2010	314	K
13	θ_1	accounting for environmental factor C_2	given by standard 3741:2010	269	K

2.5. Equipment Setup for SPL of DUT, SPL of Background Noise, and Reverberation Time Measurement

Figure 2.1 shows the equipment setup for DUT SPL measurement. This measurement used six microphone positions and four reference sound source positions. For each set, ten measurements were taken. Therefore, the total data collected was 6 x 4 x 10, or 240 measurements for the determination of Sound Power Levels. Figure A.1 (a) in Annex A of this report provides further information about the setup for SPL measurement.

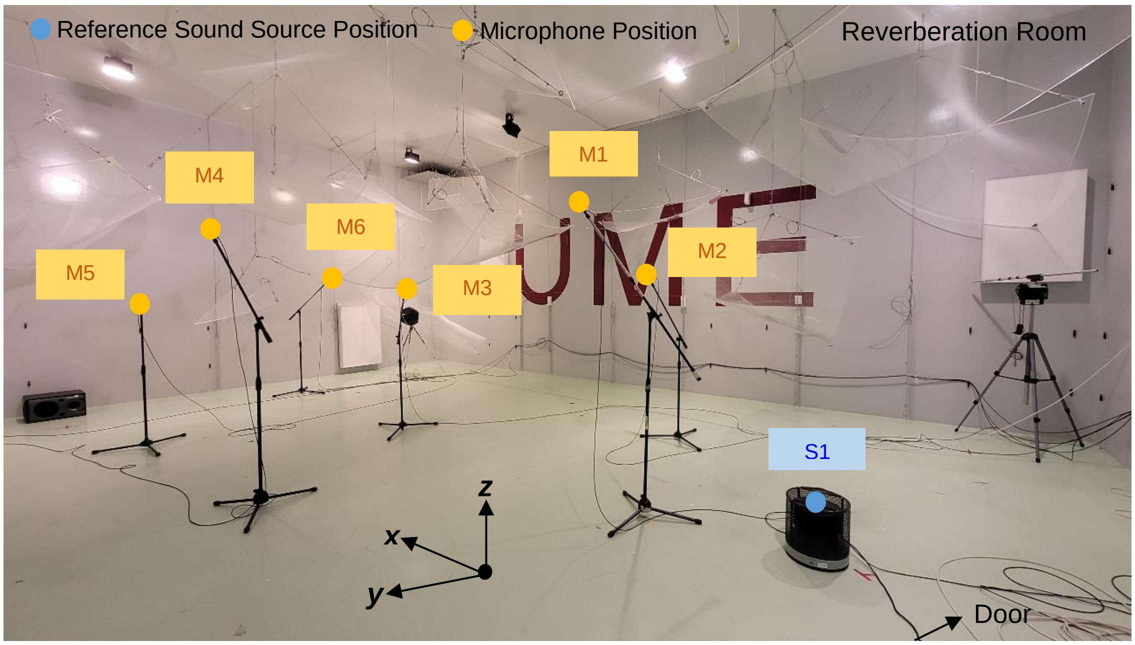

Figure 2.1. Setup for microphones and reference sound source in the reverberation room

Meanwhile, in Annex A of this report, Figures A. 1 (b) and A. 2 show the background noise measurement and reverberation time measurement setup. Similar to the SPL measurement, we collected 240 data for the background noise measurement. However, we used six microphones and three noise sources for the reverberation time measurement. For each set, we took ten measurements, so the total data collected for the reverberation time measurement was 180.

2.6. Calibration Procedures and Result

Calibration Procedure:

- ✓ Preliminary Check: To ensure accurate measurements, check the microphone performance and assess the room's diffuseness.
- ✓ Sound Pressure Level of the Device Under Test (DUT): Measure the sound pressure level of the Device Under Test (DUT) to evaluate its acoustic output.
- ✓ Sound Pressure Level of Background Noise: Measure the sound pressure level of the background noise to determine the correction factor needed for accurate measurements.
- ✓ Reverberation Time Measurement: Measure the room's reverberation time to calculate the absorption area, which will be used to correct the overall acoustic measurements results.

2.7.1. Preliminary check

2.7.1.1. Microphone performance check

Each microphone is checked individually using the Acoustics Calibrator B&K 4231, set to an SPL of 94 dB at 1 kHz. If the results are acceptable, proceed to the next step. The minimum number of microphones used during calibration of the reference sound source is six, as long as the standard deviation among the microphones is equal to or less than 1,5 dB.

2.7.1.2. Diffuseness check

Based on ISO 3741:2010, the standard deviation among the six microphones for each position is equal to or less than 1,5 dB. The setup for the diffuseness check is the same as for the DUT's SPL measurement, as shown in Figure A.1(a) of Annex A. If the standard deviation is acceptable, it can be concluded that all the measurement devices and the reverberation test room are valid for the measurements.

2.7.2. Measurement and results

2.7.2.1. Sound Pressure Level of the Device Under Test (DUT) Measurement

The setup for this measurement is shown in Figure A.1(a) of Annex A. This measurement used six microphone positions and four reference sound source positions. Ten repetitions were taken per one-third-octave frequency band for each measurement set, ranging from 100 Hz to 10 kHz. Therefore, the total data collection was 6 × 4 × 10, resulting in 240 measurements per 1/3 octave band frequencies.

2.7.2.2. Sound Pressure Level of Background Noise Measurement

The setup for this measurement is shown in Figure A.1(b) of Annex A. Six microphone positions were used, and no sound source was present. In each measurement set, ten repetitions were taken per one-third-octave frequency band, ranging from 100 Hz to 10 kHz, resulting in 240 measurements per frequency.

Background Noise Correction

If the difference between the averaged uncorrected Sound Pressure Level (SPL) of the Device Under Test (DUT) and the averaged SPL of background noise equals or exceeds 15 dB, the correction for background noise is considered zero. This criterion helps ensure that background noise does not interfere significantly with the SPL measurements of the DUT. When this threshold is met, no correction for background noise is required, as the background noise is sufficiently low compared to the DUT's sound output. The table below shows the background noise correction for the one-third-octave frequency bands, ranging from 100 Hz to 10 kHz, indicating the absence of any necessary adjustments in this scenario.

Upon further analysis, it is clear that higher background noise levels are typically observed at lower frequencies, particularly in the range below 200 Hz. As shown in the data, the difference between the corrected SPL values $L'_{p(ST)}$ and the background noise SPL ($L_{p(B)}$) consistently exceeds 15 dB, resulting in a background noise correction factor K_1 of zero. This means that the background noise within the reverberation room does not significantly influence the SPL measurements of the DUT across the specified frequency bands. The table below provides a detailed breakdown of the background noise correction for each of the one-third-octave frequency bands, confirming that the SPL measurements of the DUT remain unaffected by background noise in the reverberation room.

Table 2.5. Background Noise Correction for one-third-octave frequency band

Frequency	$L_{pi(B)}$	$L'_{pi(ST)}$	ΔL_{pi}	K_1	$\overline{L_{p(ST)}}$
Hz			dB		
100	28,56	68,66	40,10	0,00	68,66
125	26,53	71,33	44,80	0,00	71,33
160	21,05	73,59	52,54	0,00	73,59
200	18,91	73,60	54,69	0,00	73,60
250	18,49	74,28	55,78	0,00	74,28
315	15,62	74,81	59,20	0,00	74,81
400	15,41	75,07	59,65	0,00	75,07
500	15,55	75,54	59,99	0,00	75,54
630	15,47	76,32	60,85	0,00	76,32
800	15,34	77,84	62,51	0,00	77,84
1000	14,59	78,64	64,06	0,00	78,64
1250	13,08	79,88	66,80	0,00	79,88
1600	12,22	79,91	67,69	0,00	79,91
2000	10,13	79,35	69,22	0,00	79,35
2500	8,93	76,92	67,99	0,00	76,92
3150	6,76	74,97	68,21	0,00	74,97
4000	7,42	73,98	66,56	0,00	73,98
5000	7,89	72,00	64,11	0,00	72,00
6300	8,71	69,85	61,15	0,00	69,85
8000	9,48	66,71	57,23	0,00	66,71
10000	7,42	62,96	55,54	0,00	62,96

2.7.2.3. Reverberation Time Measurement

The setup for the reverberation time measurement is illustrated in Figure A.2 of Annex A. The measurement procedure involved six microphone positions and three sound source positions strategically placed within reverberation room. This configuration ensured comprehensive space coverage, capturing accurate data from various angles and distances. For each measurement set, five repetitions were conducted for each one-third-octave frequency band, which spanned from 100 Hz to 10 kHz. This was a systematic approach specified in the standard to calculate the reverberation time from the spatial average of 180 repeated measurements data for each frequency band.

2.7.3. Sound Power Level Calculation

After all the parameters in Table 2.4 are obtained, the sound power level is calculated using equation (1). Based on Table B.1 of Annex B, we obtain 92,0 dBA for the sound power level of the reference sound source at a total frequency of one-third octave. Based on ISO 3741:2010, the typical upper bound values of the standard deviation for reproducibility σ_{RO} of the method are 3,0 dB (100 Hz – 160 Hz), 2,0 dB (200 Hz – 315 Hz), 1,5 dB (400 Hz – 5 kHz), 3,0 dB (6,3 kHz – 10 kHz). Table B.2 of Annex B shows that the uncertainty is higher in low-frequency and high-frequency compared to mid-band frequency. It also shows that the uncertainty value for σ_{RO} at all frequencies is consistently below the typical upper bound values, indicating that the calibration system for determining sound power in the Acoustics Laboratory of TÜBİTAK UME is very stable. A stable calibration system ensures that the calibration results are accurate and reliable.

3. Conclusions and Future Work

Over the past three months, I have gained valuable knowledge in various calibration techniques, measurements, and evaluation methods in the fields of Acoustics, Ultrasound and Vibration (AUV). Participating in this program has been both an honour and an enriching experience, allowing me to enhance my skills significantly. It has also provided an opportunity to contribute to the growth of my institution, particularly the Acoustic and Vibration Laboratory at SNSU-BSN. The hands-on experience and exposure to advanced calibration systems have increased my understanding of AUV metrology and its real-world applications.

After returning to my country, I plan to apply all the knowledge and experiences I have gained to strengthen my laboratory's capabilities. I aim to foster collaboration with local and international experts to further develop our laboratory's research potential. In the future, I hope to collaborate with policy-makers in Indonesia to raise awareness about the importance of noise emission labelling. I am committed to advocating for regulations that benefit consumers, improve public health, and promote sustainable environmental practices.

4. Acknowledgements

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My sincere thanks also go to the Deputy for Accreditation at the National Standardization Agency of Indonesia (BSN) and the APMP Developing Economies' Committee (DEC) for providing financial support to participate in this program.

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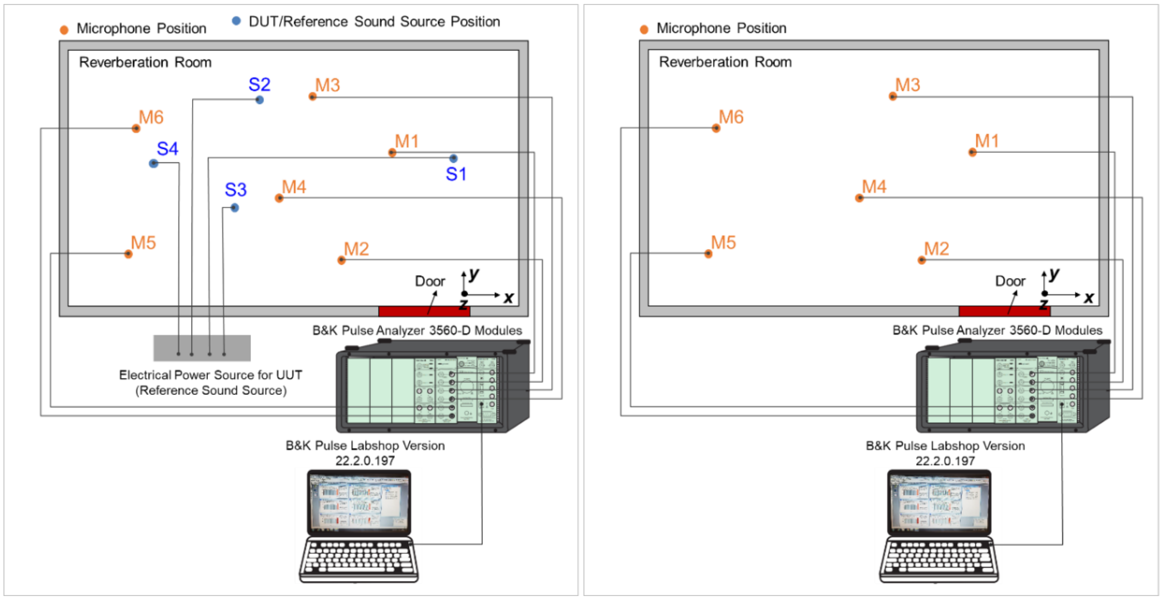
ANNEX A
Equipment Setup for Measurements



(a) (b)

Figure A.1. Setup for measurements of DUT's SPL (a) and SPL of background noise (b)

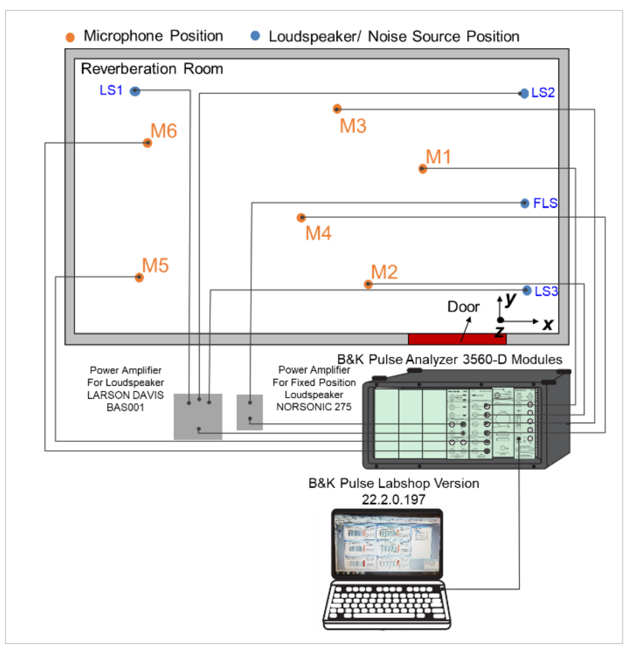


Figure A.2. Setup for reverberation time measurement

ANNEX B

The Results of Sound Power Level Determination and Uncertainty Budget

Table B.1. Sound Power Level of Calibrated Reference Sound Source

Corrected SPL of DUT and Reverberation Time				Correction Terms						Sound Power Level		
Frequency	DUT Corrected SPL $\overline{\overline{L_{p(ST)}}}$	T_{rev}	A	Term 1	Term 2	Term 3	C1	C2	Constant	L_W	A-Weighted Response	L_{WA}
Hz	dB	s	m²	dB	dB	dB	dB	dB	dB	dB	dB	dBA
100	68,7	4,4	9,67	9,9	0,16	1,55	-0,04	0,08	-6	74,3	-19,1	55,2
125	71,3	7,1	5,92	7,7	0,10	1,28	-0,04	0,08	-6	74,5	-16,1	58,4
160	73,6	6,6	6,34	8,0	0,11	1,03	-0,04	0,08	-6	76,8	-13,4	63,4
200	73,6	7,2	5,86	7,7	0,10	0,85	-0,04	0,08	-6	76,3	-10,9	65,4
250	74,3	7,7	5,47	7,4	0,09	0,69	-0,04	0,08	-6	76,5	-8,6	67,9
315	74,8	7,5	5,58	7,5	0,09	0,56	-0,04	0,08	-6	77,0	-6,6	70,4
400	75,1	7,5	5,60	7,5	0,09	0,44	-0,04	0,08	-6	77,1	-4,8	72,3
500	75,5	8,1	5,20	7,2	0,09	0,36	-0,04	0,08	-6	77,2	-3,2	74,0
630	76,3	8,4	4,98	7,0	0,08	0,29	-0,04	0,08	-6	77,7	-1,9	75,8
800	77,8	8,0	5,24	7,2	0,09	0,23	-0,04	0,08	-6	79,4	-0,8	78,6
1000	78,6	7,6	5,54	7,4	0,09	0,18	-0,04	0,08	-6	80,4	0,0	80,4
1250	79,9	6,7	6,26	8,0	0,10	0,15	-0,04	0,08	-6	82,1	0,6	82,7
1600	79,9	6,1	6,89	8,4	0,11	0,12	-0,04	0,08	-6	82,6	1,0	83,6
2000	79,4	5,3	7,93	9,0	0,13	0,09	-0,04	0,08	-6	82,6	1,2	83,8
2500	76,9	4,5	9,36	9,7	0,16	0,07	-0,04	0,08	-6	80,9	1,3	82,2
3150	75,0	3,5	12,01	10,8	0,20	0,06	-0,04	0,08	-6	80,1	1,2	81,3
4000	74,0	2,7	15,50	11,9	0,26	0,05	-0,04	0,08	-6	80,2	1,0	81,2
5000	72,0	2,3	18,55	12,7	0,31	0,04	-0,04	0,08	-6	79,1	0,5	79,6
6300	69,9	1,7	25,09	14,0	0,42	0,03	-0,04	0,08	-6	78,3	-0,1	78,2
8000	66,7	1,5	28,18	14,5	0,47	0,02	-0,04	0,08	-6	75,7	-1,1	74,6
10000	63,0	1,5	28,07	14,5	0,47	0,02	-0,04	0,08	-6	72,0	-2,5	69,5
A L	Sound Power Level, dB ref 1 pW									**92,2**	**92,0**	

Term 1 = $10\log\frac{A}{A_0}$; Term 2 = $4{,}34\frac{A}{S}$; Term 3 = $10\log\left(1+\frac{Sc}{8Vf}\right)$