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UNCERTAINTY ANALYSIS OF LABORATORY MEASUREMENT OF AIRBORNE SOUND INSULATION

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ABSTRACT

The evaluation and analysis of the uncertainty of laboratory measurement of airborne sound insulation have been carried out by Research Group for Acoustics and Vibration – National Standardization Agency of Indonesia (BSN). The aims of this work are to evaluate and analyze the uncertainty measurement of airborne sound insulation by pressure method, where it is focused only for the determination of sound transmission loss (STL) as a major product of this measurement according to ASTM, and guide to the expressions of Uncertainty in Measurement (GUM) provided by JCGM. The supplied parameter of uncertainty budgets includes measurement of sound pressure level (SPL) in a source room (L_1), and measurement of some parameters in a receiver room such as SPL (L_2), reverberation time (RT_{60}), background noise (B), test opening area (S), and volume of receiver room (V). From the result of the case study, the source of uncertainty that has a top contribution for obtaining expanded uncertainty is considered as the repeated measurement of the measured parameter such as L_1 , L_2 , and RT_{60} at the frequency range 250 Hz – 315 Hz. Meanwhile, the standard uncertainty that provided by the calibration certificate also contributes to the final result, where it is supplied by an acoustic calibrator and sound analyzer, respectively. Furthermore, the sources obtained from the readability parameter has a slight effect on this whole result. Therefore, the maximum and minimum value of expanded uncertainty is determined that their values are 0.70 dB and 0.43 dB for the frequency of 315 Hz and 1600 Hz, respectively.

Keywords: uncertainty, GUM, laboratory measurement, airborne sound insulation, sound transmission loss

INTRODUCTION

The international standard guidance of sound insulation measurement for the buildings and building materials has been published by international standard bodies such as International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM). According to these standards, the measurement of sound insulation is classified into several types, and it comprises airborne sound insulation, impact sound insulation, and field sound insulation. The first is the measurement that is applied in the laboratory for the sound that propagates through an air medium, while the second is the insulation measurement where the sound is generated by direct contact of an object on the building element [1]. Meanwhile, the last is similar to the first type of measurement, and however, it is conducted directly in the appropriate field such as hotel and office instead of in the laboratory [2].

From the categories above, therefore, airborne sound insulation is the most common measurement that has been implemented by some institutions that have the capability to provide research and service of the building acoustics field include the National Standardization Agency of Indonesia (BSN). Moreover, this measurement can be performed inside the two reverberation rooms as the main requirements and utilize the diffuse field of microphones [3]. Previously, the method to measure sound transmission loss (STL) is using the intensity method based on sound intensity received by the sample test in a particular area [4]. Even though having good accuracy, this method is difficult to be implemented, especially for the specimen that has a larger area. Hence, another method is introduced, and it is considered as a pressure method based on measurement sound pressure level (SPL) between the two rooms and has accuracy as well as the prior method. Additionally, the determination of uncertainty measurement for the corresponding method also has been introduced by BSN using a general procedure that refers to a guide to the expressions of Uncertainty in Measurement (GUM). Hence, identification of this product of measurement is necessary to be conducted to observe the influence of the associated parameters that consist of system measurement, facilities, method, and environmental conditions to the result of the measurement.

Therefore, the aims of this work are to evaluate and analyze the uncertainty measurement of airborne sound insulation by pressure method that has been performed by BSN as mentioned above, where it will be focused only for the determination of sound transmission loss (STL) as a major product of this measurement in the laboratory scope according to ASTM E413. Furthermore, the determination of an uncertainty budget and other essential quantities for the appropriate measurement along with the case study also will be discussed in this paper. In addition, this result is considered to be a reference for submitting Calibration and Measurement Capability (CMC) to The Committee of National Accreditation (KAN) as the representative organization for local accreditation.

MATHEMATICAL MODEL

The measurement of airborne sound insulation can be illustrated in FIGURE 1, and it is carried out in two reverberation rooms with the required volume (V), as mentioned above, which consists of a source room and a receiver room. The former is the room where the sound pressure level is generated by a sound source. Whilst the later is a closed space that obtains a noise from the previous room. Both of these rooms are separated by a partition with particular compositions and a test opening with a specific area (S) [5].

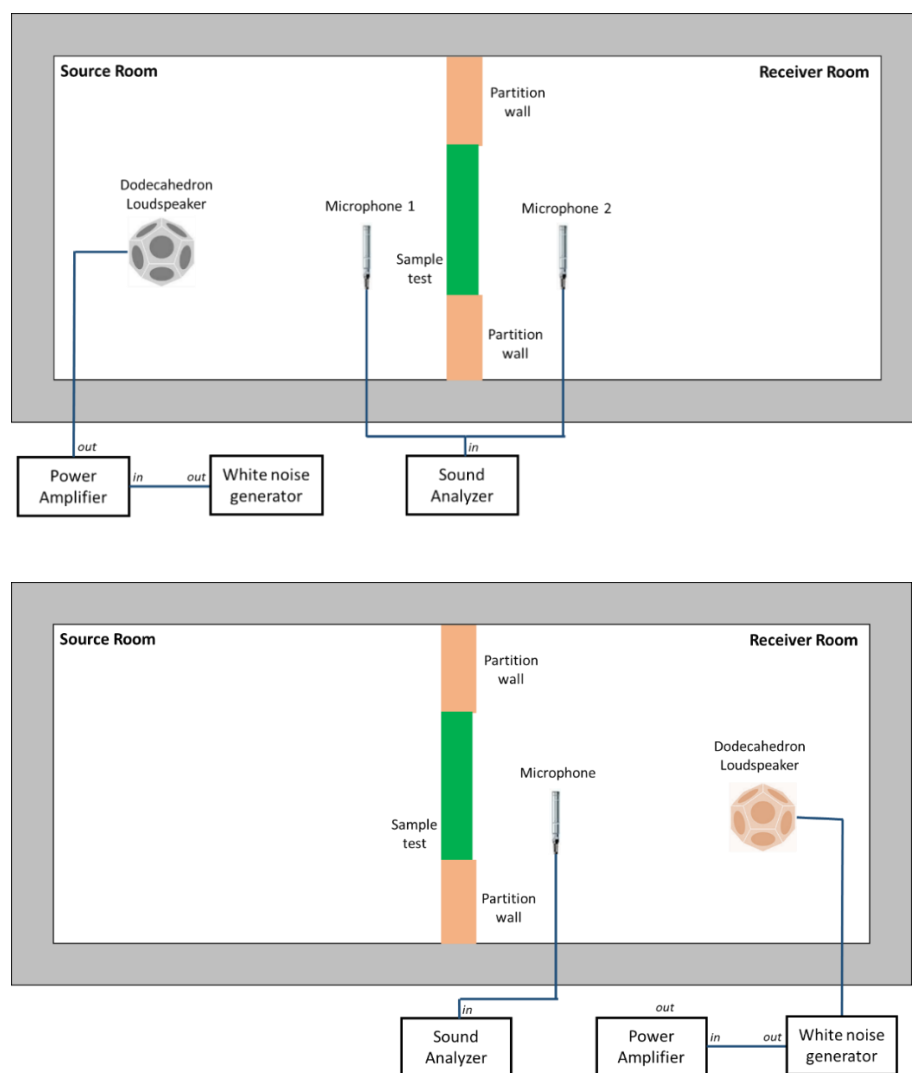


FIGURE 1. Measurement of L in two rooms (top); Measurement of RT_{60} in the receiver room (bottom).

The measurement process is initiated by adjusting the sound pressure level (L) of a dual-channel sound analyzer that connected to a pair of microphones using a calibrated sound calibrator at the reference value (94 dB). After that, it is continued by measuring sound pressure level (L , in dB) in the two rooms, and reverberation time (RT_{60} , in second) in the receiver room. After obtaining these measurands, the sound transmission loss (STL) as the main parameter in this measurement is determined as follow [6]:

$$STL = L_1 - L_2 + 10 \log \frac{S \cdot RT_{60}}{0.163 \cdot V} \quad (1)$$

Due to background noise in the receiver room (denotes as B , in dB), it needs to be put to EQUATION (1) [7]. To facilitate the determination of the uncertainty budget, the mathematical model that written above can be simplified by separating the parameters associated with logarithm, and therefore, it can be expressed as follow :

$$STL = L_1 - L_2 + B + 10 \log S + 10 \log RT_{60} + 10 \log V + 10 \log 0.163 \quad (2)$$

Therefore, uncertainty budgets can be identified based on this mathematical model.

UNCERTAINTY BUDGETS

As discussed in GUM and other publication for the related topics, the budget of uncertainty is categorized into A-type and B-type. The former is the source that is determined by conducting some measurement series, and it is evaluated with a statistical method, while the latter is defined by obtaining a scientific consideration or other information that contributes to the result of measurement or calibration [8]. For convenience, the Ishikawa diagram can be used to assign sources of uncertainty, and therefore, it is shown in FIGURE 2 for the case of measurement of airborne sound insulation.

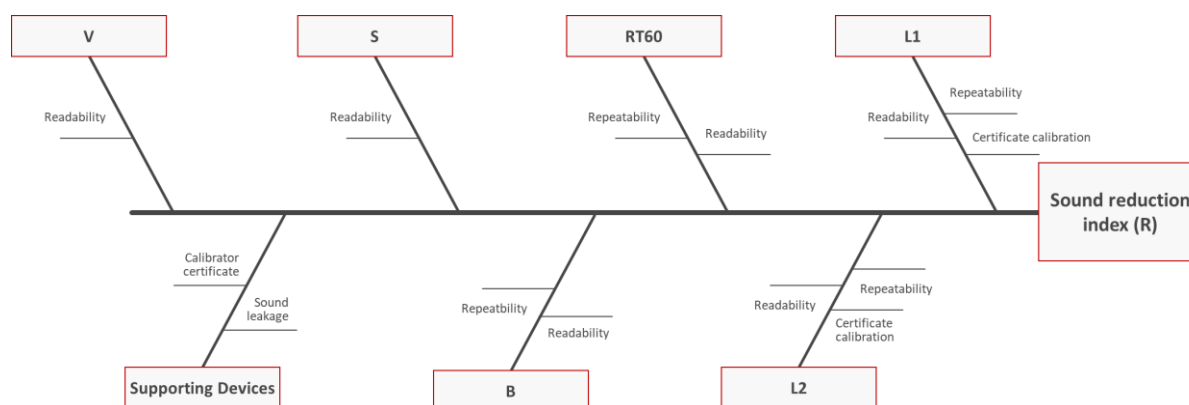


FIGURE 2. Determination of uncertainty budgets by Ishikawa diagram.

From this figure, it is shown that the components of the uncertainty budgets of this calibration method can prescribe as follow [9]:

1. Measurement of L in source room (L_1), the component comprises the repeated measurement of L (repeatability), readability of the sound analyzer in channel 1, and its certificate calibration. The first is categorized as A-type of uncertainty budget. The number of measurement data of L for the required frequencies is 20 times. After that, the standard deviation of the corresponding data is calculated later. Meanwhile, for the second and the third components, they classified as B-type of uncertainty budget, and further, they are obtained from a digit of resolution and an expanded uncertainty of calibration result of sound analyzer, respectively.

2. Measurement of L in receiver room (L_2), the components are similar to the previous parameter, and it comprises the repeated measurement of L (repeatability), readability of the sound analyzer in channel 2, and its certificate calibration. The first is categorized as A-type of uncertainty budget. The number of measurement data of L for the required frequencies also is 20 times, and the standard deviation of the corresponding data is calculated. Meanwhile, for the second and the third component, the same information also describes as the foregoing budget.
3. Measurement of reverberation time in the receiver room (RT_{60}). Again, it has similar components as the previous budgets. It comprises the repeated measurement of RT_{60} (repeatability) and readability of the sound analyzer in channel 2.
4. Measurement of background noise in the receiver room (B). The consisting components are also similar to the measurement of L_2 . However, by reason of using the same channel, the certificate calibration is not necessary to be put in this component.
5. Test opening area (S). It is measured using a laser distance meter (LDM) that has a resolution of 0.01 m and is classified into type-B of uncertainty budget.
6. Volume of receiver room (V). The same device is also used to measure this quantity, and therefore, it is classified into type-B of uncertainty budget.
7. Acoustic calibrator (C). Even though this component is not part of the mathematical model in equation (2) directly, it is used before conducting the measurement process to adjust the L value of the sound analyzer. Hence, it is necessary to be put into uncertainty evaluation. Therefore, it is categorized as a B-type of uncertainty budget that its value is obtained from the calibration certificate.

EVALUATION OF STANDARD UNCERTAINTY

According to GUM, the evaluation method to determine a standard uncertainty of the corresponding budgets comprises A-type and B-type [8]. As same as mentioned above, the former can be applied using the statistical analysis of series of measurements, where the standard deviation can determine as follow:

$$Stdev = \sqrt{\frac{1}{N-1} \sum (L_i - \bar{L})^2} \quad (3)$$

Meanwhile, for the later, it is obtained by evaluation by means other than the statistical analysis of series of observations. Therefore, the determination of the standard uncertainty of the aforementioned components along with the type, distribution, and its calculation can be summarized in TABLE 1.

TABLE 1. Determination of standard uncertainty of measurement of airborne sound insulation.

Component	Symbol	Type	Distribution	Divisor	Standard uncertainty calculation
Repeatability of L_1	u_1	A	Normal	20	$u_1 = \frac{Stdev}{\sqrt{N}}$
Readability of sound analyzer associated to L_1	u_2	B	Rectangular	$\sqrt{3}$	$u_2 = \frac{a}{\sqrt{3}}$
Certificate calibration of sound analyzer for ch 1	u_3	B	Normal 95%	2	$u_3 = \frac{U_{certificate}}{2}$
Repeatability of L_2	u_4	A	Normal	20	$u_4 = \frac{Stdev}{\sqrt{N}}$
Readability of sound analyzer associated to L_2	u_5	B	Rectangular	$\sqrt{3}$	$u_5 = \frac{a}{\sqrt{3}}$
Certificate calibration of sound analyzer for ch 2	u_6	B	Normal 95%	2	$u_6 = \frac{U_{certificate}}{2}$
Repeatability of RT_{60}	u_7	A	Normal	12	$u_7 = \frac{Stdev}{\sqrt{N}}$
Readability of sound analyzer associated RT_{60}	u_8	B	Rectangular	$\sqrt{3}$	$u_8 = \frac{a}{\sqrt{3}}$
Repeatability of B	u_9	A	Normal	8	$u_9 = \frac{Stdev}{\sqrt{N}}$
Readability of sound analyzer associated B	u_{10}	B	Rectangular	$\sqrt{3}$	$u_{10} = \frac{a}{\sqrt{3}}$
Readability of LDM associated with S	u_{11}	B	Rectangular	$\sqrt{3}$	$u_{11} = \frac{a}{\sqrt{3}}$
Readability of LDM associated with V	u_{12}	B	Rectangular	$\sqrt{3}$	$u_{12} = \frac{a}{\sqrt{3}}$
Certificate calibration of the sound calibrator	u_{13}	B	Normal 95%	2	$u_{13} = \frac{U_{certificate}}{2}$

Where N is the number of measurement data, a is half of the resolution digit that indicated by the sound analyzer, and $U_{certificate}$ is expanded uncertainty with the confidence level of 95% that taken from the calibration certificate.

In addition, the other fundamental parameters also need to be determined, and it consists of a sensitivity coefficient for the budgets of uncertainty (c_i) and a degree of freedom (ν_i). The first parameter is described as how the obtained measurand varies with changes in the values of the other parameters and is given by calculating the partial derivative of the equation (1) to the input parameter [8]. Meanwhile, for the second parameter, it depends on the type of used uncertainty method. It can be calculated by subtracting the total amount of the measurement data (N) with 1 for A-type, and it should be infinite for B-type according to JCGM and an estimation result of the published paper. Therefore, these parameters can be written serially in TABLE 2 as follow:

DETERMINATION OF COMBINED STANDARD UNCERTAINTY

Afterward, the combined standard uncertainty can be calculated using the equation as follow [10]:

$$u_c^2(STL) = \sum_{i=1}^N c_i^2 u_i^2 \quad (4)$$

TABLE 2. Determination of sensitivity coefficient and degree of freedom of airborne sound insulation

Component	Calculation c_i	Result of c_i	ν_i
Repeatability of L1	$\partial R / \partial L1$	1	N-1
Readability of sound analyzer associated to L1	$\partial R / \partial L1$	1	∞
Certificate calibration of sound analyzer for ch 1	$\partial R / \partial L1$	1	∞
Repeatability of L2	$\partial R / \partial L2$	-1	N-1
Readability of sound analyzer associated to L2	$\partial R / \partial L2$	-1	∞
Certificate calibration of sound analyzer for ch 2	$\partial R / \partial L2$	-1	∞
Repeatability of RT_{60}	$\partial R / \partial RT_{60}$	$10 / RT_{60} * \ln(10)$	N-1
Readability of sound analyzer associated RT_{60}	$\partial R / \partial RT_{60}$	$10 / RT_{60} * \ln(10)$	∞
Repeatability of B	$\partial R / \partial B$	1	N-1
Readability of sound analyzer associated B	$\partial R / \partial B$	1	∞
Readability of LDM associated with S	$\partial R / \partial S$	$10 / S * \ln(10)$	∞
Readability of LDM associated with V	$\partial R / \partial V$	$-(10 / V * \ln(10))$	∞
Certificate calibration of sound calibrator		1	∞

DETERMINATION OF EXPANDED UNCERTAINTY

The expanded uncertainty, as the final result of uncertainty calculation, can be determined by multiply the combined uncertainty that has the confidence level is 67%, with a coverage factor (k). Furthermore, there are some guides to obtain k value, and it can be identified on the t-student table or calculating the other parameter that is considered as effective of a degree of freedom that is expressed as ν_{eff} . For the first guide, the table has mentioned that the coverage factor (k) varies in the corresponding confidence level, where it is found that this parameter has the value 1,96 for the confidence level of 95%. Subsequently, the other guide also can be implemented by calculating the effective degree of freedom using the Welch - Satterthwaite formula as follows [8]:

$$\nu_{eff} = \frac{u_c^4(L)}{\sum_{i=1}^N \frac{u_i^4(L)}{\nu_i}} \quad (5)$$

Afterward, k can be calculated using the programmable software for the convenient, wherein this work, a spreadsheet excel is used that has capability to calculate k using the function of TINV(probability; ν_{eff}), where the probability is considered as a level of hesitancy that has the value of 5%, and it is assigned from the normal distribution with the confidence level of 95%. Finally, the expanded uncertainty (U) is determined by using the formula as follow:

$$U = k \cdot u_c(STL) \quad (6)$$

CASE STUDY

In this paper, the case study of evaluation of uncertainty of airborne sound insulation measurement was carried out at the frequency range of 125 Hz – 4000 Hz, where the measurement of the measured parameters and the calculation of STL was applied separately. This measurement was conducted in the laboratory of acoustics and vibration – BSN using the system apparatus and facilities that were set up, as shown in FIGURE 1, and moreover, it consists of:

- White noise generator
- Power amplifier
- Dodecahedron loudspeaker
- Two diffuse field of microphone
- Modular precision sound analyzer
- Two reverberation rooms
- Sample test 1 (sandwich panel)

During the measurement, the alteration of environmental conditions is not significant, where the average values were recorded as 27.2°C and 58%RH for ambient conditions of temperature, and relative humidity, respectively, inside the receiver room. Afterward, the measurement data was taken 20 times for L_1 and L_2 , 12 times for RT_{60} , and 8 times for B. Therefore, details of the evaluation result are shown in TABLE 3 and 4.

The two tables report the complete calculation result of uncertainty measurement for the airborne sound insulation, where TABLE 3 provides the result at the frequency of 125 Hz – 630 Hz, meanwhile the other present from 800 Hz to 4000 Hz. According to these tables, therefore, for the first parameter represented by measurement L inside the source room (L_1), it has components that consist of the repeated measurement, the instrument readability, and the certificate calibration of the same instrument. The former has the standard uncertainty value vary for these frequencies, where the maximum value is found at the frequency of 315 Hz that contributes to its uncertainty is about 0.28 dB, while the minimum value is obtained about 0.04 dB at the frequency of 1250 Hz. Meanwhile, for the second and the third components, their standard uncertainty value is seen to be equal for the corresponding frequencies that are analyzed using B-method.

Subsequently, the second parameter has the same components as the previous parameter, where the measurement of L in the receiver room (L_2) is considered as the top contributor among the corresponding components, and therefore, the maximum and minimum value are obtained at the frequency of 250 Hz and 1600 Hz that supply up to 0.26 dB and 0.03 dB respectively. Meantime, the other associated components also are identified, and their values are equal to the prior parameter.

TABLE 3. The result of uncertainty measurement of airborne sound insulation at the frequency of 125 Hz – 630 Hz

No	Uncertainty Budget		Standard Uncertainty								Unit	
	Parameter	Components	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz		
1	L1	Repeat	0.074	0.182	0.130	0.191	0.276	0.139	0.107	0.097	dB	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	dB
		L ch-1	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	dB
2	L2	Repeat	0.245	0.198	0.184	0.259	0.077	0.064	0.130	0.130	dB	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	dB
		L ch-2	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	dB
3	T2	Repeat	0.018	0.019	0.035	0.064	0.033	0.031	0.024	0.025	s	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	s
4	B	Repeat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	dB	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	dB
5	S	Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	m ²	
6	V	Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	m ³	
7	C	Certificate	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	dB	
Combined uncertainty (dB)			0.229	0.282	0.256	0.304	0.349	0.255	0.237	0.233	dB	
Effective degree of freedom			10.71	30.95	30.56	22.97	40.00	49.59	3.,88	34.95		
Coverage factor			2.23	2.04	2.04	2.07	2.02	2.01	2.03	2.03		
Expanded uncertainty (dB)			0.51	0.58	0.52	0.63	0.70	0.51	0.48	0.47	dB	

TABLE 4. The result of the uncertainty measurement of airborne sound insulation at the frequency of 800 Hz – 4000 Hz

No	Uncertainty Budget		Standard Uncertainty								Unit	
	Parameter	Components	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz		
1	L1	Repeat	0.123	0.145	0.040	0.042	0.054	0.054	0.059	0.076	dB	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	dB
		L ch-1	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	dB
2	L2	Repeat	0.046	0.078	0.085	0.034	0.085	0.117	0.044	0.087	dB	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	dB
		L ch-2	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	dB
3	T2	Repeat	0.015	0.018	0.028	0.018	0.010	0.013	0.007	0.009	s	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	s
4	B	Repeat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	dB	
		Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	dB
5	S	Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	m ²	
6	V	Readability	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	m ³	
7	C	Certificate	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	dB	
Combined uncertainty (dB)			0.241	0.254	0.215	0.213	0.215	0.216	0.215	0.222	dB	
Effective degree of freedom			44.43	46.76	32.03	31.93	31.67	29.33	33.17	35.31		
Coverage factor			2.02	2.01	2.04	2.04	2.04	2.05	2.03	2.03		
Expanded uncertainty (dB)			0.49	0.51	0.44	0.43	0.44	0.44	0.44	0.45	dB	

Therefore, the third parameter that represented by the measurement of reverberation time inside the receiver room (RT_{60}) has the standard uncertainty value tend to go up and down beyond these frequencies, and the maximum value is found at the frequency of 250 Hz also is supplied by the repeatability component that contributes the value as about 0.06 s. In addition, the resolution indicated by the sound analyzer of this parameter is higher than the L measurement, so the value of standard uncertainty for this component is smoother relatively.

Meanwhile, the contribution provided by the background noise parameter is minimum for the repeatability component. However, the readability of this component still assists the uncertainty values.

Additionally, the standard uncertainty that presented that associated with the area of sample test (S), volume of the receiver room (V), and acoustic calibrator (C) have the equal value for the aforementioned frequencies, where they assist value as 0.003 m^2 , 0.003 m^3 , and 0.05 dB respectively.

Finally, the combined uncertainty is calculated using the equation (4), and therefore, the maximum and minimum value is found at the frequency of 315 Hz , and 1600 Hz that put of the values are 0.34 dB and 0.22 dB respectively. Hence, by using the equation (6), the expanded uncertainty is obtained, and its values reach up to 0.70 dB and 0.43 dB for the corresponding frequencies. Furthermore, the effective degree of freedom that is calculated using an excel spreadsheet provides vary for these frequencies, where the obtained values is small relatively that shown in the tables. Consequently, the determined coverage factor is in the range of $2.0 - 2.3$, that means its confidence level is more than 95% , so the calculated of expanded uncertainty tends to be bigger.

CONCLUSION

In this paper, uncertainty measurement of airborne sound insulation using pressure method according to ASTM E413 has been evaluated and analyzed by Research Group for Acoustics and Vibration at laboratory acoustics and vibration-BSN, where it is focused for determination of sound transmission loss (STL) as a major product of this measurement. Furthermore, the determination of an uncertainty budget and other important quantities for the appropriate measurement along with the case study also is discussed in this paper.

From the result, the sources of uncertainty that have a top contribution to the determination of expanded uncertainty is considered as the repeated measurement of the measured parameter such as L_1 , L_2 , and RT_{60} at the frequency range $250 \text{ Hz} - 315 \text{ Hz}$. Meanwhile, the standard uncertainty that is found from the expanded uncertainty of the calibration certificate also influence the final result of this work, where it is supplied by acoustic calibrator and sound analyzer, respectively. Furthermore, the sources obtained from the readability parameter have a slight effect on this result. Therefore, the maximum and minimum value of expanded uncertainty reach up to 0.70 dB and 0.43 dB for the frequency of 315 Hz and 1600 Hz .

However, there are some sources that have been identified related to the sound leakage due to the installation of a sample test and the flanking transmission due to the vibration effect generated from the source room, partition, and other rooms. Therefore, these topics are considered to be discussed in the next publication. In addition, this work is necessary to be compared and validated with another method to evaluate uncertainty measurement using the Monte-Carlo method that gives simplification of the procedure.

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