AN ACOUSTIC MEASUREMENT UNCERTAINTY EVALUATION: CASE STUDY OF ACOUSTIC INSTRUMENT CALIBRATION USING THE PORTABLE CALIBRATION SYSTEM

EVALUASI KETIDAKPASTIAN PENGUKURAN AKUSTIK: STUDI KASUS PADA KALIBRASI ALAT UKUR AKUSTIK MENGGUNAKAN SISTEM MEDIA KALIBRASI PORTABEL

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ABSTRACT

The performance of an acoustic comparison coupler has been demonstrated. By carrying off a dual coupler method, this laboratory prototype is claimed to be utilized further as part of acoustic measurement instrument calibration and designed to support the traceability needs for the appropriate laboratory properly. To complete the requirement of calibration results provided by ISO/IEC 17025 : 2017, an evaluation and analysis of the uncertainty measurement related to this portable calibration system is strongly needed, where it has not been conducted yet. Therefore, this work aims to provide an evaluation and analysis of uncertainty measurement that is associated with sound level meter (SLM) calibration using the acoustic comparison coupler by the aforecited method through the statistical approximation by determining the major quantities such as standard uncertainty, combined uncertainty, and expanded uncertainty in accordance with JCGM - 100 : 2008. Moreover, a case study related to this instrument calibration is also discussed in this paper. This study also utilizes the class-1 of SLM as the reference instrument. Later, the obtained uncertainty values are compared to the established method that uses a multifunction acoustic calibrator in accordance with the acceptance limit values required by IEC 61672-1 : 2013.

Keywords: uncertainty measurement, acoustic comparison coupler, dual coupler method, calibration, sound level meter

ABSTRAK

Performa dari suatu acoustic comparison coupler telah diperkenalkan. Dengan menggunakan metode dual coupler, hasil riset prototipe laboratorium ini diklaim memiliki kemampuan untuk digunakan sebagai sistem kalibrasi instrumen pengukuran akustik dan juga dirancang untuk mendukung kebutuhan ketertelusuran untuk laboratorium yang membutuhkan. Untuk memenuhi persyaratan dari hasil suatu kalibrasi yang diberikan oleh ISO/IEC 17025 : 2017, evaluasi dan *analisis ketidakpastian pengukuran terkait sistem kalibrasi portabel ini sangat diperlukan, dimana hal tersebut belum dilakukan. Oleh karena itu, studi ini bertujuan untuk memberikan evaluasi dan analisis pada ketidakpastian pengukuran yang terkait dengan kalibrasi sound level meter (SLM) menggunakan acoustic comparison coupler dengan metode yang ditentukan melalui pendekatan statistik dengan menentukan besaran utama seperti ketidakpastian standar, ketidakpastian kombinasi, dan ketidakpastian bentangan mengacu pada JCGM - 100 : 2008. Selain itu, studi kasus terkait kalibrasi instrumen ini juga dibahas di sepanjang tulisan ini. Penelitian ini juga menggunakan SLM kelas-1 sebagai instrumen referensi. Kemudian, nilai ketidakpastian yang diperoleh dibandingkan dengan metode yang ditetapkan menggunakan multifunction acoustic calibrator sesuai dengan nilai batas yang dipersyaratkan oleh IEC 61672-1 : 2013.*

Kata Kunci: *ketidakpastian pengukuran, acoustic comparison coupler, metode dual coupler, kalibrasi, sound level meter*

1. INTRODUCTION

The outgrowth and innovation of acoustic devices has shown prompt acceleration over the last years significantly (Risojević et al., 2018). The acoustic measurement instruments including sound level meter (SLM) that is evolved become the smart acoustic hand-held device has been applied widely (Aletta et al., 2020). The user necessity to this instrument also grows up, especially for research institutions, universities, and medical foundations (Dwisetyo et al., 2021). Therefore, a feasible test is necessary to be implemented by comprising the system that has capability to support SLM calibration (Dwisetyo et al., 2020; Rusjadi et al., 2020).

An acoustic portable calibration system has been designed, and therefore, it is known as an acoustic comparison coupler. This system has been developed to comply with the traceability needs and support the implementation of SLM calibration that is dedicated to the industrial laboratory (Listewnik, 2019). The performance has been demonstrated in the preceding paper, and the result states that it has the future prospect to be abused as the calibration system to support the periodic test of the SLM farther (Dwisetyo et al., 2021). However, the evaluation and analysis of the uncertainty measurement produced by SLM calibration system using the acoustic comparison coupler has not been reported yet clearly. Hence, it is necessary to be carried out to identify the system calibration performance deeply.

Therefore, the purpose of this work is to carry out an estimation, evaluation, and analysis of the uncertainty measurement of the SLM calibration system that utilize the acoustic comparison coupler as the portable calibration media. Thereunto, the statistical approximation to determine the major uncertainty parameters such as standard uncertainty, combine uncertainty, and expanded uncertainty is also discussed in accordance with JCGM 100:2008. This work also reports a case study related to SLM calibration, and the result will be compared with the acceptance limit value required by IEC 61672-1 : 2013 (IEC 61672-1 : 2013, 2013).

2. ACOUSTIC COMPARISON COUPLER OVERVIEW

The design purpose of the acoustic comparison coupler is to support SLM and noise dosimeter calibration in the on-site measurement, and therefore, it is considered as a system that has a role as the portable calibration media and stabilized mechanical sound source (Dwisetyo et al., 2021). Design of the acoustic comparison coupler based on the multifunction acoustic calibrator consists the body part and the head part made from solid aluminum cylindrically with density is 2700 kg/m^3 (Listewnik, 2019) (Barwicz et al., 2006). The schematic diagram of this prototype is shown in Figure 1.

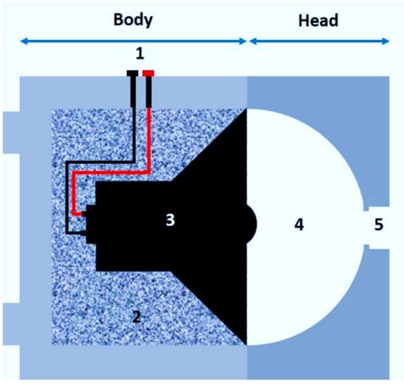

Figure 1. Two-dimensional schematic of acoustic comparison coupler

From this Figure, the body part consists of a low noise connector (1), a sound absorber (2), and a mechanical sound source (3). Meanwhile, the head section of this system consists of a concave space that has the form of a half round (4), and a coupler hole of microphones (5). Furthermore, this portable calibration medium is utilized in consort with some supporting apparatus to perform SLM calibration, where the method and experimental setup is discussed below.

3. METHODOLOGY OF SLM CALIBRATION

Method

The SLM is calibrated using the acoustic comparison coupler by dual coupler method. This method utilizes the pressure standard microphone that is intended for high-precision coupler measurements (Dwisetyo, Rusjadi, Palupi, Putri, et al., 2021). A flat frequency response in a pressure field is achieved using this working standard, and it is appropriate to be used for conducting measurements in a closed couplers, and reflective surfaces (Wu et al., 2005; Fedtke & Grason, 2014; Antônio et al., 2014). In addition, adding an external generator and a sound analyzer is applied as the supporting device.

The calibration of SLM using this method is conducted by determining a reference SPL using an acoustic calibrator at an SPL of 94 dB and a frequency of 1000 Hz. After that, this measured SPL is re-generated by the sound source inside the acoustic comparison coupler to the microphone and SLM simultaneously. In addition, the comparison value of SPL between standard and SLM is indicated at the same time.

Experimental Setup

Therefore, the experimental setup of SLM calibration using dual method is shown in figure 2, figure 3, and figure 4.

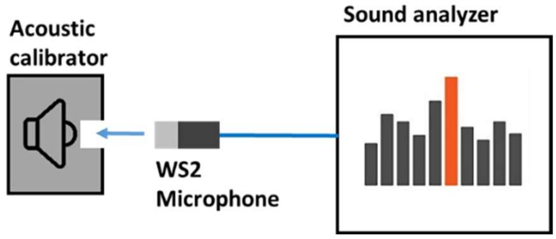

Figure.2. Determining of sound pressure level using acoustic calibrator (Dwisetyo, Rusjadi, Palupi, Putri, et al., 2021)

In the Figure 2, the working standard microphone was put into an acoustic calibrator. The SPL of 94 dB at the frequency of 1 kHz was generated by the calibrator and read by the sound analyzer in a DC voltage unit as the reference value. After that, the microphone was entered into the acoustic comparison coupler, and the system was set so to make it as Figure 3.

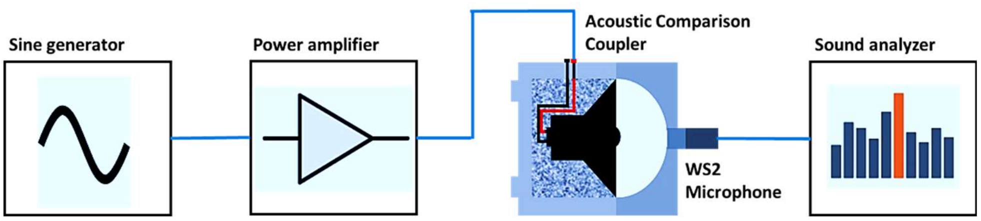

Figure 3. Generating of reference SPL through the sound source (Dwisetyo, Rusjadi, Palupi, Putri, et al., 2021)

Subsequently, by selecting the frequency measurement, organizing the input level, and generating the signal through the generator, the sound analyzer was configured so to make the display read the same value as the reference. Hereafter, a dual coupler was inserted into the acoustic coupler. After that, the microphone and SLM were put into a pair of coupler holes. Thereupon, the apparatus was arranged in order to make the system calibration set as Figure 4.

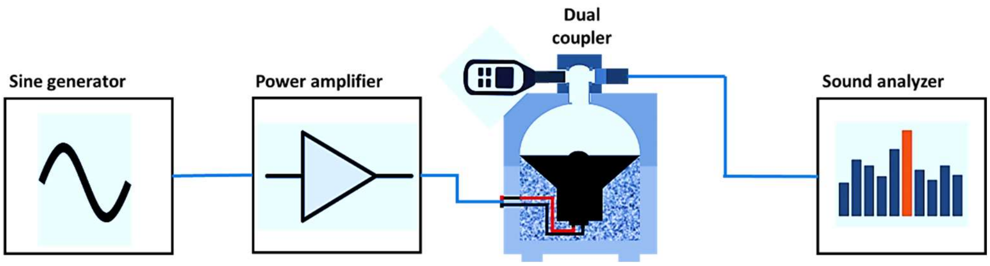

Figure.4. Calibration sound level meter using dual coupler (Dwisetyo, Rusjadi, Palupi, Putri, et al., 2021)

Eventually, the SPL was read by the two instruments at the aforementioned frequencies after generating the acoustic signal from the calibration system.

Apparatus System

In this work, the specifications of equipments that used in SLM Calibration using the acoustic comparison coupler by dual coupler method provided in Table 1.

Table 1. The apparatus system used in the SLM calibration (IEC 61672-1 : 2013, 2013)

Device/Equipment	General Specification
Signal generator (sine generator)	Frequency range 0,1 mHz – 16 MHz, resolution 7 digits, frequency accuracy 10 ppm/year,
Power amplifier	Maximum voltage gain 30 dB, frequency response 20 Hz - 20 kHz, and output impedance 0,03 Ω
The standard microphone	The standard of acoustic measurement.
Sound analyzer	IDAe-based data acquisition front-end hardware.

Later, the estimation of the measurement uncertainty of SLM calibration using acoustic comparison coupler can be determined by investigating the performance prototype, the used method and the calibration equipment system as discussed above.

4. ESTIMATION OF MEASUREMENT UNCERTAINTY

In this study, SLM calibration is conducted using the acoustic calibration system as mentioned above. Furthermore, uncertainty of measurement that produced by this acoustic measurement instrument calibration is determined in accordance with the guide that published by JCGM – 100 : 2008. The stages to estimate the measurement uncertainty consists of determining of a mathematical model, identifying of the uncertainty sources, and evaluation of the statistical uncertainty parameters including a standard uncertainty that contributed by related components, the combined uncertainty that calculated from the accumulation of the uncertainty sources, and the expanded uncertainty that is considered as a single output of estimation of measurement uncertainty of SLM calibration in this work. Hereafter, determination the aforementioned stages is discussed in this paper.

Mathematical Model

The mathematical model of SLM calibration using the acoustic comparison coupler can be defined, where it is expressed as the deviation between the sound pressure level (SPL) that measured by SLM that later is mentioned as SPL_{DUC}, and the SPL that read by the instrument standard that written as SPL_{STD}. Generally, it can be expressed by Equation (1) (Dwisetyo & Hermawanto, 2020).

$$\Delta L = (L_{STD} - L_{DUC}) \ldots\ldots\ldots\ldots\ldots\ldots[1]$$

with:

L_{DUC} is the sound pressure level (L) that measured by SLM

L_{STD} is the sound pressure level that read by the instrument standard

ΔL is the deviation between the sound pressure levels

In addition, these measurement instruments are also produced the correction value as the function of frequency, where it can be determined from the calibration result of the reference instrument, meanwhile for the device under calibration (DUC), it is informed by the manufacturer. Later, these correction values are denoted as δ_{STD} and δ_{DUC} respectively. Accordingly, the mathematical model of SLM calibration is written by equation (2) (Dwisetyo & Hermawanto, 2020):

$$\Delta L = (L_{DUT} + \delta_{DUT}) - (L_{STD} + \delta_{STD})\ldots [2]$$

with:

δ_{STD} is a correction value produced by the reference instrumen

δ_{DUC} is a correction value contributed by DUC

For certain situations, the manufacturer is not assigned the correction value information of SLM test. In this case, it is allowed to be ignored from the Equation (2), or the corrections that given by SLM test is assumed zero. Subsequently, the determination of uncertainty sources can be carried out based on this mathematical model.

Sources of Measurement Uncertainty

According to JCGM-100 : 2008, the source of measurement uncertainty consists of two categories, A-type, and B-type (JCGM - 100 : 2008, 2008). The former is the parameter that can be determined by conducting some measurement series, and therefore, it can be solved with a statistical procedure (JCGM - 100 : 2008, 2008) (Struck, 2017). Meanwhile, the latter is the source that can be acquired through a scientific judgment or other information that is stated has the contribution to provide the uncertainty related to the measurement or calibration (JCGM - 100 : 2008, 2008).

For the case of SLM calibration using the acoustic comparison coupler by dual coupler method that discussed in this study, it is found that the measurement uncertainty source is contributed by the standard instrument, the DUC, and the used calibration system that shown in Figure 3. From the first and second component, the measurement uncertainty budget consists of A-type related to applying measurement series, and B-type also that is taken from physical information that provided by these measurement instruments. Meanwhile, the measurement uncertainty source that assisted by the calibration system is considered as the B-type that also taken from the specification of system and the result of performance test.

Therefore, the Ishikawa diagram can be adopted to determine the uncertainty budgets given by SLM calibration system. By using this diagram, the uncertainty information by that provided the system can be identified conveniently (Hampel et al., 2018). Later, the following are determination of the measurement uncertainty source using the Ishikawa diagram as shown in Figure 5.

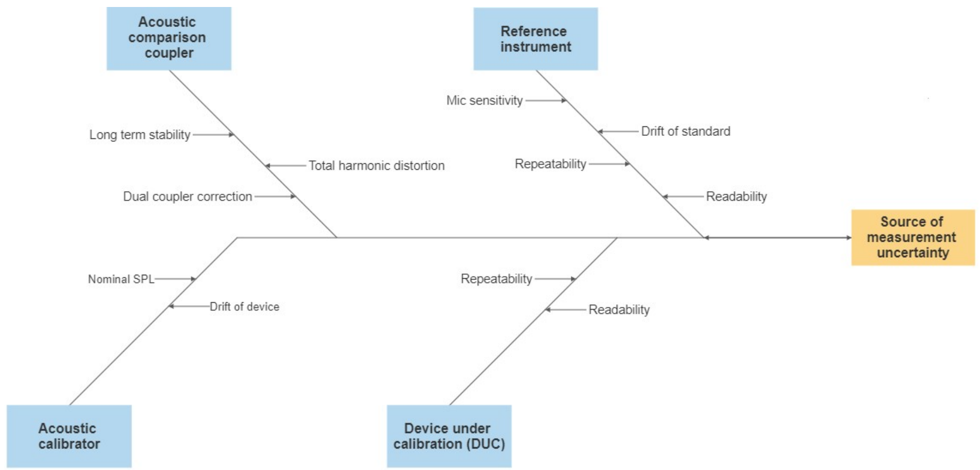

Figure.5. Ishikawa diagram to classify uncertainty budgets

From the Figure shown above, the components of the uncertainty budgets of the calibration method can be prescribed as follow:

- The working standard microphone that is used as the reference instrument provides the uncertainty measurement budget consists of the serial measurement of SPL, the microphone sensitivity that reported by the latest calibration certificate, the drift that produced due to period of use, and readability that can be indicated as the maximum resolution of an acoustic analyzer. The former of uncertainty budget is categorized as A-type. The series number of the measurement of the SPL measured frequencies is 10 times, and therefore, the average value can be obtained. After that, the standard deviation that defined as the data distribution around the average value is calculated later. Meanwhile, others are classified as B-type of uncertainty budget. The secondary microphone is calibrated periodically using the primary standard of acoustic measurement. Afterward, the deviation value can be calculated by comparing the current sensitivity to the previous, where this calculated deviation is decided as the drift of the used standard result is decided to calculate the drift. Further, the sound analyzer is necessary to be used as the supporting device to perform the indication of SPL that detected by the microphone. In this work, the maximum resolution that can be read by the analyzer is 0.001 dB.
- According to the DUC shown by Figure 5, the component consists of the repeated measurement of SPL that measured by the SLM test, and its

readability. The first component is categorized as A-type of the uncertainty source. The number of the SPL data is also 10 times at the corresponding frequencies. Then, the average of data values and the standard deviation of the corresponding data is calculated same as the reference instrument. Meanwhile, the readability of DUC is classified as B-type of uncertainty budget. Further, it depends on the type of SLM used, where the class-1 has the maximum resolution up to 0.01 dB, while the readability that holds by class-2 is 0.1 dB.

- The next parameter is provided by the acoustic calibrator, the stabilized acoustic source that is utilized to adjust the initial SPL of DUC. The uncertainty budget that is produced by this instrument comprises the calibration of a nominal SPL, and the standard drift. The first budget is subsumed as B-type of uncertainty budget. It is obtained from the calibration result using the laboratory standard microphone by insert voltage method. Meanwhile, the second budget also is characterized as B-type of uncertainty budget that the value is taken from the result of measurement through the intermediate check annually using the same standard and method. In addition, the adjustment SPL using this device is applied once before the calibration activities started without N measurement series as mentioned in the standard IEC.
- Subsequently, the last uncertainty budget is contributed by the acoustic comparison coupler, and it consists of the long-term stability, the total harmonic distortion (THD), and dual coupler correction. The former is produced by performing the measurement of calibration system with the duration time of 30 minutes. The performance result in accordance with this component has been reported in the prior paper in the previous publication, where the result of its performance was claimed to be acceptable. Meantime, the THD is obtained by measuring a harmonic distortion that produced by the system at the fundamental frequency particularly. Finally, the latter is determined by applying the serial measurement of SPL using dual coupler, where the correction can be calculated by comparing the SPL value that indicated by the microphone or SLM that put into the two-mic hole. Therefore, these components that are taken from the acoustic comparison performance are

classified as B-type of the uncertainty budget.

Evaluation of Standard Uncertainty

According to JCGM - 100 : 2008, the standard uncertainty is determined by using two manners. The first can be calculated using the statistical approximation of series of measurements. After that, the average of whole measurement data can be determined in conjunction with the standard deviation calculation. Therefore, the number of data (*N*) that acquired from the measurement series has a significant leverage to the data distributions and the measurement result quality. However, the minimum number of measurement data is required by JCGM - 100 : 2008, where for the instrument calibration case the *N* which can be taken is 5 (JCGM - 100 : 2008, 2008). Meanwhile, the second guide that can be conducted to evaluate the standard uncertainty is by observing and justifying the system and environmental that corresponds to the calibration activity, and therefore, this method is applied using statistical analysis. After that, the probability distribution that is associated to the uncertainty sources is used by considering a divisor value. Farther, types of the probability distribution are approximated in the SLM calibration, and determination of the standard uncertainty of the aforementioned components is discussed below.

The determination of standard uncertainty that supplied by the components associated with the standard microphone is as follow:

- The series measurement using the standard instrument (repeatability). it is determined by calculating the standard deviation after taking the data serially, and it can be expressed as follow:

$$Std_{dev} = \sqrt{\frac{1}{N-1}}\sum(SPL_i - \overline{SPL}) \quad ....[3]$$

with,

Std_{dev} is standard deviation of measurement series

L_i is the individual of level measurement,

$\bar{L}$ is the mean value of L measurements using the working reference microphone, and

N is number of the measurement data series at the same physical and required environmental conditions.

Where, SPL_i is the individual of level measurement, while $\overline{SPL}$ is the mean value of SPL measurements using the working reference microphone, and N is number of the measurement data series at the same physical and required environmental conditions. After that, the standard uncertainty of this budget (u_1) can be calculated using the Equation (4).

$$u_1 = \frac{Std_{dev}}{\sqrt{N}} \text{………..…......[4]}$$

with,

u_1 is standard uncertainty that contributed by repeat measurement using the reference instrument

- The calibration of microphone sensitivity provided by the reference instrument. The uncertainty value is taken from the final certificate of calibration with the confidence level is 95%. Therefore, it should use a normal distribution that has divisor of 2, and the standard uncertainty (u_2) calculated as follow:

$$u_2 = \frac{U_{mic\ certificate}}{2} \text{ ……….[5]}$$

with,

u_2 is standard uncertainty that contributed by microphone sensitivity,

$U_{mic\ certificate}$ is uncertainty value taken from the latest calibration certificate of microphone standard

- The drift of the reference instrument. As mentioned above, it is obtained from the annual check, and moreover, there is no additional information related to the distribution and its confidence level. Hence, the appropriate distribution that should be applied to this budget is the rectangle distribution with the divisor is $\sqrt{3}$. Therefore, this uncertainty budget (u_3) can be calculated as follow:

$$u_3 = \frac{U_{mic\ drift}}{\sqrt{3}} \text{ ……………...….[6]}$$

with,

u_3 is standard uncertainty that contributed by drift of microphone sensitivity,

$U_{mic\ drift}$ is uncertainty value taken from the drift measurement of microphone.

- Readability of the standard instrument. It is determined by analyzing its resolution, and therefore, the standard uncertainty of this component (u_2) can be assigned as follow:

$$u_4 = \frac{a}{\sqrt{3}} \text{ ……..………….[7]}$$

with,

u_4 is standard uncertainty that contributed by resolution of the appropriate instrument,

a is a half of DUC resolution, and

$\sqrt{3}$ is used as the divisor for the digital instrument that has uncertainty value with the same probability at the range of minimum and maximum value.

Subsequently, the standard uncertainty that supplied by the components associated with the DUC can be determined as follow:

- The series measurement of SPL using the DUC (repeatability). It is determined by calculating the standard deviation using the Equation (3). After that, the standard uncertainty of this budget (u_5) can be calculated using the Equation (8).

  $$u_5 = \frac{Stdev}{\sqrt{N}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots [8]$$

  with,

  u_5 is standard uncertainty that contributed by repeat measurement using DUC.

- Readability of the DUC. It is determined by analyzing its resolution, and therefore, the standard uncertainty of this component (u_6) can be written as follow:

  $$u_6 = \frac{a}{\sqrt{3}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [9]$$

  with,

  u_6 is standard uncertainty that contributed by resolution of the appropriate instrument

Hereinafter, the standard uncertainty that given by the acoustic calibrator can be calculated including:

The calibration of acoustic calibrator. Similar to the used working standard microphone, the uncertainty value is taken from the latest certificate of calibration with the confidence level is 95%. Therefore, the normal distribution is obtained that has divisor of 2, and the standard uncertainty (u_7) calculated as follow:

$$u_7 = \frac{U_{certificate\ of\ calibrator}}{2} \ldots\ldots [10]$$

with,

u_7 is standard uncertainty that contributed by sound pressure level of sound calibrator,

$U_{calibrator\ certificate}$ is uncertainty value taken from the latest calibration certificate of acoustic calibrator

- The drift of acoustic calibrator. As mentioned above, the appropriate distribution that should be applied to this budget is the rectangle distribution with the divisor is $\sqrt{3}$. Therefore, this uncertainty budget ($u8$) can be calculated as follow:

  $$u_8 = \frac{U_{drift\ of\ calibrator}}{\sqrt{3}} \ldots\ldots\ldots [11]$$

  with,

  u_8 is standard uncertainty that contributed by drift of acoustic calibrator,

$U_{calibrator\ drift}$ is uncertainty value taken from the drift pf calibrator.

Afterward, the standard uncertainty that supplied by the acoustic comparison coupler can be calculated as follow:

- Long-term stability of device. the standard uncertainty according to this component (u_6) can be calculated respectively as follow :

$$u_9 = \frac{U_{stability}}{\sqrt{3}} \quad \text{....................[12]}$$

with,

u_9 is standard uncertainty that contributed by system stability,

$U_{stability}$ is uncertainty value taken from measurement of system stability in a specific period.

- Total harmonic distortion and noise (THD + N). This is a part of calibration of nominal SPL of the reference instrument, and it can be calculated respectively as follow:

$$u_{10} = \frac{U_{THD}}{\sqrt{3}} \quad \text{.....................[13]}$$

with,

u_{10} is standard uncertainty that contributed by harmonic distortion component,

U_{THD} is uncertainty value taken from measurement of THD of system calibration.

- Dual coupler correction. The same step also applied, and it can be calculated as follow:

$$u_{11} = \frac{U_{dual\ coupler}}{\sqrt{3}} \quad \text{..............[14]}$$

with,

u_{11} is standard uncertainty that contributed by dual coupler correction,

$U_{dual\ coupler}$ is uncertainty value taken from deviation L between coupler.

Table 2. Uncertainty budget of SLM calibration using acoustic comparison coupler

Calibration instrument/apparatus	Component	Source	Distribution	Divider
The working standard	SPL measurement	N data series	Normal	N
	Mic sensitivity	Certificate	Normal,CL 95%	2
	Drift	Intermediate check	Rectangle	$\sqrt{3}$

	Readability	Digit resolution	Rectangle	$\sqrt{3}$
The DUC	SPL measurement	N data series	Normal	N
	Readability	Digit resolution	Rectangle	$\sqrt{3}$
Acoustic calibrator	Nominal SPL	Certificate	Normal,CL 95%	2
	Drift	Intermediate check	Rectangle	$\sqrt{3}$
Acoustic comparison coupler	Long-term stability	Measurement	Rectangle	$\sqrt{3}$
	THD	Measurement	Rectangle	$\sqrt{3}$
	Dual coupler cor	Measurement	Rectangle	$\sqrt{3}$

In addition, the principal quantities that consists of sensitivity coefficient for the budgets of uncertainty (c_i), and a degree of freedom (v_i) also is determined. The former describes how the obtained measurand varies with changes in the values of the other parameters. In particular, the alteration of the main measurand produced by a slight shift of another parameter and is given by calculating the partial derivative of the Equation (2) to the input parameter. Therefore, it can be expressed mathematically as follow:

$$c_i = \frac{\partial L}{\partial x_i} \quad \text{..........................[15]}$$

with,

c_i is sensitivity coefficient for the budgets of uncertainty,

$\frac{\partial L}{\partial x_i}$ is partial derivation of L to the appropriate uncertainty components

Meanwhile, the latter depends on the used uncertainty method. It can be calculated by subtracting the measurement of number data (N) with 1 for A-type, while for the other, it is considered to be infinite according to JCGM – 100 : 2008 and an estimation result of the published paper. Therefore, these parameters can be written for A-type and B-type respectively as follow:

$$\nu_i = N - 1 \quad \text{........................[16]}$$

$$\nu_i = \infty \quad \text{........................[17]}$$

with,

v_i is a degree of freedom

Furthermore, the combined standard uncertainty can be calculated using the Equation as follow:

$$u_c{}^2(L) = \sum_{i=1}^{N} c_i{}^2 u_i{}^2 \quad \text{............[18]}$$

with,

u_c is combined uncertainty

From this Equation, coefficient of sensitivity of the budgets is calculated using the Equation (15), where in this work, it is found that this value is 1.

Hence, the combined standard uncertainty with the confidence level is 67% can be written as follow (I.MA.2.06.U-E.2-R.0, 2019):

$$u_c(L) = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 + u_6^2 + u_7^2 + u_8^2 + u_9^2 + u_{10}^2} \quad \text{.........[19]}$$

Determination of Expanded Uncertainty

Later, the expanded uncertainty is calculated by multiplying the combined uncertainty that has with a coverage factor (k). To obtain k value, t-student table can be adopted. Another method can be applied by calculating the degree of freedom effective that 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 effective degree of freedom using Welch - Satterthwaite formula as follow:

$$\nu_{eff} = \frac{u_c^4(L)}{\sum_{i=1}^{N} \frac{u_i^4(L)}{\nu_i}} \quad \text{............[20]}$$

with,

ν_{eff} the degree of freedom effective

Afterwards, k can be calculated using the programmable software for the convenient, where in 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 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:

$$U(L) = k.u_c(L) \quad \text{..............[21]}$$

with,

$U(L)$ is the expanded uncertainty.

Later, this quantity will be compared with the acceptance limit value required by IEC 61672-1.

5. CASE STUDY

This study provides the estimation of uncertainty measurement of SLM calibration using the acoustic comparison coupler by dual coupler method in accordance with IEC 61672-3. The quantity that is calibrated in this work is frequency weighting as the mandatory parameter as mentioned above. Farther, the range of frequency measurement that is decided to be used in this research is the effective frequencies that conformance to a human auditory response, where it is considered at the range of 63Hz ~ 10kHz in an one octave frequency band (Einicke, 2014). Furthermore, the SPL of 94 dB is selected to supply the acoustic signal from acoustic calibrator and the installed mechanical sound source of acoustic comparison coupler, where this SPL value is equivalent to 1 Pa.

The reference instrument that is abused in this case is the working standard microphone with the specification mentioned in Table.1. To espouse the calibration system, an external generator and the power amplifier are selected as the initial electrical signal system that its performance has been tested and reported in the previous paper. Later, a class-2 of SLM is used as the DUC to verify their feat relative to the limit tolerance provided by the standard IEC. Furthermore, this study also utilizes class-1 of SLM as the reference instrument that is appropriate to be used by the industrial field. After that, analyzing the uncertainty measurement that associated with this SLM is needed.

The first case study is applying the SLM calibration that was conducted in a laboratory of acoustics and vibration – National Standardization Agency of Indonesia (BSN) using the system apparatus as described in Figure 2, Figure 3, and Figure 4. During the calibration, there was no alteration of environmental conditions, where it was recorded as 24.7 ˚C, 65 %RH, and 100.0 kPa for ambient conditions of temperature, relative humidity, and air pressure respectively. The data was taken 10 times for the corresponding frequencies, where the details of the result are shown in Table 3.

Table 3. Calculation result of measurement uncertainty of SLM calibration (case study 1)

Instruments/ Apparatus	Uncertainty component	Relative standard uncertainty (dB)								
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHZ	2 kHz	4 kHz	8 kHz	10 kHz
The reference instrument	Repeatability	2.E-05	3.E-05	2.E-05	4.E-05	3.E-06	3.E-05	3.E-05	4.E-05	5.E-05
	Sensitivity	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	1.E-01	1.E-01	1.E-01	1.E-01
	Drift	6.E-03	6.E-03	6.E-03	6.E-03	6.E-03	6.E-03	6.E-03	6.E-03	6.E-03
	Readability	3.E-04	3.E-04	3.E-04	3.E-04	3.E-04	3.E-04	3.E-04	3.E-04	3.E-04
Device under test (DUT)	Repeatability	4.E-02	6.E-02	4.E-02	4.E-02	3.E-02	2.E-02	3.E-02	4.E-02	9.E-02
	Readability	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02
Acoustic calibrator	Nominal SPL	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02
	Drift	4.E-02	4.E-02	4.E-02	6.E-03	4.E-02	3.E-02	2.E-02	2.E-02	3.E-02
	Stabilitas	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02
	THD	9.E-03	2.E-02	2.E-02	2.E-02	2.E-02	9.E-03	2.E-02	3.E-02	3.E-02

Acoustic comparison coupler	Dual coupler cor	6.E-02	6.E-02	6.E-02	9.E-02	9.E-02	9.E-02	1.E-01	1.E-01	1.E-01
Combined uncertainty		**1.E-01**	**1.E-01**	**1.E-01**	**1.E-01**	**1.E-01**	**2.E-01**	**2.E-01**	**2.E-01**	**2.E-01**

From the components that contributed by the standard of microphone, the series of SPL measurement supply the minimum of the standard uncertainty where the value tends to be varying and it has a tendency to be higher at the high frequency. It shows that the repeating of SPL measurement using this instrument is relatively stable. Meanwhile, the microphone sensitivity values that reported by the latest calibration certificate produces the standard uncertainty maximum at the same frequencies. A similar condition also is found in this component, where the uncertainty value at the higher frequency tends to be bigger instead of other working frequencies. Hereinafter, the drift of the standard microphone and the device resolution that also property of the acoustic analyzer tends to be constant at this range of frequencies. Subsequently, the standard uncertainty is also determined that is contributed by the DUC, where the repeat measurement and the display resolution have similar values whole frequencies. Passingly, the acoustic calibrator offers the value of standard uncertainty that originated from the nominal SPL of calibration certificate and its routine usage that gives the constant value relatively. Hereafter, the last uncertainty component that also contributes to the SLM calibration is the acoustic comparison coupler. From this item, the dual coupler correction is slightly considered as the highest contributor in this calibration method, where the obtained deviation between SPL that read by the two instruments using this acoustic converter at the same time tends to be bigger at the high frequency. Meanwhile, the long-term stability that is performed by this device is relatively steady at the corresponding frequencies, and therefore, it is shown by the table that informs a constant of standard uncertainty value at the same frequency range. Meantime, the THD of this device also contributes to the SLM calibration that provides no alteration of the obtained standard uncertainty.

Thereafter, the expanded uncertainty is determined after calculating the standard uncertainty of the contributed components, and therefore, the result that associated with this statistical quantity is described in Figure 6.

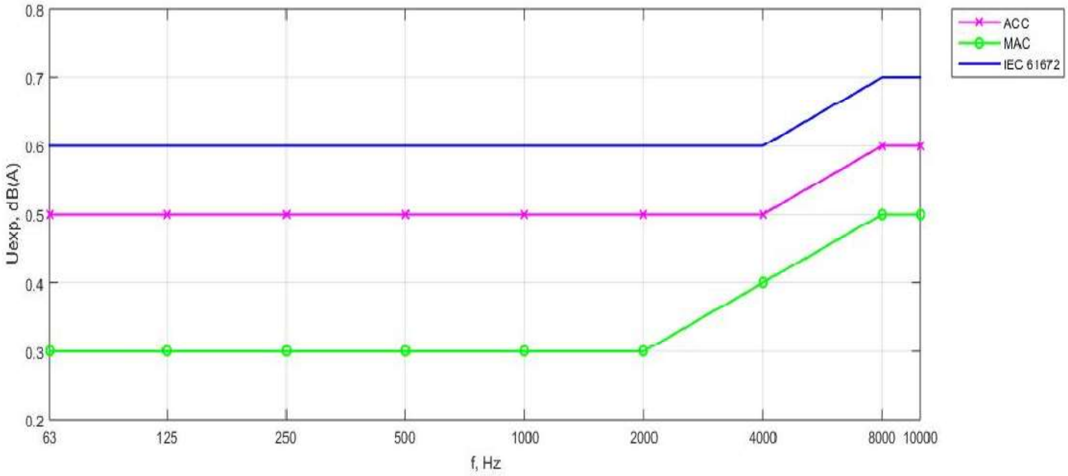

Figure 6. Determination of the expanded uncertainty of SLM calibration for case study 2

The expanded uncertainty that contributed by the acoustic comparison coupler using the standard microphone is represented by the red cross solid line, while the green circle solid line describes the expanded uncertainty of SLM calibration using the multifunction acoustic calibrator as the reference instrument, where the detail result has been proposed and reported in the previous paper. From the Figure, the uncertainty values that are provided using the two-calibration system are equal at the frequency of 63 Hz to 1000 Hz. After that, the value produced by acoustic comparison coupler is higher than other at the frequency of 2000 Hz that the calculated value is up to 0.4 dB. Afterward, the two values back to being equal at the next frequency. In contrast to the multifunction calibrator, where it provides the higher value than the former system that supplies the uncertainty value is up to 0.5 dB at the frequency of 8000 Hz. Finally, the two methods produce the same value at the last frequency. Moreover, the expanded uncertainty that is determined from these calibration systems is lower than the minimum uncertainty that required by the standard IEC that represented by a blue solid line in Figure 6. Therefore, utilization of the working standard microphone that combined with the acoustic comparison coupler provides an acceptable result.

Later, the next case study is applying the SLM calibration that was conducted using the system apparatus as mentioned in Figure 3, and Figure 4, and substituting the working standard microphone to the standard SLM and removing the sound analyzer. In this second study, the environmental conditions that monitored is steady relatively, where it was recorded as 25.3 ˚C, 67 %RH, and 100.0 kPa. Next, the details of the result are shown in Table 4.

Table 4. Calculation result of measurement uncertainty of SLM calibration (case study 2)

No	Instruments/ Apparatus	Uncertainty component	Type	Relative standard uncertainty (dB) 63 Hz	125 Hz	250 Hz	500 Hz	1 kHZ	2 kHz	4 kHz	8 kHz	10 kHz
1	Class-1 of SLM	Repeatability	A	4.E-03	3.E-03	4.E-03	3.E-03	3.E-03	5.E-03	5.E-03	6.E-03	6.E-03
		SPL	B	2.E-01	2.E-01	2.E-01	2.E-01	2.E-01	2.E-01	2.E-01	2.E-01	2.E-01
		Drift	B	1.E-01	1.E-02	1.E-02	1.E-02	1.E-02	1.E-03	1.E-02	1.E-02	1.E-02
		Readability	B	3.E-03	3.E-03	3.E-03	3.E-03	3.E-03	3.E-02	3.E-03	3.E-03	3.E-03
2	DUC	Repeatability	A	5.E-02	6.E-02	5.E-02	4.E-02	4.E-02	3.E-02	3.E-02	9.E-02	1.E-01
		Readability	B	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02	3.E-02
3	Acoustic calibrator	Nominal SPL	B	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02	5.E-02
		Drift	B	4.E-02	4.E-02	4.E-02	6.E-03	4.E-02	3.E-02	2.E-02	2.E-02	3.E-02
4	Acoustic comparison coupler	Stabilitas	B	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02	4.E-02
		THD	B	9.E-03	2.E-02	2.E-02	2.E-02	2.E-02	9.E-03	2.E-02	3.E-02	3.E-02
		Dual coupler correction	B	6.E-02	6.E-02	6.E-02	9.E-02	9.E-02	9.E-02	1.E-01	1.E-01	1.E-01
	Combined uncertainty (dB)			**2.E-01**	**2.E-01**	**2.E-01**	**2.E-01**	**2.E-01**	**2.E-01**	**2.E-01**	**3.E-01**	**3.E-01**

In this case study, the standard uncertainty that contributed by the standard SLM is highest relatively instead than other components at the aforementioned frequencies. Meanwhile, the drift of this standard SLM also provides high value at the same frequencies. Again, the device resolution of the standard SLM tends to be constant at this range of frequencies, while for the repeat measurement provides the value that tends to go up and down at the corresponding frequencies.

Subsequently, the standard uncertainty is also determined from the DUC, where the readability of the instrument test have similar values as the previous case study at whole frequencies, while the measurement series supply the uncertainty value that also go up and down. Passingly, the acoustic calibrator and the acoustic comparison coupler offer the same value of standard uncertainty as the prior case study.

Thereafter, the expanded uncertainty is determined after calculating the standard uncertainty of the contributed components, and therefore, the result that associated with this statistical quantity is described in Figure 7.

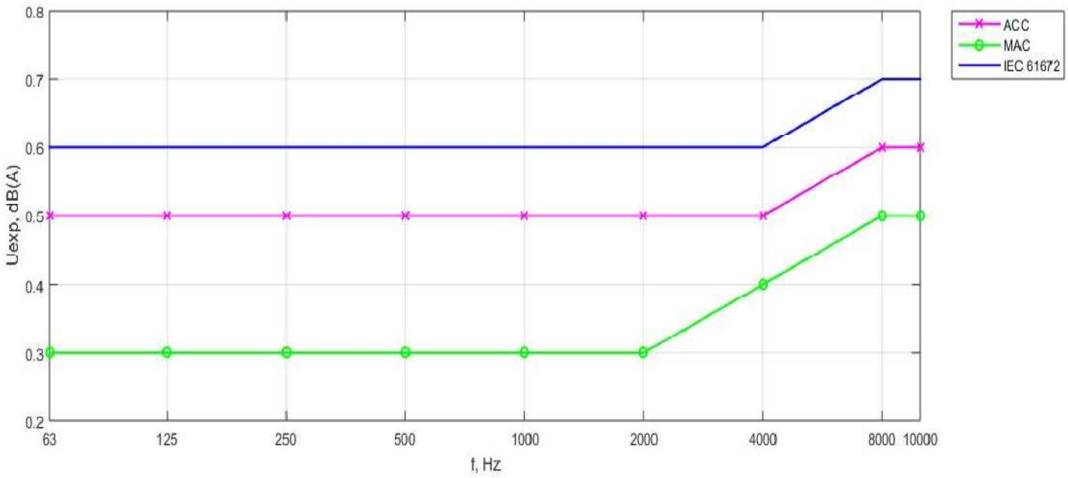

Figure.7. Determination of the expanded uncertainty of SLM calibration for case study 2

The expanded uncertainty that contributed by the acoustic comparison coupler using the standard SLM is represented by the magenta cross solid line. From the Figure, the uncertainty values that are provided using the calibration system are higher than by utilizing the multifunction acoustic calibrator at the range of frequencies. However, the uncertainty that determined using this system is still lower than the minimum uncertainty value that required by the standard IEC as seen in Figure 7. Therefore, utilization of the standard SLM that combined with the acoustic comparison coupler is acceptable.

Nevertheless, the system can be adopted to calibrate class-2 of SLM or lower class, and it is considered to be applied for the industrial scale.

6. CONCLUSION

The evaluation of uncertainty measurement of SLM calibration using the acoustic comparison coupler by dual coupler method has been conducted. Besides, the determination of an uncertainty budget, and other important attributes also have been provided.

The utilization of the working standard microphone that combined with the acoustic comparison coupler provides better result. However, utilizing the class-1 of SLM is also allowed to calibrate class-2 of SLM or lower class according the calibration result discussed above. This result also has shown that the obtained expanded uncertainty values in this work are acceptable, and therefore, this calibration system is reasonable to be proposed for the industrial scale.

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