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ORIGINAL PAPER

Measurement Uncertainty in Microphone Free-Field Comparison Calibrations

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Abstract: The present study demonstrates the use of a transportable anechoic chamber for conducting microphone free-field calibrations with lowest levels of uncertainty. A dedicated transportable anechoic chamber (make SPEKTRA, Germany) of internal volume of 2 m^3 completely lined with wedge-shaped absorbers is utilized for free-field calibrations in the frequency range of 125 Hz–20 kHz using the substitution method as per the IEC 61094-8 standard. The study has identified the usable working space inside a free-field chamber using the inverse-square pressure law, and the deviations from the inverse-square law of the free-field chamber are quantified. The measurement uncertainty of ± 0.36–0.52 dB (k = 2, 95% confidence level) is evaluated in the frequency range of 125 Hz–20 kHz and is validated in a bilateral comparison. The application of Monte Carlo simulation approach in the evaluation of measurement uncertainty in microphone free-field calibrations is also demonstrated.

Keywords: Microphone free-field calibration; Monte Carlo simulation (MCS); Law of propagation of uncertainty (LPU)

1. Introduction

Free-field microphones are generally used in outdoor measurements, and thus, the demand for free-field microphone calibrations is high. The absolute free-field sensitivity is measured using the well-known reciprocity method which can be realized by National Metrology Institutes (NMIs) only. The secondary method involves the comparison calibration of microphone under calibration with a reference microphone when exposed to same sound pressure in a free field or by utilizing the free-field corrections for estimating the free-field sensitivity without calibrating the microphone in free field. The comparison calibration can be done by measuring the ratio of output voltages either sequentially or simultaneously [1]. The modulus of ratio of free-field sensitivity to the pressure sensitivity expressed logarithmically is called the free-field correction [2]. The difference between the free field and pressure response depends dominantly on the dimension of the microphones and on the acoustic impedance of the diaphragm that varies a little from unit to unit [3].

An accurate and precise determination of the free-field correction can only be obtained by the primary method of reciprocity technique or by using comparison calibration method. A major requirement for this type of calibration is an anechoic chamber which is quite expensive especially for the industrial units, automotive, space and defence sector. Thus, utilization of a dedicated transportable anechoic chamber for microphone free-field comparison calibrations can be an optimized solution in this regard.

The present study discusses the methodology and measurement uncertainty in free-field microphone calibrations by a comparison method with the following objectives:

- presents a novel implementation of a small transportable anechoic chamber of internal volume of 2 m^3 for conducting microphone free-field calibrations using the substitution method as per the IEC 61094-8 standard with lowest levels of uncertainty,
- analyses the invalidations of free-field assumptions caused due to reflections from the walls of chamber,
- provides a comparison of the uncertainty evaluated in microphone free-field comparison calibration using the law of propagation of uncertainties (LPU) approach and Monte Carlo simulation (MCS) approach.

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2. Free-Field Calibration Set-Up and Methodology

The free-field calibration set-up described here meets the requirement of the IEC 61094-8 standard [4]. When a traceable reference microphone and a microphone under calibration are exposed to the same free-field sound pressure sequentially and under the same environmental conditions, the ratio of their free-field sensitivities for those conditions is given by the ratio of their open-circuit voltages. The free-field sensitivity level (L_{DUC}) of the device under calibration (DUC) re 1 V/Pa can be obtained as follows [1]:

$$L_{\mathrm{DUC}} = L_{\mathrm{REF}} + \Delta_M \quad (1)$$

where L_{REF} is the free-field sensitivity level of the reference microphone and

$$\Delta_M = 20\log_{10}\frac{|U_{\mathrm{DUC}}|}{|U_{\mathrm{REF}}|} \quad (2)$$

where U_{DUC} and U_{REF} are the open-circuit output voltages of the DUC and reference microphone.

2.1. Transportable Small Anechoic Chamber

Figure 1 shows the pictures of the small anechoic chamber developed by M/s SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany, installed at M/s Fluid Control Research Institute (FCRI), Palakkad, Kerala, India. The outside dimensions of the chamber are 2 m × 2 m × 2.4 m, and it can be easily disassembled or shifted by means of small trolleys put underneath. The walls are made of lightweight sandwich panel (aluminium sheet with polyurethane foam filling). The entire inner surface of the chamber is completely lined with wedge-shaped absorbers of polyurethane foam material of length 35 cm cemented to the walls and ceiling as put on to the bottom surface.

The lower cut-off frequency of this chamber derived in theory from its dimensions and the characteristics of the

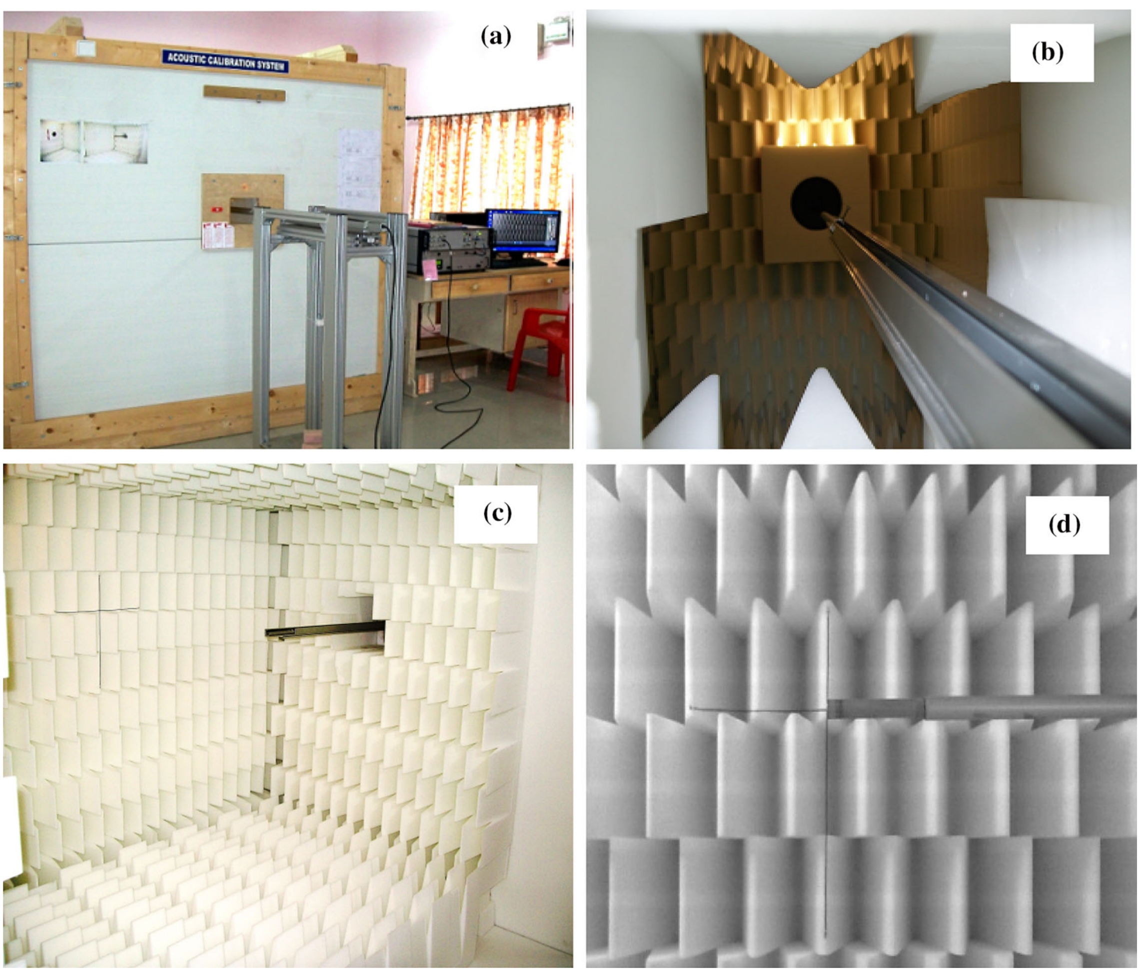

Fig. 1 **a** Photograph of free-field microphone calibration set-up; **b**, **c** anechoic chamber facility; **d** microphone positioning indication shown in a camera for free-field microphone calibration facility at FCRI, Palakkad

materials used for lining the chamber is 250 Hz. The access to the chamber is through two cut-outs on either side that are closed by two appropriately sized removable adaptor panels. The panel on the one side carries the loudspeaker used for generating the calibration signal, and panel on the other side is lined with absorbers inside. It has a hole through which the microphone with its holding fixture is introduced into the chamber [5, 6].

2.2. Calibration Set-Up

The calibration set-up consists of a free-field chamber, a stable sound source, a power amplifier, controller, computer, thermo-hygrometer, barometer and a reference microphone, as shown in Fig. 2. The electronic control unit is used for generating the excitation signal and for processing the measuring signals. This unit has two microphone inputs for reference standard and device under calibration (DUC) which accept all common type of measuring microphones. The power amplifier included in the system supplies the electric power that drives the loudspeaker in the chamber. The external computer is for controlling the operations and for recording the results. Thermo-hygrometer and barometer are for monitoring the environmental conditions and used to confirm their compliance with the required reference conditions. The present system utilizes the Calibration System CS18 (Model No. CS18 FF) developed by M/s SPEKTRA, Germany, that includes Vibration Control System SRS 35 for generating the excitation signal and for processing the measuring signals [5–7]. The system is in-housed in Noise and Vibration Laboratory of M/s Fluid Control Research Institute (FCRI), Palakkad, Kerala, India, which is a NABL (National Accreditation Board for Testing and Calibration Laboratories, India)-accredited laboratory [8] of India. The measurements were done in controlled environment in the Noise and Vibration Laboratory with room temperature, relative humidity and static pressure in the range of (23 ± 2) °C, (50 ± 10)% R.H and (101.325 ± 3) kPa, respectively.

Substitution calibration describes the process where reference microphone is first used to determine the sound pressure at specific point inside a free field and is then replaced by microphone under calibration. The acoustic centres of the two microphones can be located at the same point in the sound field. In order to confirm the microphone position inside the chamber, 2 USB cameras are placed on one side of the chamber, which can be viewed in the monitor.

3. Departure from Free-Field Characteristics

In a free field, the sound pressure is governed by the inverse-square distance law [9]. The sound pressure in a free field drops off proportional to inverse square of

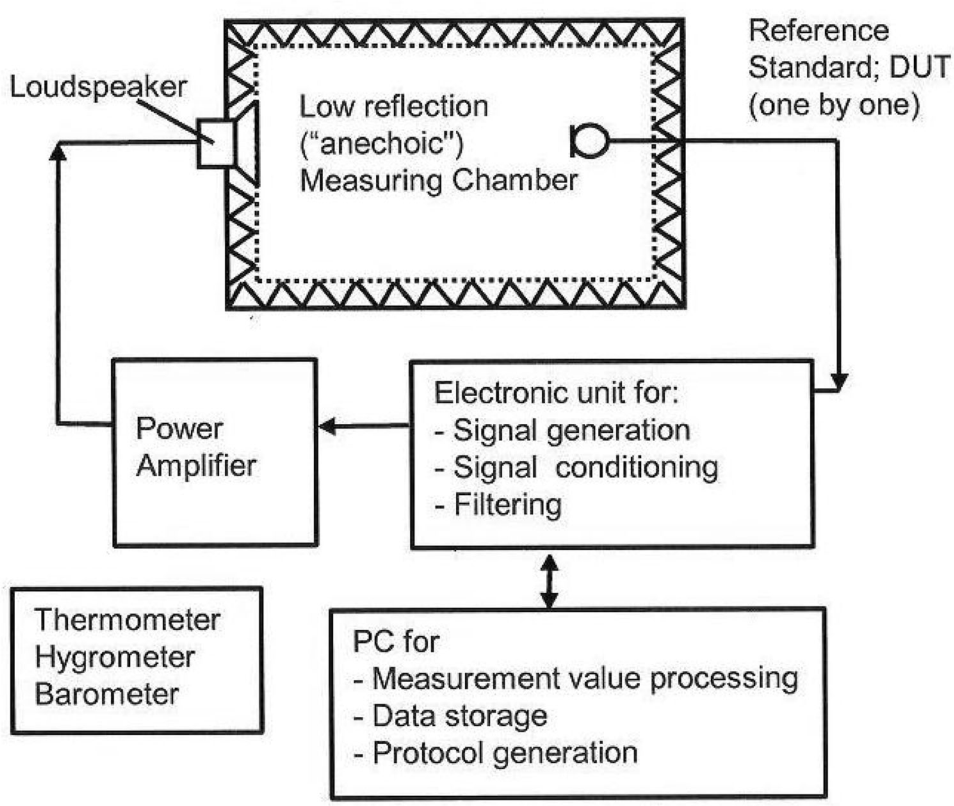

Fig. 2 Block diagram of free-field microphone calibration set-up [5]

Table 1 Maximum allowable deviations of measured sound pressure levels from theoretical levels using the inverse-square law for anechoic chamber as per ISO 26101:2012 [10]

Type of test environment	One-third octave band frequency Hz	Allowable deviations (in dB)
Anechoic	≤ 630	± 1.5
	800–5000	± 1.0
	≥ 6300	± 1.5

distance, and the verification procedures are governed by ISO 26101 [10]. This study is focused to find out the deviations from the inverse-square law of the free-field chamber. Table 1 shows the maximum allowable deviations as recommended in ISO 26101:2012 [10]. The deviation is measured using the following equations:

$$L(x) = L(x_0) - 20\log\left(\frac{x}{x_0}\right)\text{dB} \quad (3)$$

where $L(x)$ is the sound pressure level at distance x estimated by the inverse-square law, $L\ (x_o)$ is the sound pressure level at the measured distance x_o, x_0 is the reference value of distance from the loudspeaker and x is the distance of measurement point from the front of loudspeaker. The deviations from the inverse-square law can be calculated as follows [9, 10]:

$$\Delta L_{(x)} = L_{(x,i)} - L_{(x)} \quad (4)$$

where $\Delta L_{(x)}$ is the deviation from the inverse-square law (in dB), $L_{(x,i)}$ is the measured sound pressure level at measurement point i (in dB) and $L_{(x)}$ is the sound pressure level at distance x estimated by the inverse-square law.

In order to ascertain the deviations from the free-field characteristics and verify the conformance to the ISO 26101 standard, *a* ½” measuring microphone (model B&K 4191 with ½” Microtech Gefell Gmbh, MV 203 preamplifier) was used to determine the sound pressure level in the anechoic chamber as a function of distance between microphone and loudspeaker front, with the acoustical excitation kept constant. Measurements were taken at all standardized third octave band frequencies between 125 Hz and 20 kHz.

3.1. Axial Direction

Axial direction measurement covered the range of distance from 64 cm to 114 cm as shown in Fig. 3. The distances marked are distances between loudspeaker front and microphone position. The sound pressure level was measured in the anechoic chamber as a function of distance between microphone and loudspeaker front with the acoustical excitation kept constant. The deviations from the inverse-square law were calculated at all the standardized third octave band frequencies ranging between 125 Hz and 20 kHz in the tested range of distance of 64–114 cm. Figure 4a–c shows the deviations from the inverse-square law in low-frequency range from 125 to 630 Hz; middle-frequency range from 800 Hz to 5 kHz; and high-frequency range from 6.3 to 20 kHz. These deviations are compared with the allowable deviations recommended in the ISO 26101 standard [10]. Table 2 shows the deviation of measured sound pressure level from the inverse-square law in distance range between 64 and 114 cm. It can be observed in Fig. 4a that in lower-frequency range from 125 to 630 Hz, the deviations between 79 and 89 cm are within ± 1.5 dB limits. The maximum deviation of 1.1 dB was observed at 0.89 m at the frequency of 125 Hz in the measurement frequency range of 125–630 Hz. Figure 4b shows the deviations in measurement frequency range of 800 Hz–5 kHz. It was observed that the deviations were within ± 1.0 dB in the frequency range of 800 Hz–5 kHz. The maximum deviation of 0.5 dB was observed at 800 Hz at a distance of 0.89 m. Figure 4c shows the deviations in measurement frequency range of 6.3–20 kHz. It was observed that deviations were within ± 1.5 dB in this range. The maximum deviation of 0.3 dB was observed at 12.5 kHz at a distance of 0.79 m.

Fig. 3 Axial measurement positions in the range of 64–114 cm

Thus, comparing the deviations obtained in Fig. 4a–c with the allowable deviations in Table 1, the axial working space between 0.79 and 0.89 m truly complies with the free-field requirements. It was thus inferred that 0.84 m can be taken as the reference point since it is almost the axial centre of the chamber, taking the axis with respect to loudspeaker’s centre, and the observed deviations are minimal at this position as shown in Table 2.

3.2. Radial Direction

For a sphere of 1 cm radius centred at 0.84 m from loudspeaker, microphone readings were taken at top, bottom, right and left 1 cm distance points from centre as shown in Fig. 5a. The same microphone was kept at different positions for calculating difference between sound pressure level at each position and the sound pressure level at 0.84 m, which is considered as the reference. The

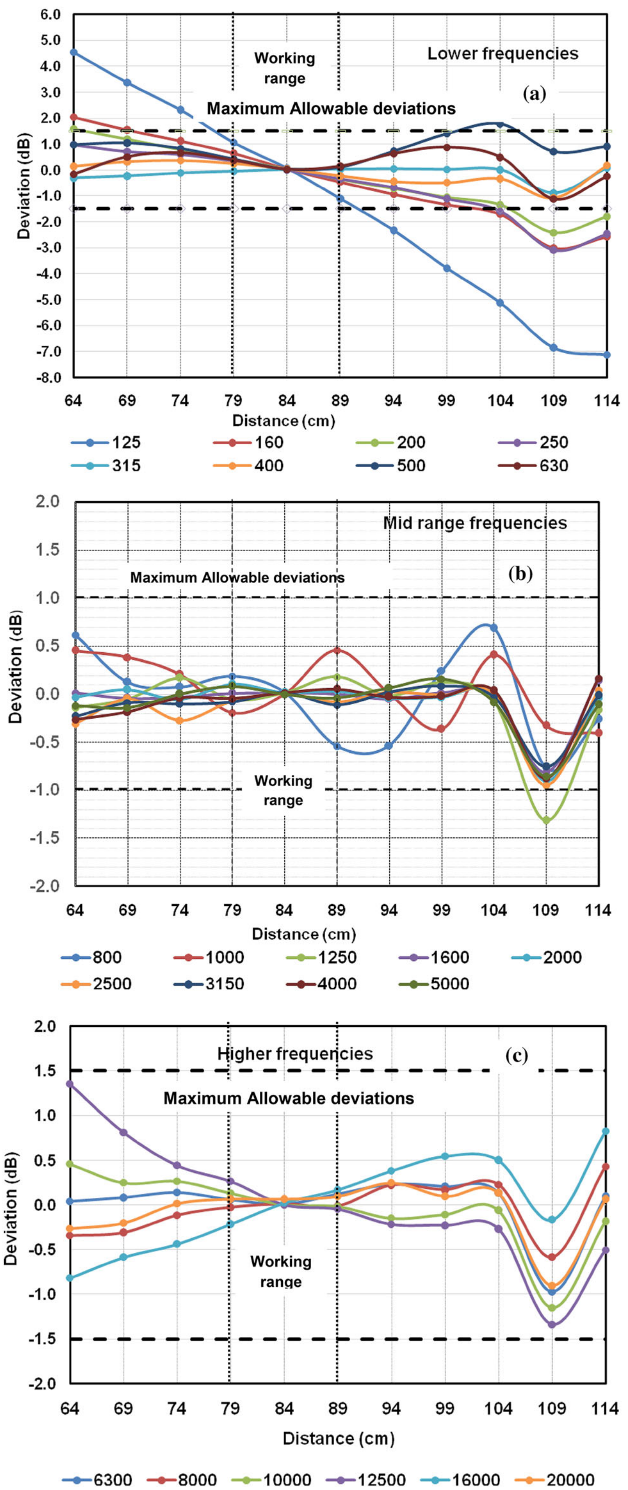

Fig. 4 Deviations from the inverse-square pressure law, **a** low-frequency range up to 630 Hz; **b** middle-frequency range of 800 Hz to 3.15 kHz; **c** high-frequency range of 6.3–20 kHz

difference in sound pressure level at each third octave bands is shown in Fig. 5b. It is inferred that the maximum deviation of 0.5 dB is observed at 12.5 kHz on the top position, while the maximum deviation of 0.4 dB is observed at 125 Hz for an axial distance of 0.83 m and 0.29 dB at 125 Hz for an axial distance of 0.85 m. Between 250 and 8000 Hz, the deviations were ≤ 0.2 dB. Below 250 Hz, the deviations were observed to be little higher. With the wedge size of 35 cm, the chamber cut-off frequency is 250 Hz. Hence, between 125 and 250 Hz, the maximum deviation of 0.4 dB was observed at 0.83 m position. However, above 8000 Hz, the deviations were lower for axial points 0.83 m and 0.85 m.

Sound pressure level measurements were taken on a cylinder of radius 1 cm and length 5 cm as shown in Fig. 6a. At each axial distance from 0.815 to 0.865 m considering a circle of radius 1 cm, the microphone readings were taken at top, bottom, right and left 1 cm distance points from centre. The deviations from the inverse-square law were observed to be within the limits recommended in Table 1. As an example, plot of 86.5 cm which is farthest from loudspeaker is shown in Fig. 6b. The maximum deviation of 0.63 dB is observed at right position at 125 Hz. The maximum deviations of 0.58 dB at 125 Hz and 0.30 dB at 1 kHz were measured at the centre position, while the deviation in the entire measurement frequency range of 125 Hz–20 kHz for all other one-third octave bands is less than 0.30 dB. Thus, the analysis of deviations shown in Figs. 5 and 6 in radial position again suggests that the axial centre can be taken as reference position taking the axis with respect to loudspeaker's centre and the observed deviations were less than 0.58 dB in the measurement frequency range of 125 Hz–20 kHz as shown in Fig. 6b.

4. Measurement Uncertainty

4.1. Using Law of Propagation of Uncertainties (LPU) Approach

The measurement uncertainty is evaluated using the law of propagation of uncertainties (LPU) approach as described by *Guide to the Expression of Uncertainty in Measurement* (GUM) [11]. The sensitivity of the reference standard microphone is the pivotal factor in free-field calibration of working standard microphones. The reference standard microphone B&K 4180 was secondarily calibrated by M/s SPEKTRA at a temperature of (23 ± 1) °C with an expanded uncertainty ranging from 0.25 dB to 0.40 dB in the frequency range of 125 Hz–20 kHz [12]. Figure 7 shows the sensitivity of the reference standard microphone B&K 4180 (S. No. 2889868) with preamplifier 2669 (S. No. 2177781) used as reference. The standard uncertainty is calculated from the expanded uncertainty divided by the

Table 2 Deviations of the measured sound pressure level from the inverse-square law (in dB) in the distance range between 0.64 and 1.14 m

Frequency (Hz)	0.64 m	0.69 m	0.74 m	0.79 m	0.84 m	0.89 m	0.94 m	0.99 m	1.04 m	1.09 m	1.14 m
125	4.52	3.36	2.31	1.05	0.06	− 1.11	− 2.34	− 3.80	− 5.13	− 6.86	− 7.13
160	2.03	1.54	1.12	0.64	0.03	− 0.47	− 0.94	− 1.34	− 1.72	− 3.01	− 2.57
200	1.58	1.19	0.78	0.40	0.03	− 0.37	− 0.72	− 1.06	− 1.36	− 2.43	− 1.81
250	0.97	0.72	0.61	0.35	0.01	− 0.34	− 0.68	− 1.11	− 1.60	− 3.09	− 2.47
315	− 0.31	− 0.23	− 0.12	− 0.05	0.02	0.03	0.05	0.03	0.01	− 0.90	0.09
400	0.14	0.32	0.36	0.24	0.04	− 0.23	− 0.45	− 0.49	− 0.34	− 1.07	0.18
500	0.97	1.04	0.82	0.42	0.03	0.11	0.73	1.39	1.77	0.71	0.91
630	− 0.16	0.51	0.66	0.37	0.02	0.15	0.63	0.87	0.49	− 1.12	− 0.25
800	0.62	0.13	0.08	0.19	0.02	− 0.54	− 0.53	0.25	0.69	− 0.76	− 0.26
1000	0.46	0.39	0.21	− 0.19	0.01	0.46	0.01	− 0.36	0.41	− 0.33	− 0.40
1250	− 0.14	− 0.05	0.17	− 0.05	0.01	0.18	− 0.01	0.13	− 0.07	− 1.32	− 0.17
1600	0.02	− 0.04	− 0.03	0.01	0.01	0.00	− 0.05	0.02	0.00	− 0.81	0.15
2000	− 0.03	0.05	− 0.05	0.11	0.01	0.03	− 0.04	− 0.03	0.01	− 0.90	− 0.04
2500	− 0.31	− 0.05	− 0.27	− 0.07	0.01	− 0.08	0.02	− 0.01	0.00	− 0.95	0.04
3150	− 0.23	− 0.09	− 0.10	− 0.08	0.01	− 0.11	0.02	0.09	− 0.03	− 0.76	− 0.01
4000	− 0.26	− 0.18	− 0.04	− 0.04	0.01	0.05	− 0.03	0.02	0.04	− 0.87	0.17
5000	− 0.12	− 0.14	0.00	0.08	0.00	− 0.04	0.07	0.16	− 0.08	− 0.85	− 0.11
6300	0.04	0.08	0.14	0.06	0.02	0.12	0.23	0.21	0.14	− 0.97	0.10
8000	− 0.34	− 0.31	− 0.12	− 0.03	0.00	− 0.01	0.22	0.17	0.23	− 0.58	0.43
10,000	0.46	0.25	0.27	0.13	0.10	− 0.02	− 0.15	− 0.11	− 0.06	− 1.15	− 0.18
12,500	1.35	0.81	0.44	0.26	0.00	− 0.05	− 0.22	− 0.23	− 0.27	− 1.34	− 0.50
16,000	− 0.82	− 0.59	− 0.44	− 0.22	0.01	0.17	0.38	0.54	0.50	− 0.17	0.82
20,000	− 0.26	− 0.20	0.02	0.07	0.06	0.10	0.25	0.10	0.14	− 0.90	0.07

coverage factor mentioned in the calibration certificate of the reference microphone.

Figure 8 shows the cause-and-effect analysis diagram for factors affecting the microphone sensitivity (in dB re 1 V/Pa) measured using the free-field comparison method. The error in voltage ratio measurements has been evaluated to be less than 0.005 dB in the measurement frequency range [13]. The gain coefficients of each channel are determined for each input via a traceable 8½ digit voltmeter [14]. The relative standard deviation of each channel of vibration control unit, *VCU*, for a gain of 66 dB was 0.06% or 0.005 dB [12].

The sensitivity of measurement microphones is affected by changes in the environmental conditions, mainly temperature and static pressure [2]. The environmental coefficients for the pressure sensitivity are well known. The final free-field sensitivity (dB re 1 V/Pa) is calculated as follows [15]:

$$M_{\mathrm{p}} = M_{\mathrm{p,ref}} + \delta_p (p_s - p_{s,\mathrm{ref}}) + \delta_t (t - t_{\mathrm{ref}}) \quad (5)$$

where $M_{\mathrm{p,ref}}$ is the pressure sensitivity of the microphone at reference frequency, δ_p is the static pressure coefficient and δ_t is the temperature coefficient. The static pressure coefficient for B&K 4180 microphone is observed to be $-\,484 \times 10^{-6}\, M_{\mathrm{p}}$ dB/V with an expanded uncertainty of 0.0002 dB/kPa, where M_{p} is the sensitivity of microphone in mV/Pa at 250 Hz. The temperature coefficient (dB/K) is − 0.00156 dB/K with an expanded uncertainty of 0.0015 [16]. The standard uncertainty component for temperature, pressure and humidity has been considered as 0.005 dB/K and 0.008 dB/kPa and 0.0005 dB/% R.H. The standard uncertainty due to polarization voltage is calculated as 0.0050 dB in entire measurement frequency range considering a rectangular distribution [17].

The crosstalk of < − 66 dB is reckoned to affect the sensitivity by no more than 0.01 dB [18]. The signal source has THD of less than 0.2% at lowest frequency and is reckoned to affect the sensitivity by < 0.005 dB. The error in frequency of generated signal is less than 10 ppm, and thus, the maximum error in the measured voltage that can arise is 0.002 dB. The maximum linearity error of 0.2 dB is evaluated using a reference generator. The standard uncertainty assuming rectangular distribution is 0.012 dB in measurement frequency range. The uncertainty contribution for the analog-to-digital conversion and frequency response varies from 0.01 to 0.02 dB [19]. The influence of substitution accounts for two errors, viz. the sound pressure in chamber has changed by δp and the original position is missed by a length of δs. The maximum pressure deviation between two series of measurements is 0.04 dB. The

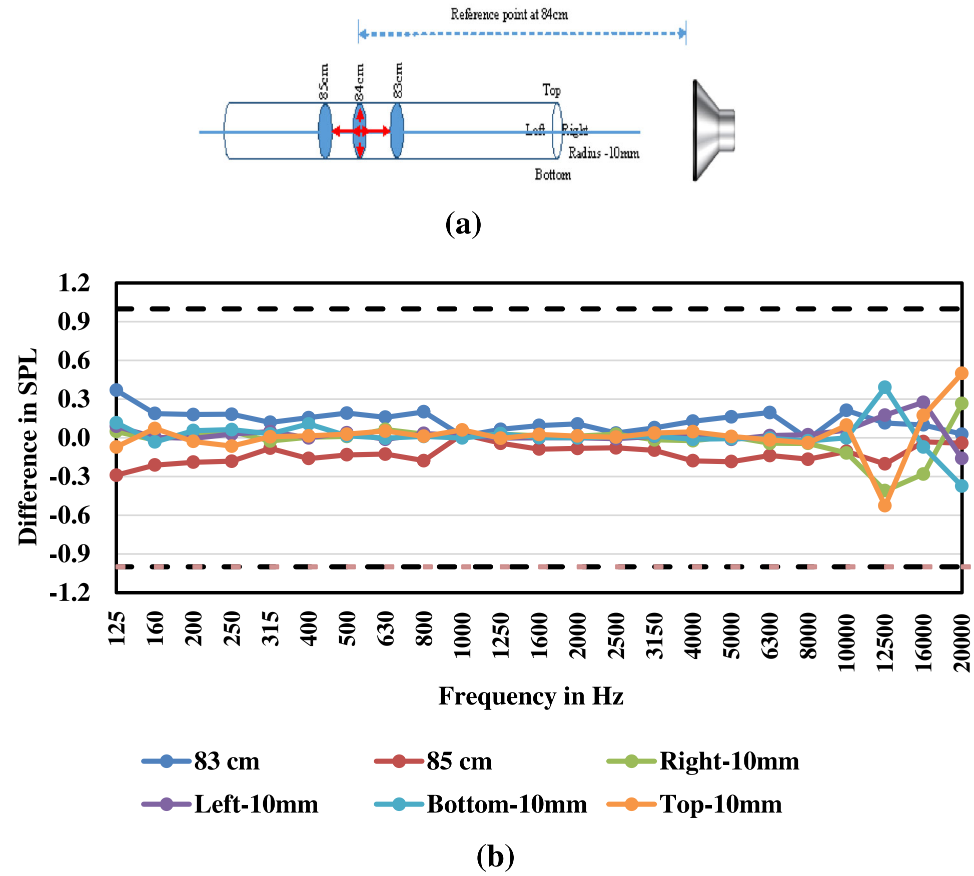

Fig. 5 **a** Radial measurement positions at reference position of 84 cm. **b** Deviations of sound pressure level from the inverse-square law at various positions

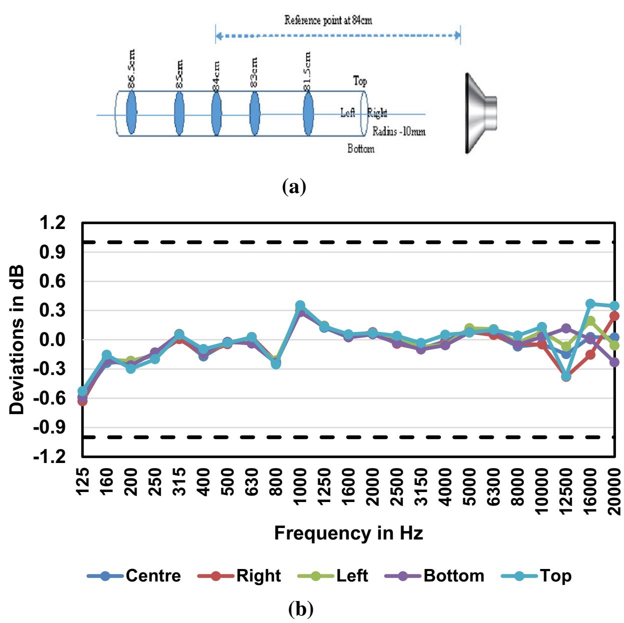

Fig. 6 **a** Radial measurement positions. **b** Deviations from the inverse-square pressure law at a radius of 1 cm at 86.5 cm

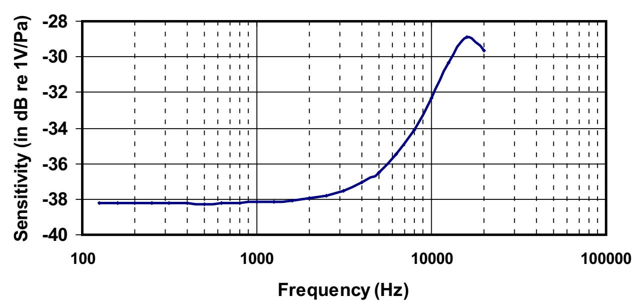

Fig. 7 Measured sensitivity (in dB re 1 V/Pa) for B&K 4180 microphone (S. No. 2889868) with measurement uncertainty up to 250 Hz: 0.3 dB, 250 Hz to 8 kHz: 0.25, > 8 kHz to 10 kHz: 0.35 dB, and > 10 kHz to 20 kHz: 0.40 dB

maximum error due to dependence on distance has been calculated as 0.035 dB/mm at 125 Hz and 0.024 dB/mm at 160 Hz, while for the measurement frequency range of 200 Hz–20 kHz, it is taken as 0.02 dB/mm. Assuming a positioning error and error due to the difference in acoustic centre of the reference and test microphones of $\delta s = \pm 1$ mm, the contribution due to combination of these two error sources is 0.05 dB at 125 Hz, 0.03 dB at 160 Hz and

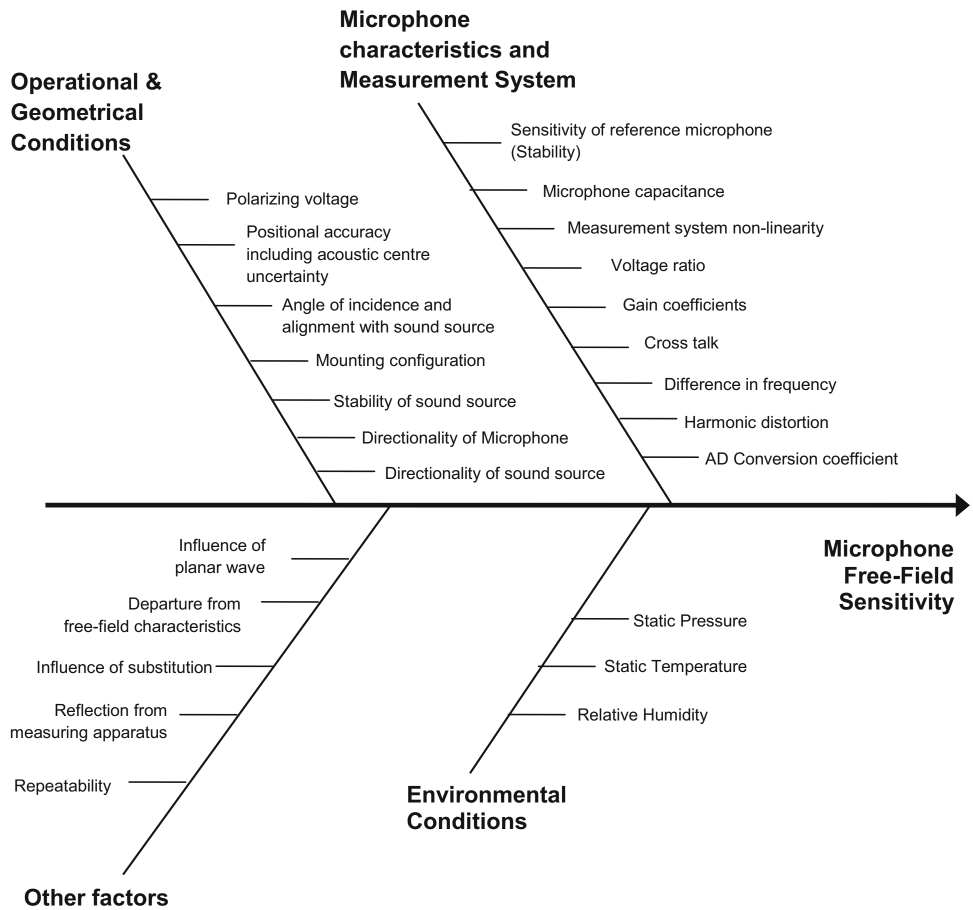

Fig. 8 Cause-and-effect analysis diagram for factors affecting the microphone sensitivity (in dB re 1 V/Pa) measured using the free-field comparison method

0.026 dB for the rest of measurement frequency range [12]. The standard uncertainty due to substitution effect is calculated assuming rectangular distribution in the measurement frequency range.

In the frequency range of 125–250 Hz, the acoustical properties of the room deteriorate gradually. The sound field in the chambers is still dominated by direct sound from the loudspeaker although in addition to that some reflections from the walls may occur due to reduction in sound absorption coefficient of the wall lining at lower frequencies [12]. Thus, an additional uncertainty contribution applied in the frequency range of 125–250 Hz to account for the departure from free-field excitation can be taken into account. The worst deviation ranging from 0.10 to 0.20 dB from the inverse-square law is taken into account as an error contribution by ‘departure from free-field characteristics’ inside the defined working space in the measurement frequency range of 125 Hz–20 kHz. The stability of sound source has been evaluated by taking repetitive measurements of sound pressure level emitted by the loudspeaker. The rounding errors are constant with frequency where values are rounded up to 0.01 dB, thus constituting an uncertainty of 0.0029 dB with rectangular distribution. The difference in the directivity pattern of both the reference and DUC is small, and thus, the contribution is neglected.

Table 3 shows the sensitivity (in dB ref 1 V/Pa) for PCB microphone Model 377B02 (S. No. LW136079) with PCB preamplifier Model No. 426E01 (S. No. LW026195) observed in the past three years. The maximum random uncertainty is observed to be 0.07 dB at 16 kHz. Table 4 thus presents the measurement uncertainty budget of microphone free-field comparison calibration. The sensitivity coefficient of unity is assumed for all the contributing components. The expanded uncertainty in microphone free-field comparison calibration is thus calculated using the law of propagation of uncertainty (LPU) as ± 0.36 dB to 0.52 dB in the frequency range from 125 Hz to 20 kHz as per the *Guide to the Expression of Uncertainty in Measurement* [11].

4.2. Monte Carlo Simulation (MCS) Approach

Monte Carlo simulation (MCS) is an alternative approach for the calculation of measurement uncertainty by means of simulating random numbers. There had been some limitations associated with LPU approach pertaining to model linearization and assumption of normality. MCS is a

Table 3 Sensitivity (in dB ref 1 V/Pa) for PCB microphone Model 377B02 (S. No. LW136079) with PCB preamplifier Model No. 426E01 (S. No. LW026195)

Frequency (Hz)	30/6/2015	29/6/2016	27/6/2017	28/6/2018	2/7/2018	4/7/2018	10/7/2018	12/7/2018
250	− 25.49	− 25.61	− 25.69	− 25.57	− 25.61	− 25.55	− 25.66	− 25.60
125	− 25.33	− 25.56	− 25.53	− 25.52	− 25.62	− 25.59	− 25.60	− 25.60
160	− 25.44	− 25.59	− 25.65	− 25.59	− 25.66	− 25.42	− 25.57	− 25.56
200	− 25.39	− 25.54	− 25.59	− 25.49	− 25.54	− 25.51	− 25.55	− 25.51
315	− 25.48	− 25.53	− 25.58	− 25.50	− 25.53	− 25.46	− 25.52	− 25.49
400	− 25.49	− 25.55	− 25.60	− 25.53	− 25.54	− 25.55	− 25.55	− 25.53
500	− 25.53	− 25.61	− 25.65	− 25.59	− 25.59	− 25.56	− 25.59	− 25.57
630	− 25.56	− 25.62	− 25.67	− 25.56	− 25.58	− 25.57	− 25.61	− 25.55
800	− 25.51	− 25.58	− 25.63	− 25.55	− 25.57	− 25.52	− 25.57	− 25.54
1000	− 25.53	− 25.57	− 25.63	− 25.47	− 25.49	− 25.48	− 25.50	− 25.48
1250	− 25.52	− 25.57	− 25.61	− 25.52	− 25.53	− 25.51	− 25.54	− 25.53
1600	− 25.51	− 25.58	− 25.60	− 25.52	− 25.53	− 25.53	− 25.55	− 25.52
2000	− 25.45	− 25.54	− 25.61	− 25.50	− 25.52	− 25.55	− 25.56	− 25.51
2500	− 25.52	− 25.56	− 25.64	− 25.55	− 25.56	− 25.57	− 25.59	− 25.56
3150	− 25.62	− 25.63	− 25.71	− 25.65	− 25.65	− 25.66	− 25.64	− 25.68
4000	− 25.41	− 25.49	− 25.60	− 25.63	− 25.65	− 25.69	− 25.66	− 25.63
5000	− 25.59	− 25.66	− 25.77	− 25.78	− 25.82	− 25.93	− 25.82	− 25.82
6300	− 25.44	− 25.56	− 25.77	− 25.80	− 25.79	− 25.79	− 25.77	− 25.82
8000	− 25.54	− 25.59	− 25.65	− 25.65	− 25.77	− 25.75	− 25.61	− 25.77
10,000	− 25.63	− 25.73	− 25.69	− 25.76	− 25.81	− 25.63	− 25.76	− 25.87
12,500	− 26.07	− 26.14	− 26.46	− 26.30	− 26.41	− 26.29	− 26.40	− 26.33
16,000	− 24.95	− 25.18	− 25.42	− 25.47	− 25.47	− 25.37	− 25.50	− 25.42
20,000	− 25.78	− 25.43	− 25.62	− 25.62	− 25.49	− 25.51	− 25.54	− 25.60

numerical procedure for solving problems by means of generating pseudorandom numbers and is a versatile tool for combining the 'distributions'. A clear and precise defined model equation for the measurement process between the measurand Z and the influencing factors or parameters is a prerequisite. The probability density function corresponding to all the sources is to be identified. A computer program generates the pseudorandom numbers for solving the model equation, thereby simulating the values of variables with a given probability density function for M number of trials [20]. The recommendations of 10^5 or 10^6 iterations seem to be enough for most of the problems [20–22]. When the skewness value of the Z forecast discrete distribution is near zero, the expanded uncertainty can be approximated as follows [20]:

$$U(Z) = \left(\frac{Z_{(1+p)M/2} - Z_{(1-p)M/2}}{2}\right) \tag{6}$$

where $Z_{(1+p)M/2}$ and $Z_{(1-p)M/2}$ correspond to the 2.5% and 97.5% percentiles of the sorted Z values for coverage probability p. The coverage factor can be evaluated as follows [20]:

$$k = U(Z)/u(Z) \tag{7}$$

where $u(Z)$ is the combined uncertainty calculated as the standard deviation of the set of values simulated in Z_1, Z_2,… Z_M trials [20]. In the present case, the MCS approach is utilized to calculate the expanded uncertainty in microphone free-field calibration. The accuracy of MCS depends upon the choice of software generating the random numbers. As such, there are various software packages such as Crystal Ball, Analytica, Stella II for carrying out MCS for the evaluation of measurement uncertainty [23, 24]. Microsoft Excel can be also used with ease for uncertainty estimation using the MCS approach [25]. The model equation considered in the present case utilizing the MCS approach is as follows:

$$M_{\mathrm{p}} = M_{\mathrm{p,ref}} + 20\log_{10}\frac{|U_{\mathrm{DUC}}|}{|U_{\mathrm{REF}}|} + \delta_p(p_s - p_{s,\mathrm{ref}}) + \delta_t(t - t_{\mathrm{ref}}) \tag{8}$$

where $M_{\mathrm{p,ref}}$ is the free-field sensitivity level of the reference microphone, U_{DUC} and U_{REF} are the open-circuit output voltages of the DUC and reference microphone and δ_p and δ_t are the static pressure and temperature coefficient of microphone at a particular frequency. The uncertainty

Table 4 Measurement uncertainty (in dB) in free-field comparison calibration of microphones in the frequency range of 125 Hz–20 kHz

Sources of uncertainty	Uncertainty value (dB)	Prob. Distribution, Dist. divisor	Uncertainty Contribution (in dB)						
			125–200 Hz	250 Hz to 1 kHz	1.25–2.5 kHz	3.15–5 kHz	6.3–8 kHz	10 kHz	12.5–20 kHz
Reference microphone	0.25–0.40	(Normal, 2)	0.15	0.125	0.125	0.125	0.125	0.175	0.20
Voltage ratio	0.005	(Rect., $\sqrt{3}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Gain coefficients	0.005	(Rect., $\sqrt{3}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Instability of reference standard with time	0.005	(Rect., $\sqrt{3}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Static temperature	0.005	(Rect., $\sqrt{3}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Static pressure	0.008	(Rect., $\sqrt{3}$)	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Relative humidity	0.0005	(Rect., $\sqrt{3}$)	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Polarizing voltage	0.0086	(Rect., $\sqrt{3}$)	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Crosstalk	0.01	(Rect., $\sqrt{3}$)	0.006	0.001	0.006	0.006	0.006	0.006	0.006
Difference in frequency	0.002	(Rect., $\sqrt{3}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Harmonic distortion	0.005	(Rect., $\sqrt{3}$)	0.003	0.001	0.003	0.003	0.003	0.003	0.003
Non linearity of analyser	0.02	(Rect., $\sqrt{3}$)	0.012	0.012	0.012	0.012	0.012	0.012	0.012
AD conversion coefficient	0.01–0.02	(Rect., $\sqrt{3}$)	0.006	0.001	0.006	0.006	0.006	0.012	0.012
Influence of substitution	0.026–0.05	(Rect., $\sqrt{3}$)	0.029	0.017	0.015	0.015	0.015	0.015	0.015
Departure from free-field characteristics	0.10–0.20	(Rect., $\sqrt{3}$)	0.115	0.058	0.115	0.115	0.115	0.115	0.09
Air attenuation	0.0004–0.0011	(Rect., $\sqrt{3}$)	0.0004	0.0001	0.0001	0.0004	0.0004	0.0011	0.0014
Rounding error	0.01	(Rect., 2 $\sqrt{3}$)	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029
Stability of sound source	(Normal, 1)		0.11	0.06	0.05	0.09	0.11	0.11	0.12
Repeatability	(Normal, 1)		0.04	0.008	0.012	0.02	0.04	0.03	0.07
Expanded uncertainty (k = 2) in dB			0.45	0.30	0.36	0.36	0.42	0.48	0.52

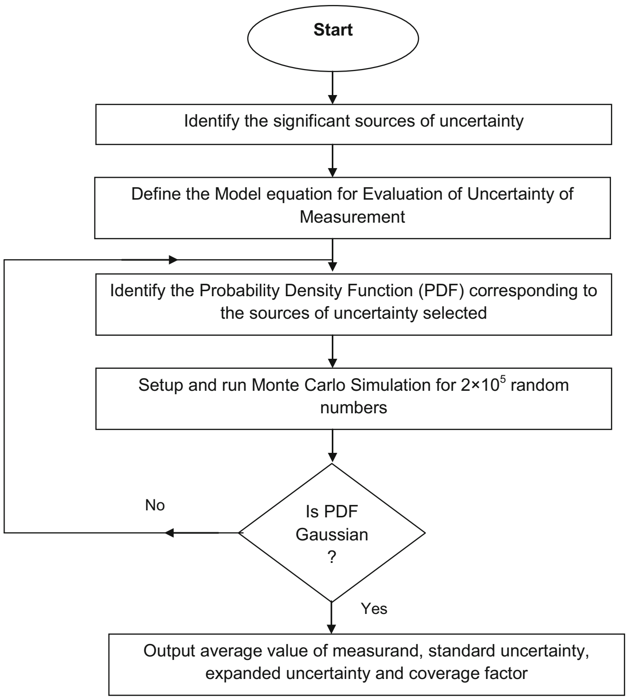

Fig. 9 Procedure for Monte Carlo simulation (MCS) for evaluating expanded uncertainty in microphone free-field calibration

and mean sensitivity level (in dB re 1 V/Pa) in free-field calibration are calculated at 250 Hz and 1 kHz frequency for PCB microphone Model 377B02 (S. No. LW136079) with PCB preamplifier Model No. 426E01 (S. No. LW026195). The value of static pressure coefficient and temperature coefficient and uncertainty is clearly known at 250 Hz and 1 kHz. Thus, the MCS simulation is carried out for 200,000 iterations by generating random numbers in Microsoft Excel as shown in Fig. 9. The reference sensitivity is assumed to be of Gaussian distribution in Eq. (8), and the rest other terms such as the open-circuit output voltages of the DUC and reference microphone and difference in static pressure and temperature from the reference conditions are considered to be of rectangular distribution. The summary of MCS results is shown in Table 5, and the frequency histogram at 250 Hz and 1 kHz is shown in Figs. 10a, b. Table 6 shows the comparison of

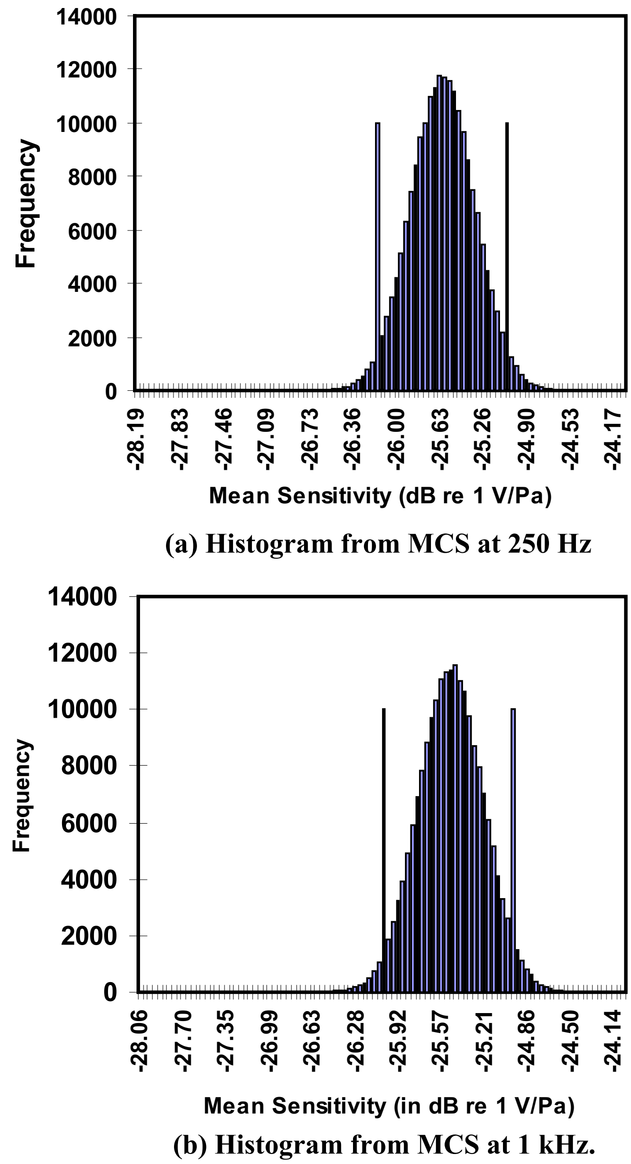

Fig. 10 **a** Histogram from MCS at 250 Hz. **b** Histogram from MCS at 1 kHz

GUM/LPU method and MCS. It can be observed that the expanded uncertainty evaluated using MCS is in good agreement with that obtained by GUM/LPU approach with

Table 5 MCS summary

Parameter	250 Hz	1 kHz
Mean value (in dB re 1 V/Pa)	− 25.62	− 25.50
Standard uncertainty (in dB)	0.138	0.138
Expanded uncertainty (in dB)	0.27	0.27
Coverage factor	1.95	1.96
Low end point (in dB re 1 V/Pa)	− 26.16	− 26.04
High end point (in dB re 1 V/Pa)	− 25.09	− 24.97

Table 6 Comparison of GUM/LPU method and MCS

Approach	Mean value of sensitivity (in dB re 1 V/Pa)	Expanded uncertainty (in dB)
250 Hz		
GUM/LPU	− 25.60	0.30
MCS	− 25.62	0.27
1 kHz		
GUM/LPU	− 25.48	0.30
MCS	− 25.50	0.27

a difference of 0.03 dB. This difference is due to the fact that the various influencing components discussed in Table 5 are not reflected in the model Eq. (8). However, the results obtained through both the approaches show a satisfactory concordance as shown in Table 6. Thus, the MCS approach can be used to evaluate the measurement uncertainty in the entire measurement frequency range provided the values of static pressure and temperature coefficient and their associated uncertainty are exactly known at all these frequencies. An important consideration in that aspect shall be the difference in evaluated uncertainty between the two approaches which shall be due to the consideration of various influencing factors in LPU method that are not reflected in the model equation.

5. Measurement Uncertainty Validation and Traceability

The free-field calibrations are compared with M/s SPEKTRA values for two microphones: B&K 4180 and B&K 4191 (make Brüel & Kjær, B&K). Figure 11 shows the difference in measured sensitivity with that of M/s SPEKTRA values. For B&K 4180 microphone, the deviation is observed to be less than 0.16 dB in the entire measurement frequency range, while for the B&K 4191 microphone, the deviation is observed to be less than 0.25 dB in the entire measurement frequency range, which validates the measurement uncertainty evaluated in the entire measurement frequency range.

The present system shall be in future traceable to the indigenously developed microphone free-field calibration system by CSIR-National Physical Laboratory, which is the National Metrology Institute (NMI) of India. However, future participation in inter-laboratory comparisons with other laboratories realizing the free-field comparison calibrations shall be further instrumental in the validation of the measurement uncertainty and inclusion of Calibration and Measurement Capabilities (CMCs) in Key Comparison data base [26–30]. Also, future efforts focussed on the development of a free-field primary standard in anechoic chambers of CSIR-National Physical Laboratory, India; upgradation of microphone pressure reciprocity calibration standard and sound level meter calibration facility shall be pivotal steps in strengthening the measurement traceability chain throughout the country and inclusions of some more CMCs (at least five) in Key Comparison data base [31–35]. Thus, the establishment of traceable, ISO/IEC-compliant measurement standards shall be very valuable for accurate and precise environmental noise measurements, noise mapping and noise pollution control in Indian cities [36].

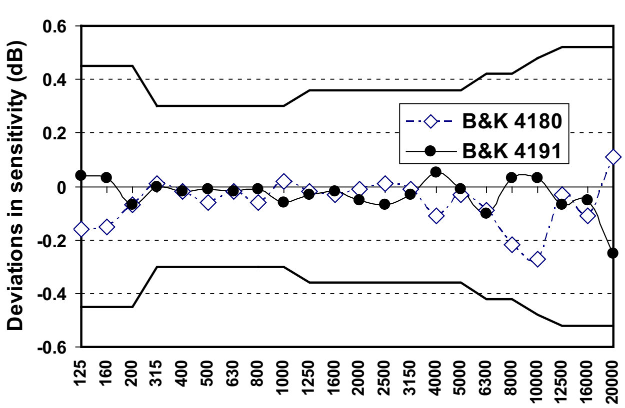

Fig. 11 Difference in measured sensitivity (in dB re 1 V/Pa) in comparison with M/s SPEKTRA, Germany, values for free-field microphone calibration of B&K 4180 and B&K 4191 microphones

6. Conclusions

This paper has presented a novel implementation of a small transportable anechoic chamber for conducting microphone free-field calibrations with lowest levels of uncertainty that serves as a cost-effective solution for conducting microphone free-field calibrations. The microphone free-field comparison calibration using the substitution method as per the IEC 61094-8 standard in a small free-field chamber of internal volume of 2 m^3 is demonstrated. The present detailed study that has not been presented so far has identified the usable working space inside a free-field chamber using the inverse-square pressure law, and the deviations from the inverse-square law of the free-field chamber are quantified. The measurement uncertainty of $\pm$ 0.36–0.52 dB (k = 2, 95% confidence level) is evaluated in the frequency range of 125 Hz–20 kHz and is validated in bilateral comparison with other laboratories. The paper also demonstrates the application of Monte Carlo simulation (MCS) approach in the evaluation of the measurement uncertainty in microphone free-field calibration. Future efforts in this regard shall be undertaken on reducing the measurement uncertainty in low-frequency free-field microphone calibrations and application of Monte Carlo simulation approach in the entire measurement frequency range and its comparison with GUM/LPU approach.

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calculations and for identification of the usable working space inside a free-field chamber using the inverse-square pressure law.

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