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Uncertainty analysis for pressure sensitivities of laboratory standard microphones

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Abstract: Pressure sensitivities of laboratory standard microphones are acoustic standards required for precise measurement in the audible frequency range. The National Metrology Institute of Japan (NMIJ) has developed a pressure calibration system that enabled absolute calibration of pressure sensitivities. In this study, we analyzed the measurement uncertainty of pressure sensitivities calibrated at NMIJ in detail by using the pressure sensitivity formula and examining every possible component that contributed to the uncertainty. The analysis revealed several dominant components, such as repeatability in the measurement of the voltage transfer function, cavity volume of the coupler, capillary tube correction factor, and instability of the microphone. Within a frequency range in which the expanded uncertainty was constant, the expanded uncertainty (coverage factor $k = 2$) was 0.04 dB for Brüel & Kjær 4160, a type LS1P microphone, and 0.09 dB for Brüel & Kjær 4180, a type LS2aP microphone.

Keywords: Laboratory standard microphone, Pressure sensitivity, Pressure calibration, Reciprocity technique, Measurement uncertainty

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1. INTRODUCTION

Pressure sensitivities of laboratory standard microphones are used as acoustic standards in the audible frequency range and absolutely calibrated by using a technique called the pressure calibration method [1,2]. In the National Metrology Institute of Japan (NMIJ), the pressure calibration system has been improved to realize more precise calibration of pressure sensitivities [3,4].

In this study, we analyzed measurement uncertainty of pressure sensitivities calibrated at NMIJ in detail, examining every possible component that contributed to the uncertainty. Analysis was based on an international document, "Guide to the Expression of Uncertainty in Measurement" (GUM) [5].

2. PRESSURE CALIBRATION PROCEDURE [6]

2.1. Pressure Calibration Method by Using Reciprocity Technique

In the pressure calibration method, three laboratory standard microphones A, B, and C are used to make three different pairs of transmitters and receivers, namely, (A,B), (A,C), and (B,C). For each pair, microphones are set into a coupler (Fig. 1) and the contacting surfaces between the microphones and the coupler are sealed with grease to prevent leakage of both gas and sound out of the cavity. The voltage transfer function (VTF) between an input terminal of the transmitter and an output terminal of the receiver is measured. The capacitance of the reciprocal microphone B is also measured (The electrical impedance of the microphone can be regarded as a capacitance). Unknown pressure sensitivities of microphones B and C are calculated as follows, taking into account a correction factor (We don't calibrate pressure sensitivity of microphone A because it is used just for the transmitter).

$$20\log K_{\mathrm{B}} = \frac{1}{2}(T_{\mathrm{AB}} - T_{\mathrm{AC}} + T_{\mathrm{BC}}) - 10\log\frac{\gamma P C_{\mathrm{B}} K_0^2}{V} + H \quad (1)$$

$$20\log K_{\mathrm{C}} = \frac{1}{2}(-T_{\mathrm{AB}} + T_{\mathrm{AC}} + T_{\mathrm{BC}}) - 10\log\frac{\gamma P C_{\mathrm{B}} K_0^2}{V} + H \quad (2)$$

where K_{B} and K_{C} are pressure sensitivities of microphones B and C, respectively, T_{AB}, T_{AC}, and T_{BC} are the VTFs for the three pairs of (A,B), (A,C), and (B,C),

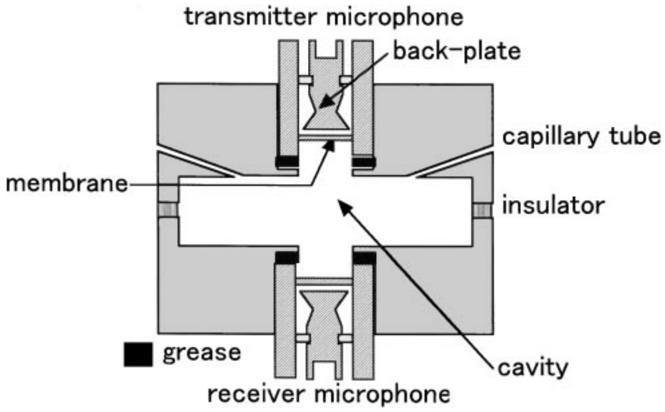

Fig. 1 Schematic of microphones set into a large-volume coupler with grease.

respectively, γ is the ratio of specific heats of the gas, P is static pressure, C_B is the capacitance of microphone B, V is the cavity volume of the coupler, and K_0 is equal to 1 V/Pa. Here, H is a coupler correction factor to compensate for the heat conduction at the walls of the coupler, the shunting effect of capillary tubes, the acoustic impedance of the microphone membrane, and the wave motion in longitudinal and radial mode [2,7].

2.2. Pressure Calibration System

Figures 2 and 3 show the pressure calibration system for measuring the VTF and the transmitter capacitance, respectively. The VTF was measured by using an insert voltage technique [2]. In the measurement of the transmitter capacitance, current through the transmitter was transformed into voltage by using a current amplifier and then the transmitter capacitance was measured in comparison with a reference capacitance. Systems for measuring VTF and transmitter capacitance are easily reconfigured simply by changing cable connections.

2.3. Microphones and Couplers [1,2]

We calibrate three kinds of laboratory standard microphones, namely, type 4160 (Brüel & Kjær) and type MR103 (Tokyo Riko Co.), which are classified as type LS1P microphones, and type 4180 (Brüel & Kjær), which is classified as a type LS2aP microphone. In this study, uncertainty of pressure sensitivities was analyzed for types 4160 and 4180, which are commonly used throughout the world. In our pressure calibration system, a large-volume coupler was used and gas in the cavity was exchanged from air to hydrogen at higher frequency range to increase the speed of sound within the cavity. The large-volume coupler has an advantage of realizing more precise calibration than a plain wave coupler because the corresponding coupler correction factor is relatively small and is less sensitive to microphone parameters and to dimensions of the coupler.

For type 4160, the measurement frequency range was 20 Hz to 12.5 kHz, cavity volume was 19.62 cm^3, and hydrogen was used when the frequency range was above 1.5 kHz. For type 4180, measurement frequency range was 20 Hz to 20 kHz, cavity volume was 1.043 cm^3, and hydrogen was used when the frequency range was above 4 kHz.

3. UNCERTAINTY ANALYSIS PROCEDURE [5]

Measurement uncertainty u_p of pressure sensitivity was analyzed by using Eq. (1). The influence of each relevant

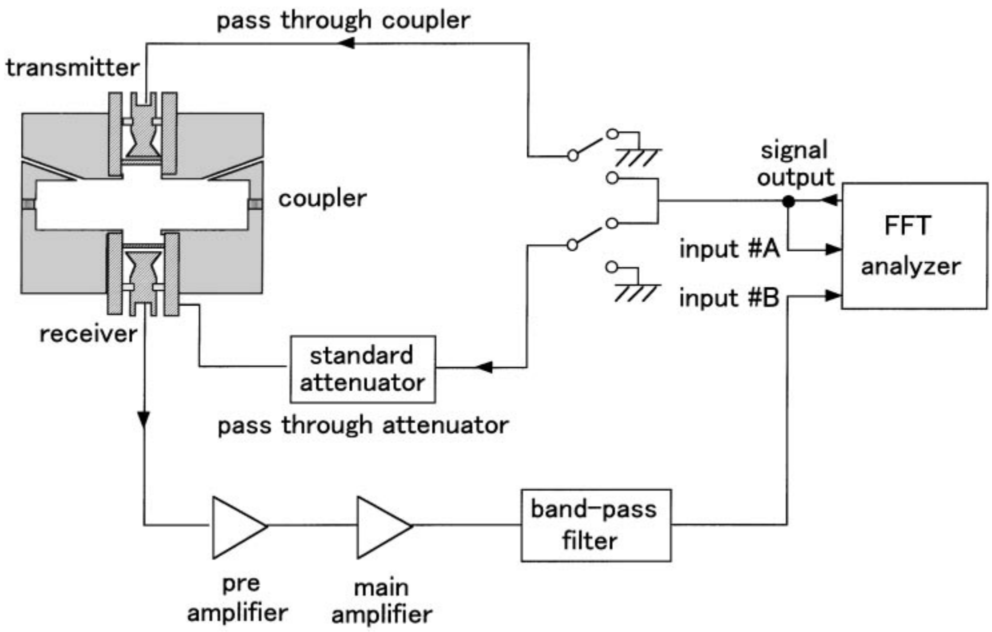

Fig. 2 Schematic of the VTF measurement circuit in a pressure calibration system.

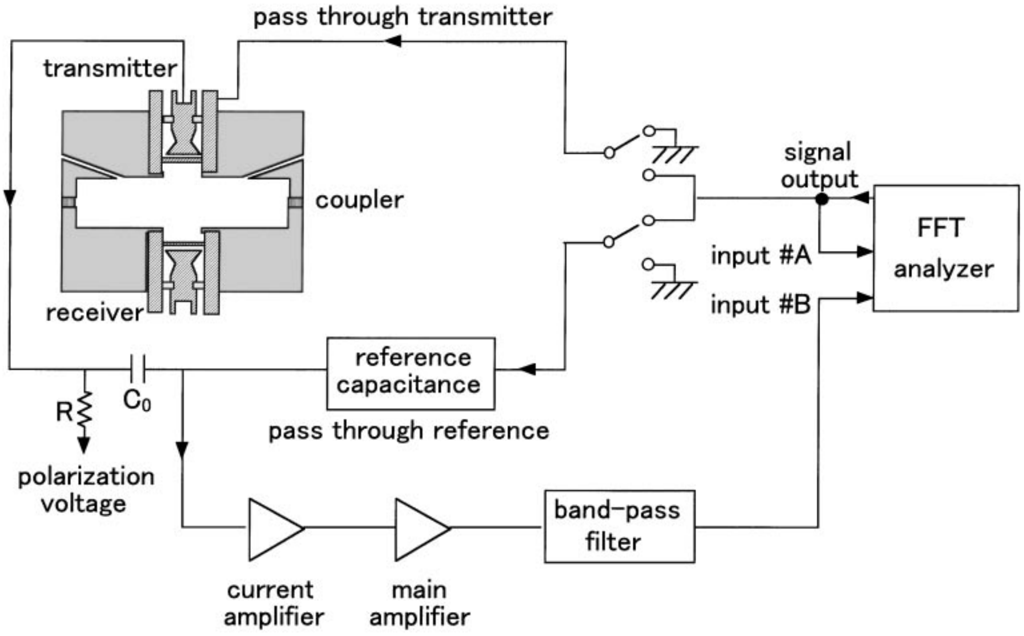

Fig. 3 Schematic of the measurement circuit for the transmitter capacitance in a pressure calibration system.

component on u_p was calculated by using its uncertainty that was obtained either from a statistical method such as repetition of the measurement (This type of uncertainty is called type A) or from a method other than type A, such as a calibration certificate of an instrument used in the pressure calibration system (This type of uncertainty is called type B). Because various components contribute to u_p [2], the components were classified here into two types: those related to the electrical circuit of the pressure calibration system, such as the VTF and the transmitter capacitance measurement, and those related to the acoustic circuit of the system, such as characteristics of the microphone (temperature and pressure dependency of pressure sensitivity) and the coupler correction factor. Because acoustic components depend on fundamental parameters, such as measurement environmental conditions, dimensions of the coupler, and microphone parameters, first the uncertainties of the relevant fundamental parameters were estimated and then the u_p caused by the uncertainty of the acoustic component was analyzed.

4. UNCERTAINTY COMPONENTS RELEVANT TO THE ELECTRICAL CIRCUIT

4.1. VTF

4.1.1. Cross-talk

The signal-to-noise ratio related to the cross-talk was measured for the passes through the coupler and the attenuator as shown in Fig. 2. Because this ratio exceeded 77 dB within the measurement frequency range, uncertainty u_{v1} of the VTF due to the cross-talk (type B, rectangular distribution) was $0.0012/\sqrt{3} = 0.0007$ dB. u_{v1} was divided by $\sqrt{3}$ to estimate the standard deviation [5].

4.1.2. Linearity of FFT analyzer

We used an FFT analyzer (Ono Sokki Co., type CF5220) to obtain synchronously averaged data, such as VTF and transmitter capacitance. Linearity of the FFT analyzer was evaluated as follows. First, a reference resistance attenuator was calibrated by using a DC power supply and a multi-meter (Keithley Instruments KK, type 2000). According to the calibration certificate of the multimeter, the maximum uncertainty of the measured voltage was 0.0001 dB (type B, rectangular), which is negligible. Then, linearity of the FFT analyzer was measured by using this reference attenuator. Based on this measurement, the maximum uncertainty u_{v2} of the VTF caused by deviation from the linear characteristics in the FFT analyzer (type B, rectangular) was $0.001/\sqrt{3} = 0.0006$ dB within the measurement frequency range if the difference in input voltage in the FFT analyzer was less than 6 dB (In our pressure calibration system, the difference in input voltage in the FFT analyzer could be controlled to less than 6 dB by adjusting the standard attenuator).

4.1.3. Standard attenuator

A standard attenuator used in the insert voltage technique was calibrated in comparison with a reference transformer (Sun Jem Co., type 6415-A). The measurement frequency was 525 Hz because characteristics of the standard attenuator were relatively independent of frequency (The maximum difference in the calibrated value was 0.001 dB within the measurement frequency range). First, based on the calibration certificate of the transformer, the uncertainty of the ratio that was set on the transformer (type B, rectangular) was 0.5 ppm, which is negligible. Then, the standard attenuator was calibrated in comparison with this reference transformer by using the FFT analyzer. Uncertainty in this comparative measurement (type B, rectangular) was regarded as the uncertainty of the FFT analyzer, namely 0.0006 dB, as described above in sec. 4.1.2. Based on these components, uncertainty u_{v3} of the VTF due to the uncertainty of the calibrated value in the standard attenuator was 0.0012 dB (type B, rectangular).

4.1.4. Leakage of sound

To examine the effect caused by leakage of sound out of the cavity, VTF was measured within a frequency range between 20 Hz and 1.5 kHz, with and without grease on the contacting surfaces between the microphones and the coupler. Measurements were repeated three times for each condition.

There was no significant difference in the measurements with and without grease, indicating that the uncertainty u_{v4} of the VTF due to sound leakage (type A) was negligible.

4.1.5. Repeatability

Uncertainty u_{v5} of the VTF due to its repeatability (type A) was determined from five measurements during a 1-day period, as shown in Fig. 4. Table 1 lists the measurement conditions at each measurement frequency. After each measurement, the microphones were completely removed from the coupler and set into it again for the next measurement.

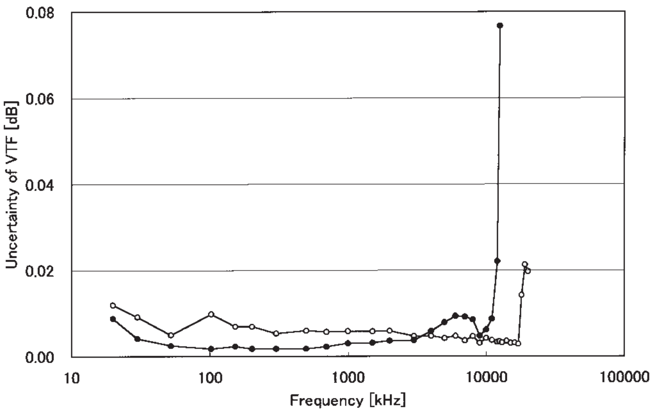

Fig. 4 Uncertainty u_{v5} of the VTF caused by its repeatability for type 4160 (●) and 4180 (○) microphones.

The measurements revealed that u_{v5} was frequency dependent. Furthermore, based on past calibration records at NMIJ, u_{v5} at higher frequency range (above 9 kHz for type 4160, and above 18 kHz for type 4180) might be underestimated if a different microphone pair was used or if measurements were repeated on different days. Therefore, in this higher frequency range, the maximum uncertainty given in past calibration records should be considered the u_{v5}.

4.1.6. Combined uncertainty

Tables 3 and 4 list the combined uncertainty u_v of the VTF (type A) calculated by using a law of propagation of uncertainty [5] for 4160 and 4180, respectively. For both microphones, u_{v5} (VTF repeatability) was the dominant component in u_v. In the following sections, each uncertainty component listed in Tables 3 and 4 is discussed (For simplicity, values shown in these tables should be multiplied by 10^{-3}; for example, "5" means 0.005 dB).

4.2. Transmitter Capacitance

4.2.1. Linearity of FFT analyzer

The transmitter capacitance was measured in comparison with a variable reference capacitance by using the FFT analyzer. The uncertainty u_{c1} of the transmitter capacitance caused by the characteristics of the FFT analyzer was 0.0006 dB, as discussed above in sec. 4.1.2 (type B, rectangular).

4.2.2. Reference capacitance

Uncertainty u_{c2} of the transmitter capacitance caused by the uncertainty of the calibrated value in the reference capacitance (type B, rectangular) was negligible, because the uncertainty of the capacitance bridge (GenRad Co., type 1615A) used to calibrate the reference capacitance was $0.0002/\sqrt{3} = 0.0001$ dB, based on the calibration certificate of the capacitance bridge.

4.2.3. Ground shield and mechanical force during setting of the microphone into the attachment

A microphone must be fitted into a mechanical attach-

Table 1 VTF measurement conditions.

Microphone type	Measurement frequency (Hz)	Input voltage (V)	Frequency resolution (Hz)	Average number of signals
4160	20 to 50	5	0.5	25
	100 to 1 k	3	2.5	25
	1.5 k to 12.5 k	1	25	50
4180	20 to 50	5	0.5	25
	100 to 700	3	2.5	25
	1 k to 3 k	1	5	25
	4 k to 20 k	1	25	50

ment that has a ground shield configuration specified in IEC 61094-1 [1]. The transmitter capacitance was measured for three different mechanical attachments to evaluate the effect of the differences in configuration of each attachment. To exclude the uncertainty caused by acoustic noise, polarization voltage was not applied during the measurements. Moreover, each time an attachment is fitted to a microphone, its center electrode might push the backplate of the microphone at a slightly different force, possibly causing a change in the capacitance. Therefore, these measurements were repeated three times for each attachment. After each measurement, the microphone was completely removed from the attachment and then set into it again for the next measurement.

As a result of a total of nine measurements, uncertainty u_{c3} of the transmitter capacitance related to the attachment was 0.002 dB for both 4160 and 4180 (type A).

4.2.4. Stray capacitance

As shown in Fig. 3, a capacitance C_0 (2.2 μF) was inserted between the transmitter and the current amplifier to avoid polarization voltage to the current amplifier. Considering that the maximum transmitter capacitance was 55 pF, the uncertainty of the transmitter capacitance due to insertion of C_0 (type B, rectangular) was $1 + 55 \times 10^{-12}/2.2 \times 10^{-6} = 1.00003$, namely, 0.0002 dB, which is negligible.

However, current through the transmitter strayed to a capacitance C_c (stray capacitance of the cable between the transmitter and C_0) and a resistance R. Considering that the stray capacitance of the cable was 100 pF/m and the cable length was 15 cm, C_c was 15 pF. The uncertainty of the transmitter capacitance caused by C_c (type B, rectangular) was $1 + 15 \times 10^{-12}/2.2 \times 10^{-6} = 1.000007$, namely, 0.00006 dB, which is negligible. The maximum uncertainty of the transmitter capacitance caused by R (2 MΩ), which occurred at the lowest measurement frequency (20 Hz), was $(1 + (2\pi \times 20 \times C_0R)^{-2})^{1/2} = 1.000002$, namely, 0.00002 dB, which is negligible (type B, rectangular).

Stray capacitance of the cables between C_0 and the current amplifier and between the reference capacitance and the current amplifier was not examined because input impedance of the current amplifier was regarded as zero.

Therefore, based on these components, the uncertainty u_{c4} of the transmitter capacitance due to stray capacitance (type B, rectangular) was 0.0002 dB, which is negligible.

4.2.5. Repeatability

Uncertainty u_{c5} of the transmitter capacitance due to its repeatability was measured under the same measurement conditions as the VTF. The maximum u_{c5} was 0.002 dB within the measurement frequency range (type A).

4.2.6. Combined uncertainty

Based on u_{c1} to u_{c5}, the combined uncertainty u_c of the transmitter capacitance was 0.003 dB (type A).

4.3. Frequency

The uncertainty u_f of the input-signal frequency generated by the FFT analyzer was 50 ppm based on the calibration certificate of the FFT analyzer (type B, rectangular). In the plot of frequency characteristics vs. pressure sensitivity, the steeper the slope, the larger the influence u_f has on the uncertainty u_{p_f} of pressure sensitivity (type B, rectangular). Because the maximum slope was 2 dB/kHz for 4160, u_{p_f} was 2 dB/kHz × 50 ppm = 0.0001 dB, which is negligible. For 4180, u_{p_f} was also negligible because frequency characteristics of 4180 had a much gentler slope (maximum 0.5 dB/kHz), compared with that of 4160.

4.4. Polarization Voltage

Three components contributed to the uncertainty of polarization voltage. The first is uncertainty of the polarization voltage indicated on the multi-meter (type B, rectangular). The calibration certificate of the multi-meter showed that this uncertainty was 0.00002 dB, which is negligible. The second component is uncertainty of polarization voltage due to its fluctuation during the VTF measurement (about 15 mins.). Past calibration records showed that the maximum uncertainty was 0.001 V, namely, 0.0005 dB (type A). The third component is uncertainty of polarization voltage due to poor insulation resistance of the microphone (type B, rectangular). This uncertainty was $1 + 10^8/10^{12} = 1.0001$, namely, $0.0009/\sqrt{3} = 0.0006$ dB, because the input impedance of a preamplifier was designed to be 100 MΩ and the insulation resistance of the microphone was checked to be over 10^{12} Ω before the calibration was started. Therefore, based on these three components, the combined uncertainty u_b of polarization voltage was 0.0011 dB (type A) and regarded as the uncertainty u_{p_b} of pressure sensitivity caused by u_b.

5. UNCERTAINTY OF FUNDAMENTAL PARAMETERS

5.1. Measurement Environmental Conditions

5.1.1. Temperature of the microphones and coupler

Three components contributed to the uncertainty of temperature in the microphones and the coupler. The first component is uncertainty of temperature indicated by a reference thermometer (Techno Seven Co., type D642). The calibration certificate of the reference thermometer showed that this uncertainty (type B, rectangular) was $0.03/\sqrt{3} = 0.02$°C within a range between 18°C and 28°C. The second component is uncertainty of the thermometer (Keithley Instruments KK, type 2010) that was attached to the side of the coupler and calibrated in comparison with this reference thermometer. This uncertainty (type B, rectangular) was $0.14/\sqrt{3} = 0.08$°C. The third component is fluctuation of temperature during the VTF measurement. Past calibration records showed that the maximum fluctuation was 0.10°C (type A). Based on these three components, the combined uncertainty u_{temp} of temperature was 0.13°C (type A). As seen in Eq. (1), u_{temp} influences u_p via γ, H, and temperature dependency of pressure sensitivity itself.

In this analysis, the temperature difference between the microphones and the coupler was not considered because they were handled carefully so that heat transferred from the operator's hands was minimized.

5.1.2. Static pressure

Two components contributed to the uncertainty of static pressure. The first component is uncertainty of static pressure indicated by a barometer (Yokogawa Denshikiki Co., type F4711). The calibration certificate of the barometer showed that this uncertainty (type B, rectangular) within a range between 90 kPa and 110 kPa was 0.002 kPa, namely, 0.0002 dB, which is negligible. The second component is fluctuation of static pressure during the VTF measurement. Past calibration records showed that the maximum fluctuation was 0.01 kPa, namely, 0.001 dB (type A). Based on these two components, uncertainty u_{pres} of static pressure was 0.001 dB (type A). u_{pres} influences u_p via γ, P, H, and pressure dependency of pressure sensitivity.

5.1.3. Humidity

Two components contributed to the uncertainty of humidity. The first component is uncertainty of humidity indicated by a hygrometer (Rotronic Instruments Co., type HP100A). The calibration certificate of the hygrometer showed that this uncertainty (type B, rectangular) was $1.5/\sqrt{3} = 1\%$ within a range between 10% and 90%. The second component is fluctuation of humidity during the VTF measurement. Past calibration records revealed that the maximum fluctuation was 2% (type A). Based on these two components, the combined uncertainty u_{hum} of humidity was 3% (type A). u_{hum} influences u_p via γ and H. Humidity dependency of pressure sensitivity was neglected as described in IEC 61094-2 [2].

5.2. Dimensions of the Coupler

5.2.1. Dimensions of the cavity

Dimensions of the cavity in the coupler were measured by using a microscope (Olympus Co., type STM5) that was calibrated as follows. First, the uncertainty of a block gauge used as a reference length (type B, rectangular) was $0.06/\sqrt{3} = 0.04\,\mu m$, which is negligible, based on the calibration certificate of the block gauge. Then, the microscope was calibrated by measuring the length of this block gauge. The uncertainty in this measurement (type B, rectangular) was $10/\sqrt{3} = 6\,\mu m$. Based on these two components, the uncertainty u_l of the length measured by the microscope was 6 µm (type B, rectangular). u_l was used for the uncertainties of the lengthwise dimensions in the cavity.

When the inner diameter of the cavity was measured, four measurement points were selected on the circumference of the cavity to measure the X and Y coordinates. The best-fit diameter was estimated by using a least square method. The uncertainty of the inner diameter due to this estimation was 10 µm (type A), and as described above the uncertainty u_l of the X and Y coordinates (type B, rectangular) was 6 µm. Based on these two components, the combined uncertainty u_d of the inner diameter measured by the microscope was 12 µm (type A). u_l and u_d influence u_p via V and H.

Based on u_l and u_d, the uncertainty u_{vol} of V (type A) was calculated as 0.016 dB for the coupler used to calibrate the type 4160, and 0.053 dB for that used to calibrate the 4180 (Dimensions of the cavity are described in IEC 61094-2).

5.2.2. Dimensions of capillary tubes

As shown in Fig. 1, two capillary tubes were attached to the cavity for hydrogen replacement. Each tube was 10 cm in length and 0.5 mmϕ in inner diameter for the coupler used for the 4160, and 10 cm and 0.3 mmϕ, respectively, for the 4180. Dimensions of these capillary tubes influence H via capillary tube correction factor. However, these dimensions given by the manufacturer were not sufficiently reliable for determining uncertainty. Furthermore, precise measurement of the inner diameter by using a microscope was difficult. Therefore, the uncertainty u_{capil_d} of the inner diameter was estimated from an operation manual of Brüel & Kjær type 5998, reciprocity calibration apparatus as $17/\sqrt{3} = 10\,\mu m$ (type B, rectangular) [8]. This estimation is reasonable because the capillary tube correction of the large-volume coupler is relatively insensitive to the inner diameter, compared with the plane-wave coupler.

The maximum uncertainty u_{capil_l} for the length of the capillary tubes (type B, rectangular) was estimated to be 0.1 mm, considering uncertainty in the mechanical processes used in manufacturing the tubes. This estimation also seems sufficient because capillary tube correction is much less sensitive to the tube length than to the inner diameter, as discussed in sec. 6.2.3.

5.3. Microphone Parameters

Microphone parameters, such as resonance frequency, quality factor, and tension of the membrane, influence H. Table 2 lists these microphone parameters and their respective uncertainties u_{f0}, u_q and u_{tens} (type A), obtained from the measurement of four 4160s and five 4180s. Resonance frequency and quality factor were measured by using the frequency dependency of the microphone's electrical impedance. Tension of the membrane was estimated by measuring the microphone capacitance with

Table 2 Values and uncertainties of microphone parameters.

Microphone type	Resonance frequency (kHz)	Quality factor	Tension (kN/m)	Equivalent volume (mm^3)
4160	7.4 ± 0.2	1.03 ± 0.02	2.5 ± 0.2	143 ± 12
4180	22.0 ± 0.5	0.95 ± 0.04	2.5 ± 0.1	8.9 ± 0.4

and without a small amount of pressure (± 0.5 kPa) and considering the shape and dimensions of the membrane and the back-plate. Table 2 also lists the equivalent volume calculated from the tension for reference.

6. UNCERTAINTY COMPONENTS RELEVANT TO THE ACOUSTIC CIRCUIT

6.1. Temperature and Pressure Dependency of Pressure Sensitivity

Rasmussen previously measured temperature and pressure coefficients of pressure sensitivity for numerous 4160s and 4180s [9]. Because these coefficients slightly differed among microphones of the same type, Rasmussen normalized the coefficients to obtain coefficients that can apply to every microphone of the same type. The frequency was normalized by using the resonance frequency of the microphone, and temperature and pressure coefficients were normalized by the corresponding values at 250 Hz. Therefore, uncertainty of the temperature (or pressure) coefficient was caused by uncertainty u_{f0} of the resonance frequency (type A) and uncertainty u_{co250} of the temperature (or pressure) coefficient at 250 Hz (type B, rectangular). The u_{co250} reported by Rasmussen is as follows; the uncertainty of the temperature coefficient at 250 Hz was $0.0019/\sqrt{3} = 0.0011$ dB/K for 4160 and $0.0015/\sqrt{3} = 0.0009$ dB/K for 4180, and the uncertainty of the pressure coefficient at 250 Hz was $0.0002/\sqrt{3} = 0.0001$ dB/kPa for 4160 and $0.0002/\sqrt{3} = 0.0001$ dB/kPa for 4180.

Based on u_{f0} and u_{co250}, the uncertainty u_{temp_co} of the temperature coefficient and the uncertainty u_{pres_co} of the pressure coefficient at the measurement frequency (type A) were calculated by using linear interpolation, unless the coefficients were already reported by Rasmussen [9].

The larger the difference between the measured temperature and the reference environmental conditions (23°C, 101.325 kPa and 50%) [2], the larger the uncertainty of pressure sensitivity caused by u_{temp_co}. Moreover, the larger the temperature coefficient, the larger the uncertainty of pressure sensitivity caused by the uncertainty of temperature u_{temp}. Therefore, based on these two components, the combined uncertainty u_{p_temp} of the pressure sensitivity related to temperature (type A) was calculated, considering the temperature of the calibration room was kept at 23.0 ± 0.5°C.

This analysis procedure was similarly applied to the combined uncertainty u_{p_pres} of the pressure sensitivity related to static pressure, considering that static pressure fluctuated at 101.325 ± 2 kPa (Static pressure was not controlled). As seen in Tables 3 and 4, u_{p_temp} and u_{p_pres} were relatively independent of frequency.

6.2. Coupler Correction Factor [2,7]

We calculated the coupler correction factor H as the sum of the effects of heat conduction, capillary tubes, microphone membrane, and wave-motion. In this section, the contribution of the uncertainty of each component described in chap. 5 (e.g., environmental measurement conditions, dimensions of the coupler and microphone parameters) to the uncertainty of the coupler correction factor was analyzed, and then the combined uncertainty of the coupler correction factor was obtained.

Table 3 Uncertainty budget of pressure sensitivity for type 4160 microphones. For simplicity, values shown should be multiplied by 10^{-3}; for example, "5" means 0.005 dB.

Component	Type	Distrubution	Explanation	Uncertainty value ($\times 10^{-3}$ dB) at measurement frequency (Hz)										
				20	30	100	300	1 k	3 k	6 k	8 k	9 k	10 k	12.5 k
u_v	A	Normal	Combined VTF	9	4	2	2	3	4	9	8	20	80	80
u_c	A	Normal	Combined transmitter capacitance	3	3	3	3	3	3	3	3	3	3	3
u_g	A	Normal	Specific-heat ratio	2	2	2	2	2	2	2	2	2	2	2
u_{pres}	A	Normal	Static pressure	1	1	1	1	1	1	1	1	1	1	1
u_{vol}	A	Normal	Cavity volume	16	16	16	16	16	16	16	16	16	16	16
u_h	A	Normal	Combined coupler correction factor	3	4	5	3	3	3	2	1	1	2	4
u_{p_temp}	A	Normal	Pressure dependency of pressure sensitivity	0	0	0	0	0	1	2	1	1	1	1
u_{p_pres}	A	Normal	Temperature dependency of pressure sensitivity	0	0	0	0	0	1	0	3	3	3	2
u_{p_f}	B	Rectangular	Frequency	0	0	0	0	0	0	0	0	0	0	0
u_{p_b}	A	Normal	Polarization voltage	1	1	1	1	1	1	1	1	1	1	1
u_{p_m}	A	Normal	Microphone instability	15	15	15	15	15	15	15	15	15	15	15
u_{p_r}	B	Rectangular	Rounding error	1	1	1	1	1	1	1	1	1	1	1
u_p			Combined pressure sensitivity	19	18	18	18	18	18	19	19	25	71	72
U_p ($k = 2$)			Expanded pressure sensitivity	38	36	36	35	35	36	38	38	49	143	143

Table 4 Uncertainty budget of pressure sensitivity for type 4180 microphones. For simplicity, values shown should be multiplied by 10^{-3}; for example, "5" means 0.005 dB.

Component	Type	Distrubution	Explanation	Uncertainty value ($\times 10^{-3}$ dB) at measurement frequency (Hz)												
				20	30	100	300	1 k	3 k	6 k	10 k	12.5 k	16 k	18 k	19 k	20 k
u_v	A	Normal	Combined VTF	12	9	10	5	6	5	5	4	3	3	20	30	60
u_c	A	Normal	Combined transmitter capacitance	3	3	3	3	3	3	3	3	3	3	3	3	3
u_g	A	Normal	Specific-heat ratio	2	2	2	2	2	2	2	2	2	2	2	2	2
u_{pres}	A	Normal	Static pressure	1	1	1	1	1	1	1	1	1	1	1	1	1
u_{vol}	A	Normal	Cavity volume	53	53	53	53	53	53	53	53	53	53	53	53	53
u_h	A	Normal	Combined coupler correction factor	29	10	5	4	2	2	2	2	2	3	3	3	3
u_{p_temp}	A	Normal	Pressure dependency of pressure sensitivity	0	0	0	0	0	0	1	1	2	2	2	1	1
u_{p_pres}	A	Normal	Temperature dependency of pressure sensitivity	0	0	0	0	0	0	0	0	0	2	3	3	3
u_{p_f}	B	Rectangular	Frequency	0	0	0	0	0	0	0	0	0	0	0	0	0
u_{p_b}	A	Normal	Polarization voltage	1	1	1	1	1	1	1	1	1	1	1	1	1
u_{p_m}	A	Normal	Microphone instability	30	30	30	30	30	30	30	30	30	30	30	30	30
u_{p_r}	B	Rectangular	Rounding error	1	1	1	1	1	1	1	1	1	1	1	1	1
u_p			Combined pressure sensitivity	50	42	41	41	41	40	40	40	40	40	44	48	66
U_p ($k = 2$)			Expanded pressure sensitivity	101	84	83	81	81	81	81	81	81	81	88	96	132

6.2.1. Dependency on measurement environmental conditions

The maximum combined uncertainty u_{h1} of the coupler correction factor due to u_{temp}, u_{pres}, and u_{hum} was 0.0002 dB, which is negligible (type A).

6.2.2. Dependency on dimensions of coupler cavity

The combined uncertainty u_{h2} of the coupler correction factor due to u_l and u_d was relatively independent of frequency (type A).

6.2.3. Dependency on dimensions of the capillary tubes

Uncertainty u_{h3} of the coupler correction factor due to u_{capil_d} is shown in Fig. 5 (type A). Type 4180 showed a significant u_{h3} at a lower frequency range below 30 Hz.

Uncertainty of the coupler correction factor due to u_{capil_l} was neglected because it was 0.0002 dB maximum within the measurement frequency range.

6.2.4. Dependency on microphone parameters

The combined uncertainty u_{h4} of the coupler correction factor due to uncertainties of the microphone parameters was relatively independent of frequency (type A). Uncertainty of the equivalent volume was not considered because it was already included in terms of the tension in the microphone membrane. u_{h4} was multiplied by $\sqrt{2}$, because the uncertainties of the parameters for the transmitter microphone were the same as those for the receiver microphone.

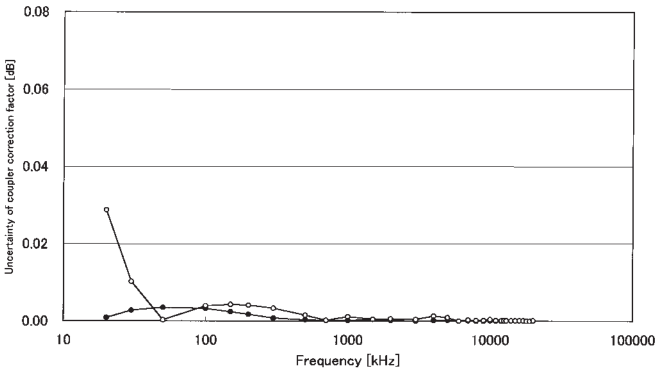

Fig. 5 Uncertainty u_{h3} of coupler correction factor caused by uncertainty of the inner diameter in capillary tubes for type 4160 (●) and 4180 (○) microphones.

6.2.5. Radial wave-motion

Uncertainty of the coupler correction factor due to the effect of radial wave-motion was already included in the calculation procedure [7], together with longitudinal wave-motion.

6.2.6. Screw threads inside the microphone front cavity

The effect of screw threads inside the microphone front cavity was not considered because it is not currently included in IEC 61094-2.

6.2.7. Combined uncertainty

Based on u_{h1} to u_{h4}, the combined uncertainty u_h of the coupler correction factor (type A) for 4160 was a maximum of only 0.005 dB, and therefore relatively independent of frequency. However, for 4180, u_h was significant below 30 Hz due to u_{h3} (inner diameter of the capillary tubes).

6.3. Specific-Heat Ratio

Based on the formula described in IEC 61094-2, the uncertainty of the specific-heat ratio (type B, rectangular) was 3.2×10^{-4}, namely, $0.0028/\sqrt{3} = 0.0016$ dB. Because the specific-heat ratio is a function of temperature, static pressure, and humidity, its uncertainty caused by the respective uncertainties u_{temp}, u_{pres}, and u_{hum} was calculated as 0.00002 dB (negligible), 0.0001 dB (negligible), and 0.0005 dB, respectively (type A). Based on these components, the uncertainty u_g of the specific-heat ratio was 0.0017 dB (type A).

6.4. Instability of Microphone

Past calibration records showed that one of the uncertainty components of pressure sensitivity might be the instability of the microphone characteristics, such as the distance between a microphone's membrane and back-plate, and the tension of the membrane. The uncertainty $u_{\rm p\_m}$ of pressure sensitivity caused by this instability was 0.015 dB for 4160 and 0.030 dB for 4180 (type A) [10].

6.5. Rounding Error

In the calculation of the pressure sensitivity, interim results were rounded off to the third decimal place. Therefore, uncertainty $u_{\rm p\_r}$ of the pressure sensitivity due to round-off error (type B, rectangular) was $0.001/\sqrt{3} = 0.0006$ dB.

7. COMBINED UNCERTAINTY OF PRESSURE SENSITIVITY

The combined uncertainty $u_{\rm p}$ of the pressure sensitivity was obtained by using the following equation, which includes every possible component that contributed to $u_{\rm p}$:

$$u_{\rm p}^2 = \frac{3}{4}u_{\rm v}^2 + \frac{1}{4}(u_{\rm g}^2 + u_{\rm pres}^2 + u_{\rm c}^2 + u_{\rm vol}^2) + u_{\rm h}^2 + u_{\rm p\_temp}^2 + u_{\rm p\_pres}^2 + u_{\rm p\_f}^2 + u_{\rm p\_b}^2 + u_{\rm p\_m}^2 + u_{\rm p\_r}^2 \quad (3)$$

Tables 3 and 4 reveal several dominant components, such as $u_{\rm v5}$ (VTF repeatability), $u_{\rm vol}$ (cavity volume), $u_{\rm h3}$ (capillary tube correction) and $u_{\rm p\_m}$ (microphone instability).

For 4160, $u_{\rm p\_m}$ was the dominant component below 8 kHz, whereas $u_{\rm v5}$ was the dominant component above 9 kHz. It would be difficult to improve $u_{\rm p\_m}$ because it is based on inherent characteristics of the microphone, as described in sec. 6.4. Furthermore, $u_{\rm v5}$ is also inherent because the frequency range at which $u_{\rm v5}$ was dominant was above the resonance frequency of the microphone membrane.

For 4180, both $u_{\rm vol}$ and $u_{\rm p\_m}$ were dominant below 17 kHz, whereas $u_{\rm v5}$, in addition to $u_{\rm vol}$ and $u_{\rm p\_m}$, was dominant above 18 kHz. $u_{\rm vol}$ had a much stronger influence for 4180 than for 4160 because the cavity volume in the coupler used for the 4180 was smaller. Furthermore, the influence of $u_{\rm h3}$ increased as the frequency decreased, especially below 30 Hz. To improve $u_{\rm h3}$, a more accurate method is needed for measuring the inner diameter of capillary tubes.

Finally, the expanded uncertainty [5] $U_{\rm p}$ of pressure sensitivity was calculated as $U_{\rm p} = ku_{\rm p}$ (where k is the coverage factor and was equal to 2). As shown in Tables 3 and 4, $U_{\rm p}$ was 0.04 dB for 4160 (20 Hz to 8 kHz) and 0.09 dB for 4180 (30 Hz to 18 kHz), respectively. Figure 6 shows the frequency dependency of $U_{\rm p}$.

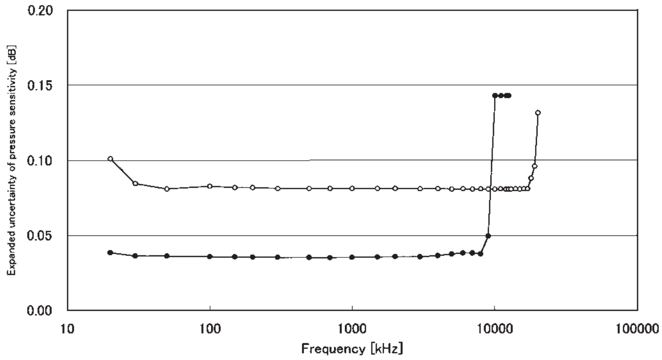

Fig. 6 Expanded uncertainty $U_{\rm p}$ of pressure sensitivity for type 4160 (●) and 4180 (○) microphones.

8. CONCLUSION

This study analyzed in detail the uncertainty of pressure sensitivities for two types of laboratory standard microphones, Brüel & Kjær types 4160 and 4180. Every possible component that influenced the uncertainty was examined based on the pressure sensitivity formula, and then the expanded uncertainty was deduced. The analysis revealed several dominant components, such as repeatability of the VTF measurement, cavity volume of the coupler, capillary tube correction, and instability of the microphone.

Future research will include examining the uncertainty caused by differences in the pressure calibration system used by NMIJ and the Brüel & Kjær type 5998, which is used in many National Metrology Institutes (NMIs) throughout the world, and estimating the uncertainty of coupler correction factor experimentally by using different shapes and sizes of couplers.

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