How the reliable environmental noise measurement is ensured

— Development of acoustic standards and a new calibration service system —

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To ensure the reliable results in acoustic measurement such as environmental noise measurement, NMIJ/AIST has developed essential calibration techniques and established a traceability system based on the Japanese Measurement Law with acoustic standards at the highest level of accuracy. A new calibration service for reliable acoustic measurements under this system realized a minimum uncertainty in the environmental noise measurements, indispensable to sustain high quality of our daily life.

Keywords : Environmental noise measurement, laboratory standard microphone, pressure sensitivity, coupler reciprocity method, measurement microphone, sound level meter, free-field sensitivity, anechoic chamber

1 Introduction

In some way or another, we are exposed to sound in our daily life. Sound disturbing our conversation or uncomfortable sound is regarded as noise. Noise affects our daily life in many ways such as sleep disturbance or inefficiency in working and in some cases will result in serious health damage of hearing loss.

The Japanese Basic Environment Law provides basic principles of environmental preservation and the measures for its realization to secure our healthy and cultural life, and to contribute to the welfare of human beings. The law deals with environmental problems such as noise pollution and air pollution, and gives regulations and standards on the environmental noise. The Noise Regulation Law provides regulations for the noise from specific plants, construction machines and cars. Environmental quality standards to be achieved by the government are set for traffic, Shinkansen (Bullet train) and airplane noise. NMIJ/AIST has been requested to solve technical problems necessary for the reliable environmental noise measurement and thus to sustain high quality in our daily life from the standpoint of environmental noise.

Physically speaking, sound wave is a phenomenon in which the vibration of a sound source causes the vibration of a medium (air) surrounding it and the vibration of the medium is spatially transmitted[1]. The vibrational transmission causes change in time and spatial distribution of medium density, resulting in pressure fluctuation. Sound pressure is defined as pressure fluctuation from static pressure caused by the sound wave. Sound pressure is a main physical quantity in acoustics and thus its precise measurement is essential[2].

In many cases, the magnitude of the sound pressure is expressed as sound pressure level[Term 1]. Decibel and dB is used as its unit and symbol, respectively. If two types of test sounds have the same sound pressure level but different frequency (pitch), they are recognized as different loudness because our hearing is dependent on frequency. Frequency weighting which imitates our hearing is named frequency weighting A and the sound pressure level considering frequency weighting A is named A-weighted sound pressure level, or more generally, the sound level. The unit of the sound level is decibel, the same as the sound pressure level. (In the past, the unit of the sound level was phon but it is internationally standardized to decibel now.) The sound level is used to evaluate the environmental noise or the noise from instruments[3].

As shown in Fig. 1, the sound pressure level or the sound level is measured by acoustic measuring instruments such as measurement microphones[4] or the sound level meters[5,6]. The sound pressure can be got from the output voltage of the measurement microphone which is used as a sensor of the sound pressure. The sound level meter can directly display sound pressure levels or sound levels to be measured because it works as a sensor of the sound pressure and calculates those quantities.

Typical end-users of sound level meters are as follows; (1) providers who officially verify the environmental measurement results by a certificate of the measured sound level or the environmental measurement specialists who constitute the providers, (2) local autonomies who measure the environmental noise in various districts, (3) manufacturers who measure acoustic characteristics of their products, (4) scientists in universities or institutes who conduct acoustic measurements.

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The Japanese Measurement Law has regulated “specific measuring instruments” essential for business dealings or certification. To realize the reliable measurement, the law provides items to be tested for structure and measurement accuracy, and the corresponding criteria to be reached. The sound level meter is designated as one of the specific measuring instruments and has been tested. At present, about fifty thousand sound level meters have passed the testing and they are used for official noise measurement.

In the testing procedure of the sound level meter, the sound pressure applied to the microphone, namely the sound pressure at the tip of the sound level meter is precisely measured to evaluate the indication of the sound level. A laboratory standard microphone is used to determine this sound pressure. As shown in Fig. 2, it is a special measurement microphone superior to the others in stability[7,8]. In other words, sensitivity of the laboratory standard microphone as a sensor of the sound pressure, namely the ratio of the output voltage to the input sound pressure, is adopted as the national standard in acoustic measurement (the acoustic standard). The laboratory standard microphone used as a reference to test the sound level meter is named the reference standard for the sound level. NMIJ/AIST has calibrated a lot of reference standards for the sound level for nearly half a century including the time of the former Agency of Industrial Science and Technology / Electrotechnical Laboratory[9,10].

The Japanese testing system has allowed only sound level meters which passed the testing to be used for business dealings and certification, and this will be continued into the future. However, the testing does not cover the concept of uncertainty which has been internationally expressed in recent years. Uncertainty of calibration results is not expressed in the testing reports of the reference standards for the sound level. In the testing procedure of the sound level meter as a specific measuring instrument, it is judged to fulfill the criterion only by comparing its indication of the sound level with the value determined by the reference standard for the sound level and determining that it is within the normal tolerance.

Uncertainty is now introduced into IEC and ISO international standards and JIS, which prescribe specification and calibration methods of the measuring instruments. From the scientific point of view, any measurement result essentially has some extent of uncertainty. Uncertainty of the measurement results should be properly stated to ensure objective reliance. Moreover, World Trade Organization / Technical Barriers to Trade (WTO/TBT) arrangement was made among the countries including Japan in 1995. Each country took similar responsibility to ensure the conformity to the international standards of measuring instruments in its country. Each country was required to develop the domestic traceability system[Term 2] of measuring instruments to the national standard and to verify technical equivalence of national standards among the countries.

Similarly in the acoustic area, uncertainty evaluation of acoustic measuring instruments became essential to verify their conformity to the corresponding standards[11]. Establishment of a measurement traceability system (Fig. 3) was indispensable to verify that end-users’ acoustic measuring instruments fulfill the standards.

In addition to the environmental noise measurement, measurement of the noise from household appliances (refrigerator, washing machine, vacuum cleaner, etc.) and information equipment (copying machine, personal computer, printer, etc.) has recently become important. Measurement microphones are used to evaluate the noise from these kinds of equipment[12,13].

Manufacturers of household appliances and information equipment cannot obtain reliable data on the acoustic

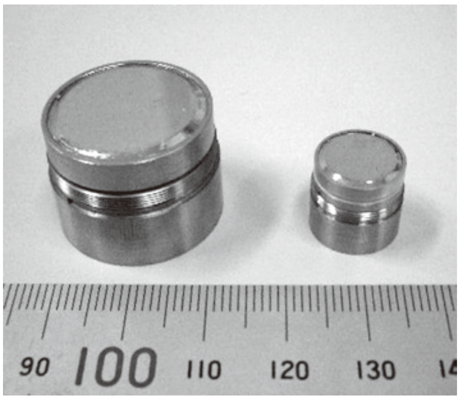

Fig. 1 Measurement microphone (left) and sound level meter (right).
Measurement microphone is a sensor of sound pressure and generates the output voltage proportional to the sound pressure applied to the diaphragm (circular surface in the left figure). Type WS1 and WS2 microphones are available for the audible frequency range (20 Hz to 20 kHz). They are different in size and in suitable frequency range. The larger (left) is type WS1.
Sound level meter senses sound pressure by the measurement microphone at the tip (left in the right figure) and calculates sound pressure level or sound level. Sound level meter consists of microphone, amplifier, frequency weighting circuit, calculation circuit and indicator.

characteristics of their own products and ensure the quality of the products internationally until their acoustic measuring instruments are verified to be in conformity with the international standards or the equivalent JIS. The establishment of a traceability system for acoustic measuring instruments was an essential technology to develop the products envisioned on a road map of future technical development by the industrial world, namely products with high quality which are environmentally friendly and safe. Such a change of needs in the industrial world resulted in the establishment of a new calibration service system of acoustic standards, which is different from the traditional testing system.

For the reliable environmental noise measurement, end-users should not only use the traceable measuring instruments but evaluate the influence specific to the measurement site such as environmental conditions (temperature, static pressure and wind) and indirect sound from the surroundings. Uncertainty related to a sound field (a space in which the sound wave is transmitted) containing indirect sound has not been technically evaluated up to this point. Influence of indirect sound depends on relative positions between acoustic measuring instruments and sound reflecting objects such as the ground or buildings. In the past, measured data were averaged by changing the position of the measuring instrument. Uncertainty caused by indirect sound could be decreased by this method, but the obtained data were not reliable enough because the remaining uncertainty could not be quantitatively evaluated.

The calibration of acoustic measuring instruments had the same technical problem. Acoustic measuring instruments are usually calibrated within an anechoic chamber which is designed to minimize the influence of indirect sound. However, even a high-performance anechoic chamber cannot realize a space completely free from indirect sound. Indirect sound was the main cause of uncertainty in the calibration of acoustic measuring instruments. JIS of sound level meters[6] requires uncertainty decrease by placing the sound source and the sound level meter at several positions and by averaging the measured data. However, it is just one of the procedures to judge if the specification of the sound level meter fulfills the criterion, and the uncertainty still remained not properly evaluated.

Considering such a situation, NMIJ/AIST developed the technique necessary to evaluate the uncertainty of the sound field caused by indirect sound and thus solved the technical problem.

Furthermore, there was one more technical problem in the calibration of acoustic measuring instruments. Acoustic standards realized so far did not have measurement uncertainty small enough to evaluate the conformity of some acoustic measuring instruments to the corresponding standard. Development of advanced (high-precision) acoustic standards was essential to decrease the uncertainty.

In the following chapters, research results are described which were done to solve these problems and to realize the reliability of environmental noise measurement.

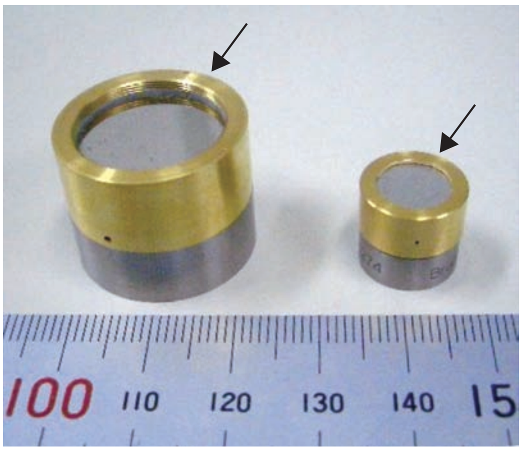

Fig. 2 Laboratory standard microphone.
Laboratory standard microphone is one of the measurement microphones but its sensitivity must be sufficiently stable compared with the others because it is required to be reliable as an acoustic standard. It has a special structure around the diaphragm (gold part and indicated by an arrow in the figure) to protect the diaphragm when it is fitted to the coupler for the sensitivity calibration as will be explained later. Left is type LS1P and right is LS2aP microphone, respectively.

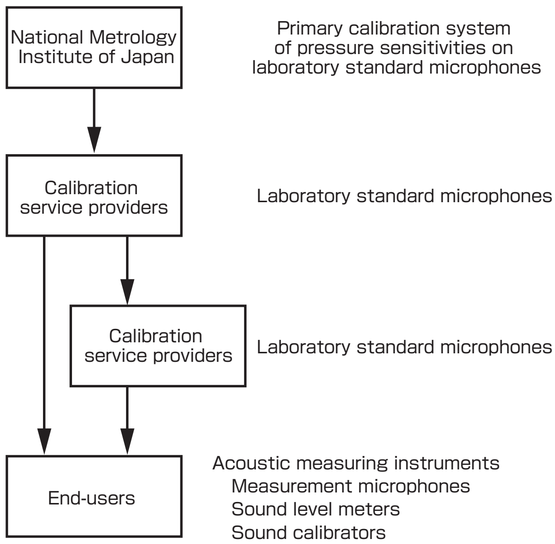

Fig. 3 Schematic of traceability system in acoustic measurement.
Laboratory standard microphones possessed by a high-ranking calibration service provider are calibrated by using a primary calibrated system NMIJ developed. Lower-ranking provider's microphones are calibrated in comparison with higher-ranking provider's microphones. End-users' acoustic measuring instruments are calibrated in comparison with higher or lower ranking provider's microphones.

2 Elemental technologies and research scenario

Elemental technologies are necessary to solve the two technical problems mentioned in the last chapter and to achieve a research goal of realizing the reliable environmental noise measurement.

The first elemental technology is the uncertainty decrease in sensitivity calibration of laboratory standard microphones. Calibration uncertainty of laboratory standard microphones realized by NMIJ/AIST thus far was around 0.1 dB at the smallest. According to JIS, however, calibration uncertainty of a high-grade sound calibrator used to check sound level meters[14] (a portable sound source which generates the given sound pressure to calibrate the instruments) was less than 0.1 dB. The laboratory standard microphone with an uncertainty of 0.1 dB was not suitable as a reference to evaluate the performance of the sound calibrator. Therefore, an advanced calibration system of laboratory standard microphones became essential. Signal-to-noise ratio of the calibration system was improved by introducing the digital signal processing technique etc. and the uncertainty was decreased to 0.04 dB.

The second elemental technology is the development of the method necessary to evaluate the uncertainty caused by the imperfection (existence of indirect sound) of the sound field which is used to calibrate acoustic measuring instruments. The developed method made it possible to evaluate the uncertainty quantitatively by visualizing the influence of the indirect sound and to remove unnecessary indirect sound by using the digital signal processing technique.

Lastly, the traceability system of acoustic measuring instruments was required to return these research results to society. It is not until the traceability system is established that the advanced calibration technique of laboratory standard microphones and acoustic measuring instruments gives more reliable measurement results to end-users. NMIJ/AIST established the traceability system, providing acoustic standards as the highest level of accuracy, and calibration service providers could calibrate end-users' acoustic measuring instruments using these acoustic standards.

The traceability system is required to confirm the measurement capability of the constituent organizations in each level, namely NMIJ/AIST and calibration service providers. NMIJ/AIST internationally participated in several round robin tests among the national metrology institutes and

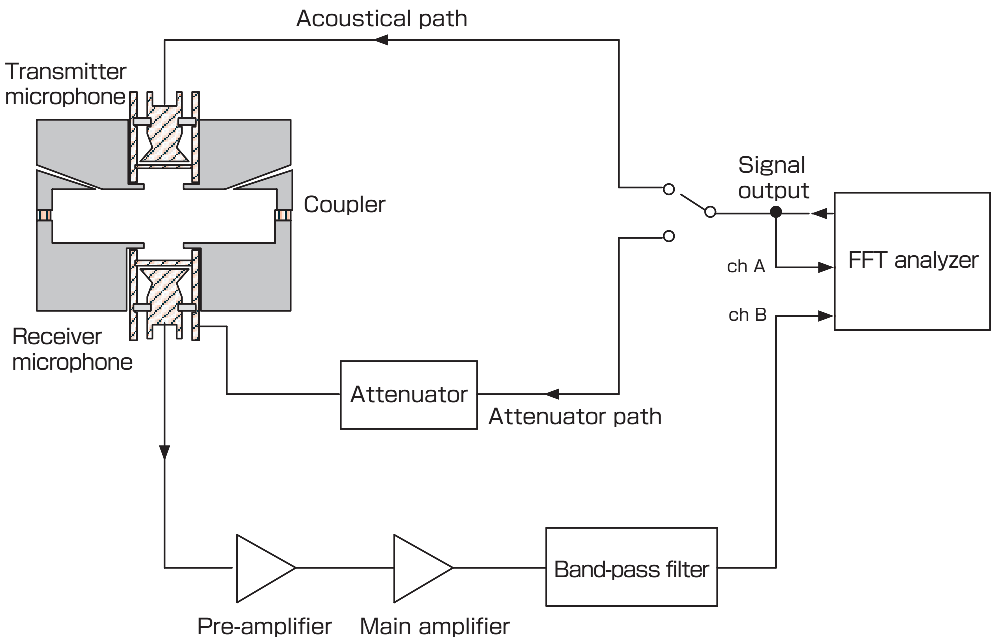

Fig. 4 Schematic of primary calibration system of laboratory standard microphones by the coupler reciprocity method.
Coupler reciprocity method uses two laboratory standard microphones, one as a transmitter and the other as a receiver. Sound wave is generated from the diaphragm of the transmitter by applying the input voltage, arrives at the diaphragm of the receiver through a cavity of the coupler and the output voltage is detected at the receiver.
Sensitivity product of the two microphones are obtained from the cavity volume of the coupler and the voltage ratio between the input terminal of the transmitter and the output terminal of the receiver, by using a principle of an electro-acoustic transducer that the sensitivity of the transmitter is equal to that of the receiver. Introduction of one more laboratory standard microphone enables the sensitivity of each microphone to be determined by measuring the voltage ratios for the three combinations of the transmitter and the receiver.
This method requires cancellation of influence caused by the output impedance of the receiver and the gain of the amplifier to measure the open-circuit output voltage of the receiver precisely. Thus, the calibration system has two signal paths, namely the acoustical path and the attenuator path. Ratio of the receiver's output voltages between the two paths cancels this influence.

also technically supported the tests for domestic calibration service providers. Constituent organizations were assessed for their calibration procedures and uncertainty evaluation methods by a third party to verify their measurement capability objectively.

Development of individual elemental technologies and their integration by the traceability system resulted in an international scheme of providing the reliable environmental noise measurement results for end-users.

3 Microphone as national standard

3.1 Primary calibration of pressure sensitivity

The microphone as a national standard (laboratory standard microphone) has two requisites: the stability of pressure sensitivity[Term 3] and the established method for precise absolute calibration (primary calibration) of the pressure sensitivity. The coupler reciprocity method[15] is used for primary calibration of pressure sensitivities on laboratory standard microphones. As shown in Fig. 4, the sound wave is kept within the acoustic coupler (a cavity with small volume) during calibration. Other calibration methods were not adopted because one cannot cover the whole audible frequency range (20 Hz to 20 kHz)[16] and the others have a drawback of having larger uncertainties[14,17].

NMIJ/AIST introduced digital signal processing technique into the coupler reciprocity method and improved the calibration uncertainty from the point of view of noise reduction, attenuator calibration and cross-talk minimization[18].

Firstly, digital signal processing by using an FFT analyzer[Term 4] was adopted as a new noise reduction technique because analogue signal processing by a traditional filter with narrow bandwidth had a problem in measurement repeatability. Synchronous average method by using a built-in signal source of the FFT analyzer improved measurement repeatability from 0.02 dB to 0.007 dB in the main frequency range and reduced measurement time by half.

Secondly, small output voltage (0.1 mV to 0.8 mV) which was attenuated to adjust a signal level could not be directly measured with small uncertainty to that point[19]. If the ratio of attenuation is pre-determined, small uncertainty can be ensured with only the measurement of large input voltage applied to the attenuator. Thus, the advanced calibration method for attenuators was developed by using the FFT analyzer and it decreased the uncertainty from 0.01 dB to 0.001 dB.

Lastly, measurement circuits were re-designed to minimize the cross-talk. It is one of the uncertainty factors, meaning that a signal is wrongly mixed due to bypassing the unexpected paths. Severe measures were taken as in the high frequency circuits and the uncertainty caused by the cross-talk was decreased from 0.01 dB to 0.001 dB.

3.2 Instability of pressure sensitivity

However, deviation of the pressure sensitivity still remained after the calibration system was improved. The author supposed that the cause of instability might be inherent in the microphone to be calibrated and considered various causes to verify this hypothesis. Theoretical analysis on frequency characteristics of the sensitivity deviation revealed that the microphone is deformed when contacting surfaces between the microphone and the coupler are sealed with grease and that the change of microphone’s acoustic characteristics results in instability of the pressure sensitivity[20].

Such deviations were remarkable to a specific type of domestic laboratory standard microphones and thus this type was not adopted as an acoustic standard[21]. At present, the uncertainty due to instability of the microphone sensitivity is 0.012 dB for LS1P microphones and 0.008 dB for LS2aP, respectively (Refer to Fig. 1 for the difference between LS1P and LS2aP microphones).

3.3 Measurement uncertainty of pressure sensitivity

As a result of improvement, of the uncertainty components reformable at the state of the art, the influence could be minimized to a negligibly small level. Remaining uncertainty components are the instability of the microphone sensitivity and the internal volume of the coupler. Volume uncertainty of the coupler used for LS1P microphones (its internal volume is approximately 20 cm^3) is 0.008 dB and that for LS2aP (1 cm^3) is 0.015 dB, respectively. In the main frequency range, the uncertainty (95 % level of confidence) of the pressure sensitivity for both LS1P and LS2aP microphones is evaluated to be 0.04 dB. This uncertainty is half of what it was before [22].

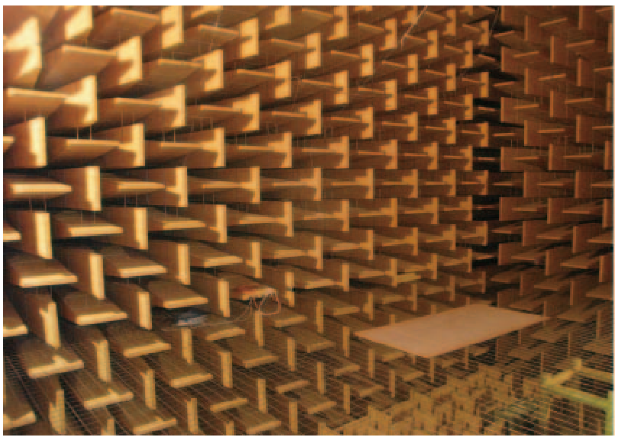

Fig. 5 Anechoic chamber of NMIJ/AIST.
Many sound absorbing wedges made of glass wool protrude from the inside wall of the anechoic chamber. Plywood was put on the wire meshed floor for a better view.

4 Evaluation of sound field

4.1 Indirect sound

Secondary calibration of acoustic measuring instruments is made in comparison with a reference standard microphone, usually within an anechoic chamber. A lot of sound absorbing wedges protrude from the inside wall of the anechoic chamber including its ceiling and bottom to minimize indirect sound. A floor necessary to carry measuring instruments into the anechoic chamber has a special structure of a wire meshed floor[Term 5] to decrease sound reflection[23]. However, actual sound field within the anechoic chamber is still influenced by indirect sound, due to incompleteness of sound absorbing wedges and the wire meshed floor. For the NMIJ/AIST's facility shown in Fig. 5, the degree of indirect sound is approximately 1 to 2 % of the direct sound. Furthermore, structures necessary to fix the reference microphone (laboratory standard microphone with pre-determined free-field sensitivity[Term 6]) or acoustic measuring instruments to be calibrated also influence sound reflection. Deviation of the sound field from an ideal situation due to indirect sound cannot be theoretically estimated and thus the corresponding uncertainty must be experimentally evaluated.

4.2 Secondary calibration of acoustic measuring instruments

Description in the following sections of chapter 4 is focused on calibration of measurement microphones. However, a similar approach can be applied to sound level meters.

Two secondary calibration methods are applicable to acoustic measuring instruments, namely sequential method and simultaneous method[24]. Both methods have the common procedures as follows. The reference microphone and the test microphone (the measurement microphone to be calibrated) are placed ahead of a loudspeaker. Ratio of the output voltages between the two microphones, namely the ratio of sensitivities is measured. Sensitivity of the test microphone is determined as the product of this ratio by the sensitivity of the reference microphone. Two methods are different in the placement of the microphones.

In the sequential method, the reference microphone is replaced by the test microphone and the output voltage of the microphone is sequentially measured. This method assumes that equal sound pressure is applied to both microphones during the measurement. However, actual sound pressure fluctuates because the characteristics of the loudspeaker changes with the generation of heat and this phenomenon results in calibration uncertainty.

In the simultaneous method, both microphones are placed at close positions and are exposed to the sound field simultaneously. Fluctuation of sound pressure caused by the loudspeaker's instability does not cause a problem because the output voltage ratio of the microphones becomes stable due to the cancellation effect. Measurement time can be decreased by half compared with the sequential method. As described later, however, uncertainty related to the sound field increases because the two microphones are placed at different positions within the sound field; partly because sound pressure has a spatial distribution in the sound field and partly because the existence of one microphone disturbs the sound field to which the other microphone is exposed.

A drawback of the sequential method can be solved by placing a third microphone in front of the loudspeaker to monitor the fluctuation of sound pressure and by correcting the change. In this research, the sequential method was adopted because it can evaluate the uncertainty more

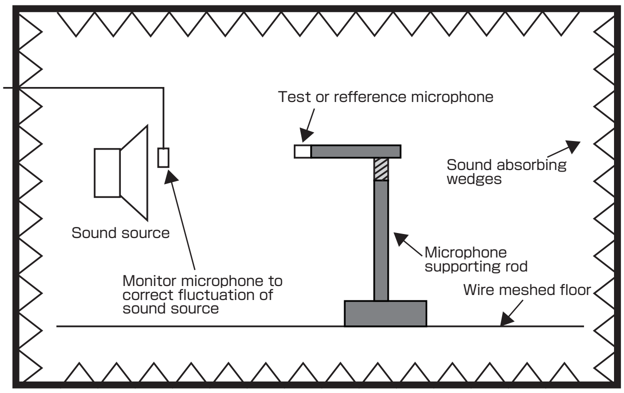

Fig. 6 Schematic of secondary calibration system of measurement microphones by the sequential method.
A lot of sound absorbing wedges protrude from the inside wall of the anechoic chamber to minimize indirect sound. However, it is quite difficult to realize an ideal free-field even in the high-performance anechoic chamber. As will be explained later, reflection from the object closest to the test or reference microphone has dominant influence. In this measurement system, reflection is mainly caused by the upper end of vertical rod which supports the microphone (area with oblique lines in the figure).

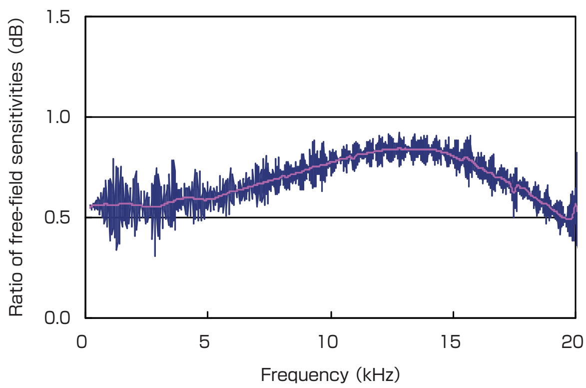

Fig. 7 Frequency characteristics of ratio of free-field sensitivities between reference and test microphones.
Influence of indirect sound is visualized as vertical fluctuation in the blue curve. The pink curve has smooth frequency characteristics because this influence was minimized by using digital signal processing technique as will be explained later.

precisely by introducing the monitor microphone. Figure 6 shows a schematic of secondary calibration system of measurement microphones by the sequential method.

4.3 Visualization of influence by indirect sound

Indirect sound reaches the microphone through a path different from direct sound and they interfere with each other. Thus on the frequency domain, sound pressure at the microphone position has local minimums and maximums alternately. Indirect sound adds small waves to the frequency characteristics of the microphone output voltage which would be inherently smooth without indirect sound. Influence of indirect sound changes with relative positions of the loudspeaker, microphone and sound reflecting objects. Reflection from the object closest to the microphone has dominant influence.

Influence of indirect sound also depends on the shape of microphone housing and even on the slight difference of positions between the reference and test microphones. Therefore, measured sensitivity ratio between the microphones has frequency characteristics as shown in the blue curve of Fig. 7. The amplitude of the waves is equal to the uncertainty caused by indirect sound and frequency of the waves corresponds to the distance between the sound reflecting object and the microphone. Frequency dependence of sensitivity ratio enabled the specification of the most influential object and taking the measures necessary to decrease indirect sound.

In some cases, influence of indirect sound was decreased by averaging the sensitivity ratio in the vicinity of the measurement frequency. This method is not appropriate from the point of view of calibration results and uncertainty.

4.4 Reduction of influence by indirect sound − application of sound absorbing material −

The author tried to decrease the influence of indirect sound simply by covering the sound reflecting object with sound absorbing material. This method was effective if the reference and test microphones belonged to the same type but it was not sufficient for the different types.

4.5 Reduction of influence by indirect sound − application of digital signal processing technique −

Uncertainty caused by indirect sound can be decreased if the indirect sound is separated and removed from the direct sound on the time domain, since the indirect sound reaches the microphone later than the direct sound. However, simple application of pulse waveform with short duration as an input signal cannot give sufficient signal-to-noise ratio because the energy of the waveform is essentially distributed to the frequencies other than the measurement frequency. In this research, NMIJ/AIST developed a virtual pulse method to solve this problem[25]. This method makes use of computer simulations to determine time response which would be obtained by the application of pulse waveform. Sufficient signal-to-noise ratio can be ensured because a continuous waveform is used to measure the data necessary for simulation. The virtual pulse method could not be realized until digital signal processing by the FFT analyzer was introduced into the measurement.

In the method, time response is calculated on condition that a virtual pulse signal is applied to the system with transfer function as shown in the blue curve of Fig. 7. Only direct sound is taken from the calculated pulse response waveform by applying the time window function and it is transformed into the frequency domain. As a result, smooth frequency characteristics not influenced by indirect sound can be achieved as shown in the pink curve of Fig. 7.

After indirect sound was removed by digital signal processing technique, still remaining small uncertainty related to the signal processing, namely uncertainty caused by slight difference of parameters used in the signal processing were evaluated. These were such differences as the frequency bandwidth of the pulse waveform and duration and center position of the time window function to remove indirect sound.

5 Establishment of traceability system on acoustic measuring instruments by JCSS

As described in chapter 1, a new calibration service system of acoustic standards, different from the traditional measurement management system based on the testing of sound level meters, was required. Basis of the new system was JCSS (Japan Calibration Service System) in the Japanese Measurement Law[26]. In the system, firstly NMIJ/AIST evaluates calibration uncertainty of laboratory standard microphones as national standards and calibrates laboratory standard microphones of calibration service providers in comparison with one of the national standards. Then calibration service providers calibrate end-users' acoustic measuring instruments in comparison with one of their laboratory standard microphones and ensure traceability to the national standards. Special attention was paid to the following points to establish the system.

- The system allows calibration service providers to develop individual measurement management procedures. In addition to the receiving supply of national standards directly from NMIJ/AIST, they can also get acoustic measuring instruments traceable to the national standards from other high-ranking calibration service providers. Furthermore, measurement management is possible by using acoustic measuring instruments other than laboratory standard microphones as working standards for daily calibration use.

・The system can introduce new technology fairly rapidly by reconsidering technical requirements essential for the assessment of calibration service providers whenever necessary.
・JCSS can verify the performance of acoustic measuring instruments within the audible frequency range (20 Hz to 20 kHz) while the testing of sound level meters was limited to a range of 20 Hz to 12.5 kHz.
・Calibration service providers are required to have technical performance suitable for essential players of the traceability system. Calibration service providers registered at present have years of accomplishments as a specific testing laboratory of sound level meters or specific manufacturers of them in the Japanese Measurement Law.

6 Validation of measurement capability

6.1 Validation of equivalence among national standards

In 1999, mutual recognition arrangement of measurement standards was made among countries including Japan[27]. In this arrangement, national metrology institutes of the countries approve the equivalence among national standards and accept calibration certificates of each other. Institutes of signatory nations are required to establish the quality system[Term 7] conformable to the international rule of ISO/IEC 17025[28] and to verify their measurement capability objectively by participation in international comparisons (round robin tests).

NMIJ/AIST established the quality system on self-developed acoustic standards. The National Institute of Technology and Evaluation (NITE) assessed NMIJ/AIST from the point of view of conformity to ISO/IEC 17025, based on ASNITE-NMI (a program to accredit national metrology institutes). NMIJ/AIST was accredited in the field of acoustics in January 2003.

As to international comparisons, CIPM/CCAUV (International Committee for Weights and Measures / Consultative Committee for Acoustics, Ultrasound and Vibration) planned four international comparisons on laboratory standard microphones and NMIJ/AIST took part in all of them. International comparisons on pressure sensitivities of LS1P and LS2aP microphones have already finished and the results revealed that uncertainties (95 % level of confidence) declared by the main institutes including NMIJ/AIST range from 0.03 dB to 0.05 dB within the main frequency range[29,30]. Difference of the results between NMIJ/AIST and other institutes was less than the uncertainty evaluated by NMIJ/AIST. Thus, NMIJ/AIST could verify its equivalence to the other national standards.

The number of participants in the international comparisons organized by CCAUV is limited to around ten and all the national metrology institutes in the world cannot be included. Therefore, similar international comparisons were individually conducted in several areas of the world.

In Asia and Pacific area including Japan (this area is called APMP /Asia Pacific Metrology Programme), NMIJ/AIST acted as a pilot laboratory of the first international comparison for pressure sensitivity of LS1P microphones; NMIJ/AIST prepared the technical protocol, monitored

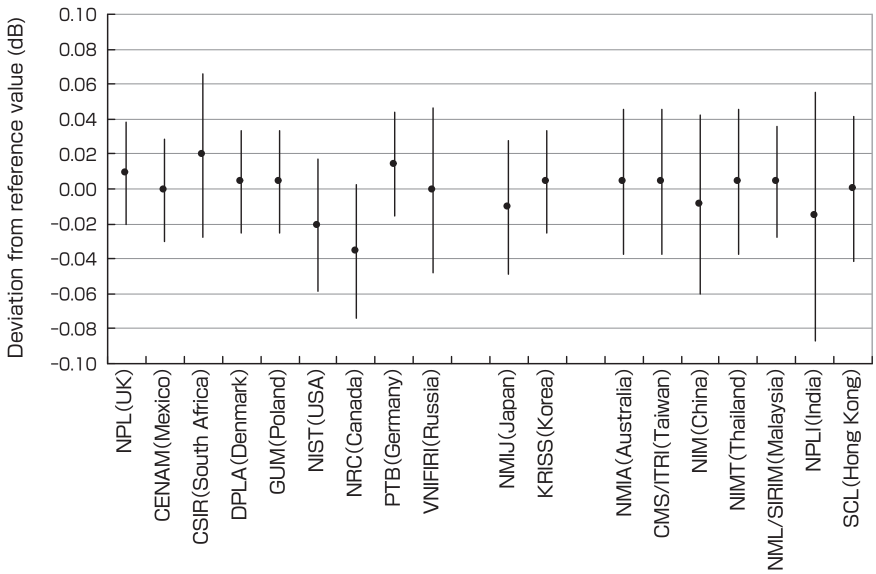

Fig. 8 Results of international comparison at 1 kHz.
Acronyms of national metrology institutes which participated in the international comparison are listed along the horizontal axis. Vertical axis shows deviation of each participant's results from the reference value, determined as the arithmetic mean of all the participants' results. If the deviation of a participant (marked as •) is within the range of uncertainty at 95 % level of confidence (which was self-declared by the participant and denoted by a bar), it is concluded that the national standard is equivalent to the other participants.

stability of traveling standards (laboratory standard microphones to be calibrated), analyzed calibration results of the participants, and developed the method to link the results of this international comparison to those of corresponding international comparisons by CCAUV[31]. Figure 8 shows results of the international comparison on pressure sensitivity of LS1P microphones. Figure 8 revealed that each participant's result agrees to the others within the uncertainty of the participant. Thus, mutual equivalence of acoustic standards among the participants was verified based on this data.

6.2 Validation of measurement capability of calibration service providers

NMIJ/AIST supported publishing a guide[32] for applying technical requirements given in ISO/IEC 17025 to the field of precise acoustic measurement. Calibration service providers established their quality systems by using this guide. Round robin tests were conducted to verify their measurement capability and NMIJ/AIST provided reference values as criteria. NMIJ/AIST also supported NITE from the technical viewpoint in the assessment of calibration service providers for accreditation. At the end of August, 2009, six calibration service providers were accredited as JCSS providers and their measurement capability was verified accordingly.

7 Research results

In this research, NMIJ/AIST made technical development indispensable to ensure the reliable environmental noise measurement and thus to sustain safety in our daily life. Firstly, primary calibration system of pressure sensitivities on laboratory standard microphones was advanced, resulting in a new calibration service of acoustic standards. Uncertainty caused by electrical characteristics of the calibration system was minimized to the limit at the present time. This revealed that instability of the microphone sensitivity is a dominant factor of uncertainty and that different types of microphones have different degrees of stability.

Secondly, NMIJ/AIST developed the method essential to evaluate the uncertainty related to the sound field. This evaluation has been an unsolved problem in secondary calibration of end-users' acoustic measuring instruments, conducted in comparison with laboratory standard microphones. Introduction of digital signal processing technique succeeded in decreasing the influence of indirect sound.

Lastly, the above technical development resulted in the new calibration service system of acoustic standards, ensuring traceability based on the Japanese Measurement Law. Measurement capability of calibration service providers was verified by several ways: supply of acoustic standards, discussion of the guide used to take technical requirements into account, provision of reference values in the round robin tests, and technical support in the assessment.

Besides calibration service providers, NMIJ/AIST was also assessed to get accreditation and took part in several international comparisons to verify the equivalence of national standards among the main institutes. NMIJ/AIST acted as a pilot laboratory in the first international comparison conducted in Asia and Pacific area.

These results greatly contribute to not only secure the performance of end-users' acoustic measuring instruments but also to improve the reliability of measurement by end-users. The method to evaluate indirect sound enabled the operator to find the cause and degree of indirect sound clearly. Thus, influence of indirect sound could be easily decreased by taking suitable measures and the effect of the measures could be quantitatively evaluated. As a result of the development, reliability of the measurement results became almost independent of the operator's skill and even an inexperienced operator could easily get reliable data.

8 Conclusion

NMIJ/AIST developed a calibration service system of acoustic standards based on the Japanese Measurement Law, with acoustic standards at the highest level of accuracy in the traceability system and started a new calibration service to meet the demands of the times.

The future theme is to expand the calibration frequency of acoustic standards outside of the audible frequency range. Equipment generating airborne ultrasound over 20 kHz is increasing around our living circumstances. However, sound pressure level cannot be quantitatively evaluated because acoustic standards are not yet established in the airborne ultrasound range. To discuss the problem of human safety under the exposure to strong airborne ultrasound, development of acoustic standards in high frequency range is essential[33].

On the other hand, complaints against infrasound less than 20 Hz are increasing. Although common measurement procedures have been suggested for infrasound, reliability of the measurement results cannot be ensured without acoustic standards. Acoustic standards in low frequency range should also be essentially developed[34]. NMIJ/AIST is conducting research and development of acoustic standards and measurement technology necessary to expand the available frequency range.

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Terminology

Term 1. Sound pressure level: Sound pressure is normally expressed as sound pressure level because hearing ability of normal person ranges widely. Sound pressure level L_p is defined by the following equation:

$$L_p = 10\log \frac{p^2}{p_0^2}$$

where p is rms value of sound pressure and p_0 is reference sound pressure of 20 μPa which is minimal audible value for a sinusoidal signal of 1 kHz.

Term 2. Traceability: Traceability of a measuring instrument is ensured if the reasons for its uncertainty analysis can be deduced from the national standards.

Term 3. Pressure sensitivity: Pressure sensitivity is ratio of the open-circuit output voltage of the microphone to the sound pressure uniformly applied to the diaphragm.

Term 4. FFT analyzer: FFT analyzer is an instrument to calculate FFT (Fast Fourier Transform) of the input signal and it is useful for frequency analysis of acoustic signal.

Term 5. Wire meshed floor: Wire meshed floor is composed of crossed wires, tense enough for persons to walk on. Indirect sound can be decreased because sound wave passes through the squares of grillwork.

Term 6. Free-field sensitivity: Free-field sensitivity is ratio of the open-circuit output voltage of the microphone to the sound pressure that would exist at the position of the microphone in the absence of the microphone for plane progressive sound field.

Introduction of the microphone into the sound field changes sound pressure at the position of the microphone because sound wave is reflected or diffracted by the microphone. Free-field sensitivity of a laboratory standard microphone is essential for secondary calibration of acoustic measuring instruments to get precise sound pressure which is not influenced by the existence of the microphone.

Ratio of free-field sensitivity to pressure sensitivity depends on the shape of microphone housing and acoustic characteristics of the diaphragm. Thus specific type of microphones has particular value of the ratio. Measured ratio and its uncertainty are given for laboratory standard microphones[35].

Term 7. Quality system: Quality system requires documenting the process of quality control based on the standard concerned to ensure the reliable calibration results. It consists of grounds for uncertainty analysis, practical calibration procedures, handling of instruments, personnel and calibration records.

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Discussion with Reviewers

1 Primary calibration method other than coupler reciprocity method

Question (Akira Ono, AIST)

In this paper, the coupler reciprocity method was used as a primary calibration method. Please introduce other methods if any. What kind of methods is adopted for primary calibration by the other national metrology institutes which participated in the international comparison? If some institutes used methods other than the coupler reciprocity method, please explain the reason.

Answer (Ryuzo Horiuchi)

The free-field sensitivity of a laboratory standard microphone is used as a reference in the secondary calibration of acoustic measuring instruments and it is normally determined by multiplying a correction term to the pressure sensitivity which was obtained by using the coupler reciprocity method. Direct primary calibration of the free-field sensitivity by using the free-field reciprocity method is not practically used because the pressure sensitivity can be more precisely and easily determined than the free-field sensitivity.

In the free-field reciprocity method, two laboratory standard microphones are faced with each other in the anechoic chamber instead of the coupler's cavity and the voltage ratio is measured in the same way as the coupler reciprocity method. However, this method takes a long time for the measurement of voltage ratio and requires strict measures to decrease the cross-talk because signal-to-noise ratio deteriorates at the lower frequency range. Influence of indirect sound should be also minimized because the calibration is conducted in the anechoic chamber. These reasons prevent the method from being used as a routine calibration service. Thus the other national metrology institutes use the coupler reciprocity method as a primary calibration method.

There is the "laser-pistonphone" which is available as a primary calibration technique of the pressure sensitivity only for the lower frequency range. In this method, a piston attached to a shaker is used as a transmitter and generates sound pressure within the coupler. The vibration amplitude of the piston is optically measured and translated into the sound pressure. At the same time, output voltage of the laboratory standard microphone exposed to the sound pressure is measured and the pressure sensitivity is determined. NMIJ/AIST is developing a laser-pistonphone as a primary calibration system at infrasound range.

2 Methods used by other national metrology institutes for evaluating influence of indirect sound

Question (Akira Ono)

I think the method developed by NMIJ/AIST for evaluating influence of indirect sound in the secondary calibration is an excellent research result. Do other national metrology institutes adopt a similar technique or not?

Answer (Ryuzo Horiuchi)

Other national metrology institutes use methods different from NMIJ/AIST's to evaluate and minimize the influence of indirect sound in the secondary calibration of acoustic measuring instruments. TDS (Time Delay Spectrometry) eliminates indirect sound by using a narrow bandwidth filter which works considering the arriving time of indirect sound. MLS (Maximum Length Sequence) uses special random signals to obtain a pulse response rapidly. These methods have common characteristics of separating indirect sound from direct sound on the time domain. However, no methods have been internationally standardized yet. The FFT analyzer-based virtual pulse method developed by NMIJ/AIST will be adopted as one of the methods in the international standard under discussion.

3 International level of acoustic standards and Japanese way to go in the future

Question (Akira Ono)

Figure 8 seems to show little difference between the results of main institutes which participated in the international comparison organized by CCAUV and the results of institutes in Asia and Pacific area, from the point of view of uncertainty or deviation from the reference value. It seems that, seen from another angle, Asia and Pacific institutes have smaller deviation from the average while some of the main institutes have larger deviation. Does this imply that calibration technique for acoustic standards became mature and it was transferred to the developing countries, resulting in technical equivalence among the countries? I would appreciate it if you could give me your view.

Furthermore, what will be necessary in the future for Japan to surpass the other countries from the point of view of reliability in acoustic measurement? Do you have any suggestions to the middle class of the traceability system (calibration service providers), to the lower class (end-users who conduct measurement at the site), or to the manufacturers of acoustic measuring instruments?

Answer (Ryuzo Horiuchi)

As the reviewer pointed out, the results of the international comparison (Fig. 8) show that there is little difference between the developing institutes in Asia and the leading institutes which have developed acoustic standards. This is due to the following reasons peculiar to acoustic standards. Many of the institutes in the world use the same type of primary calibration systems for laboratory standard microphones produced by one manufacturer of acoustic instruments. Calibration results can be reproduced once the operator becomes proficient in the calibration procedure. Technical information necessary for uncertainty analysis can be got without much difficulty. Therefore, even the institute with limited experience in microphone calibration can realize acoustic standards equivalent to those developed by the leading institutes. It is natural that calibration results obtained by using the same type of primary calibration systems have little deviation in the international comparison.

Just five institutes in the world (only NMIJ/AIST in Asia) have the advanced technology to develop primary calibration systems. The system developed by each leading institute has electrical or mechanical elements slightly different from other institutes. International comparison is the only way to validate their equivalence to the other institutes. It is concluded under the present technical situation that the international comparison shows good agreement among the institutes irrespective of calibration system specifications. Study of reasons for the remaining deviation would be necessary to improve the reliability of acoustic standards.

On the other hand, NMIJ/AIST is requested to take the technical leadership such as in the development of a new acoustic standard to surpass the other institutes from the point of view of reliable acoustic measurement. As described in the main text, our present theme is to expand the frequency range of acoustic standards. NMIJ/AIST is developing technical basis to sustain our daily life without any health damages caused by airborne ultrasound or infrasound.

At the same time, NMIJ/AIST should publish the research results by further study of measurement reliability from various viewpoints. In the international comparison, common calibration principles and traveling standards are adopted to validate the equivalence among the results of participants. Further consideration would be necessary to confirm the consistency among the results obtained by different calibration principles or by different types of acoustic standards. For example, influence of microphone types (LS1P or LS2aP) on the measurement results is not well evaluated yet.

Finally, as a suggestion to the calibration service providers, manufacturers and end-users of acoustic measuring instruments, I would like to appeal to them of certain necessary points to ensure the reliability of their measurement results. In addition to ensuring the traceability to national standards, uncertainty analysis on various components inherent in the measurement methods should be considered. I think the evaluation on the influence of indirect sound is a good example.

4 International and societal role of NMIJ/AIST in the future

Question (Katsuhisa Kudo, Evaluation Division, AIST)

Acoustic standards are essential in a lot of fields such as industrial, scientific and technological fields with wide-ranging end-users. Please tell us the international and societal role NMIJ/AIST should fulfill in the development of acoustic standards considering the technical trend.

Answer (Ryuzo Horiuchi)

As described in the main text, measurement of the noise from household appliances or information equipment has become important lately. Acoustic power level is mainly used to evaluate these noise sources instead of sound pressure level or sound level. Although traditional sound level intuitively gives noisy circumstances at the measurement points, acoustic power level can give total acoustic output generated by the noise source.

To ensure the reliable measurement of the acoustic power level, absolute calibration technique on a “reference sound source” should be established. It is a sound source specially designed for the precise measurement of the acoustic power level and it constantly generates noise with a wide bandwidth. The acoustic power level of the test sound source can be calibrated in comparison with the reference sound source whose acoustic power level is pre-determined. To secure the reliable measurement results for end-users, NMIJ/AIST is planning to develop precise calibration technique of reference sound sources and establish practical standards of the acoustic power level.

5 Problem requiring most time to solve

Question (Katsuhisa Kudo)

Please tell us the most difficult problem you have faced and the measures taken to solve the problem, ranging from the development of acoustic standards to the realization of the calibration service.

Answer (Ryuzo Horiuchi)

The most difficult technical problem in the development of acoustic standards was to discover the cause of instability in the pressure sensitivity of laboratory standard microphones. As described in the main text, the primary calibration system of laboratory standard microphones was advanced and uncertainty related to the electric circuit of the calibration system was minimized to the limit at present. After the improvement of the system, I got suspicious about the stability of the microphone sensitivity and studied the cause of the instability. In other words, the instability of the microphone sensitivity could not be observed until the system was advanced.

Possible causes of instability were physical distortion of the microphone described in the main text, sensitivity dependence on environmental conditions such as temperature and static pressure, poor insulation of the microphone, application of bias voltage necessary for the workings of the microphone, physical force applied to the microphone by its connection to the pre-amplifier. However, causes except the physical distortion of the microphone could not explain the measurement results.

The unstable phenomenon could not be observed by the simple repetition of the measurement. Usually the measured value has very small deviation but at a certain time it suddenly changes to an unexpected value. Quite a long time was spent to obtain a set of data under some measurement condition to confirm the stability. Besides the repetition of the measurement, measurement conditions were changed by trial and error. It took three or four years to come to the conclusion.