Influence of reflecting plane having finite surface density on sound power level of reference sound sources calibrated in hemi free-field

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ABSTRACT

The NMIJ, National Metrology Institute of Japan planned to start calibration service for reference sound sources (RSSs) by 2015 and we have been developing the RSS calibration system in accordance with ISO 6926. In our system, hemi-anechoic environment necessary for the calibration is realized by laying down wooden boards on a wire meshed floor of our anechoic room. In this study, we investigated the influence of such a reflecting plane having finite surface density on sound power level of the RSS theoretically and experimentally. We especially examined sound energy transmission through wooden boards and their vibration caused by the RSS operation. We also experimentally confirmed that our hemi-anechoic environment satisfies an inverse square law of sound intensity within a tolerance in ISO 3745. Furthermore, sound power level of the RSS determined by our system agreed with that by the SP, Technical Research Institute of Sweden within a range of SP's expanded uncertainty. These results show that our hemi-anechoic environment is suitable to determine sound power level of RSSs in accordance with ISO 6926.

Keywords: Reference sound source, Sound power level, Free-field over a reflecting plane, hemi-anechoic room I-INCE Classification of Subjects Numbers: 71.9, 72.4, 73.2

1. INTRODUCTION

Sound power level is used for the evaluation of sound emitted from electrical and mechanical apparatus. ISO 3740 series prescribe several procedures to determine sound power levels of such apparatus by using sound pressure and are categorized by the required accuracy [1-4]. Practically, a reference sound source (RSS) is often used to determine sound power level of the apparatus by comparison. If sound power level of the RSS is known, that of the apparatus under test can be precisely determined, with less influence by measurement environment.

However in Japan, we don't have calibration laboratories which carry out the RSS calibration service in accordance with ISO 6926 [5]. We have been also requested from RSS users to calibrate them domestically. Thus, the NMIJ (National Metrology Institute of Japan) determined to develop the calibration system based on ISO 6926 by ourselves and to start calibration service by 2015. We have the anechoic room for precise acoustic measurement but it is not convenient for the RSS calibration because it is not easy to realize spherical measurement surface around the RSS. Thus, hemi-anechoic environment is selected and realized by laying down wooden boards on a wire meshed floor of the anechoic room. In this paper, we investigated theoretically and experimentally the influence of a reflecting plane by wooden boards on sound power level of the RSS because they have finite surface density. In particular, we examined sound power transmission through wooden boards and their vibration caused by the RSS operation. Furthermore, we experimentally confirmed that our hemi-anechoic environment satisfies an inverse square law of sound intensity within a tolerance in ISO 3745.

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2. CALIBRATION SYSTEM

2.1 Hemi-anechoic environment

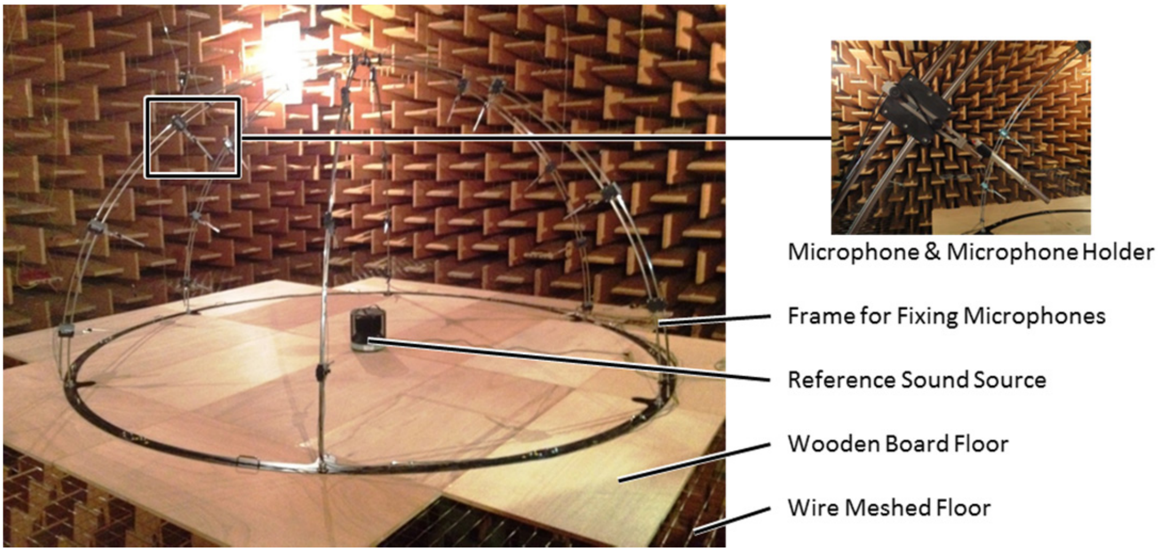

Figure 1 – Calibration system for sound power level of RSS

Figure 1 shows the photo of our calibration environment and apparatus. Hemi-anechoic environment is realized by laying down wooden boards on a wire meshed floor of the anechoic room. The dimensions of the anechoic room are 9.5 m in width, 8.0 m in depth and 7.2 m in height, respectively. The wire meshed floor is fixed 5.6 m below the celling of the room. Cut-off frequency of sound absorbing wedges is 40 Hz. Wooden boards are 0.92 m by 1.83 m. Their thickness is 24 mm and surface density is 7.5 kg/m^2. Reflecting plane consists of 16 wooden boards on the wire meshed floor and another 16 wooden boards stacked on the first layer. Thus, the wooden board floor is 48 mm in thickness and 15.0 kg/m^2 in surface density. The wooden board floor is 26.9 m^2 in area and covers 35% of the wire meshed floor.

2.2 Calibration Apparatus

We designed the hemispherical frame for fixing microphones and placed it on the wooden boards. It is 2.0 m in radius and made by thin steel pipes. Twenty WS2F microphones [6] (type MI-1234, Onosokki) are fixed to the frame and connected with preamplifiers (type MI-3111, Onosokki). Output voltages of the microphones are acquired simultaneously by 20 ch FFT analyzer (type DS-2000, Onosokki). PC controls the FFT analyzer and calculates sound power level, accordingly.

2.3 Calculation of Sound Power Level Radiated from RSS

Sound power level of the RSS, L_w [dB] is calculated as follows:

$$L_W = L_{pf} + 10\log_{10}\frac{S}{S_0} + C \quad (1)$$

where S [m^2] is the area of the measurement hemisphere, S_0 is 1.0 m^2. C [dB] is correction term to reference environmental conditions (23 C°, 101.325 kPa). L_{pf} [dB] is surface sound pressure level. C and L_{pf} are calculated as follows:

$$C = -10\log_{10}\left(\frac{B}{101.325}\sqrt{\frac{313.15}{273.15+t}}\right) - 10\log_{10}\left(\frac{B}{101.325}\sqrt{\frac{296.15}{273.15+t}}\right) \quad (2)$$

$$L_{pf} = 10\log_{10}\left[\frac{1}{20}\sum_{i=1}^{20}10^{0.1L_{pi}}\right] \quad (3)$$

where B [kPa] is static pressure and t [C°] is room temperature during the calibration. L_{pi} [dB] is the time-averaged one-third octave band sound pressure level measured at the ith microphone position.

3. CHARACTERISTICS OF REFLECTING PLANE MADE BY WOODEN BOARDS

3.1 Influence of Sound Power Transmission through Floor

3.1.1 Theoretical Derivation of Sound Power Transmission

Precisely speaking, the wooden board floor is not acoustically rigid and sound energy radiated from the RSS will not be perfectly reflected on the floor. Sound energy may be absorbed into the floor or transmitted through the floor. However, we assumed that sound absorption is negligible compared with sound transmission by considering the thickness of wooden boards. Thus, we theoretically evaluated the energy loss by applying a mass law [7]. We also assumed that the RSS is a point sound source and its acoustic center coincides with geometric center, namely 15 cm above the bottom of the RSS.

Firstly, we considered simple plane wave. Transmission coefficient τ_θ of sound power for sound incident angle θ [rad] is derived as follows:

$$\tau_\theta = \frac{1}{1+\left(\frac{\omega m}{2\rho c}\cos\theta\right)^2} \tag{4}$$

where, ω is angular frequency of the sound, ρ [kg/m^3] is density of air, c [m/s] is sound speed in air and m [kg/m^2] is surface density of a reflecting plane.

Then we considered spherical wave based on Eq. (4). Figure 2 shows sound emission from a point sound source on spherical coordinates (r, θ, φ) and Figure 3 depicts the schematic view of our calibration system. As shown in Figures 2 and 3, the polar angle θ corresponds to sound incident angle and changes from 0 to $\theta_{\max}$.

Total sound power transmitted through the floor, W_{t} [W] is calculated by integrating the transmitted sound power at each angle within the range of $0 \le \theta \le \theta_{\max}$ and $0 \le \varphi \le 2\pi$:

$$W_{\mathrm{t}} = \int_0^{\theta_{\max}} \int_0^{2\pi} \tau_\theta w(R)\, R^2 \sin\theta d\varphi\, d\theta \tag{5}$$

where, R [m] is the distance from acoustic center of the sound source to the floor in the θ direction and $w(r)$ [W/m^2] is sound intensity in the radial direction on a sphere of radius r.

Thus τ_{cal}, the ratio of W_{t} to total sound power P [W] emitted from the sound source is calculated as follows:

$$\begin{aligned}\tau_{\mathrm{cal}} &= \frac{W_{\mathrm{t}}}{P} \\ &= \frac{\int_0^{\theta_{\max}} \tau_\theta \sin\theta\, d\theta}{2}.\end{aligned} \tag{6}$$

τ_{cal} becomes zero for sufficiently rigid floor.

Finally, we calculate the influence of the sound power transmission on sound power level. The difference of sound power level ΔL_{w} [dB] between a floor having finite surface density and a rigid floor is calculated using τ_{cal}:

$$\begin{aligned}\Delta L_W &= L_{W\_\mathrm{finite}} - L_{W\_\mathrm{rigid}} \\ &= 10\log_{10}(1-\tau_{\mathrm{cal}}).\end{aligned} \tag{7}$$

where, L_{W_finite} and $L_{W\,\mathrm{rigid}}$ [dB] are sound power levels for the floor having finite surface density and the rigid floor, respectively.

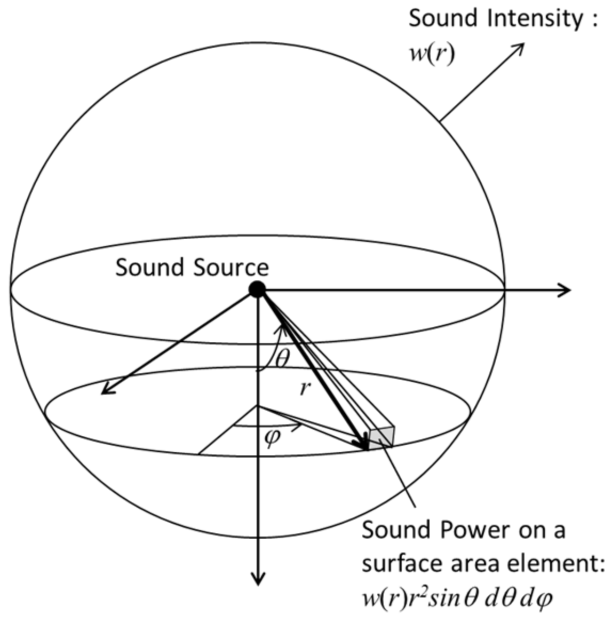

Figure 2 – Sound emission from point sound source on spherical coordinates (r, θ, φ). $w(r)$ is sound intensity in radial direction.

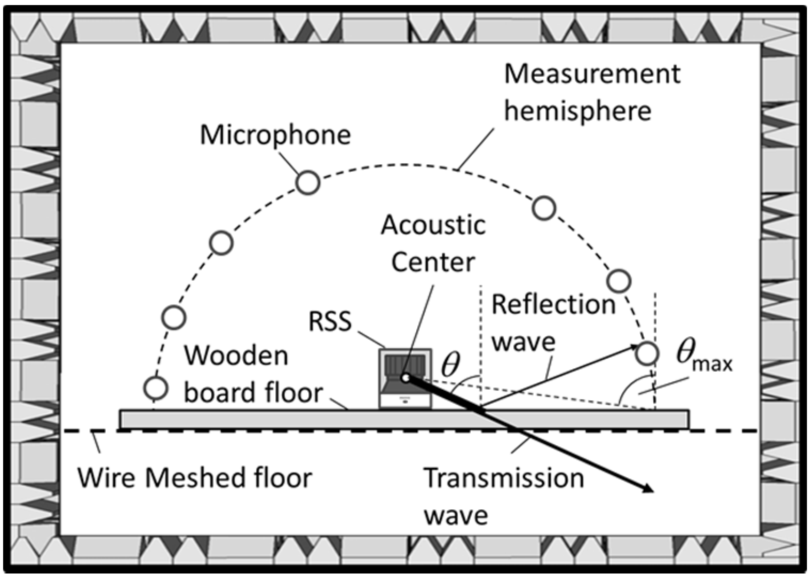

Figure 3 – Schematic view of sound incident angle θ and θ_{max}

3.1.2 Theoretical Evaluation of Sound Power Transmission

Preceding analysis shows that sound power transmission depends on surface density of the floor. We simulated two cases and ΔL_w is shown in Figure 4: Surface density m is 7.5 kg/m^2 and 15.0 kg/m^2, corresponding to single-stacked and double-stacked wooden boards, respectively. In both cases, air density ρ is 1.2 kg/m^3 and sound speed c is 340 m/s. As expected, Figure 4 shows that transmitted sound power depends on the surface density of the floor and increases at lower frequencies. This result implies that the influence of the surface density on sound power transmission may be predicted and corrected theoretically for precise calibration, especially at lower frequencies less than 1 kHz.

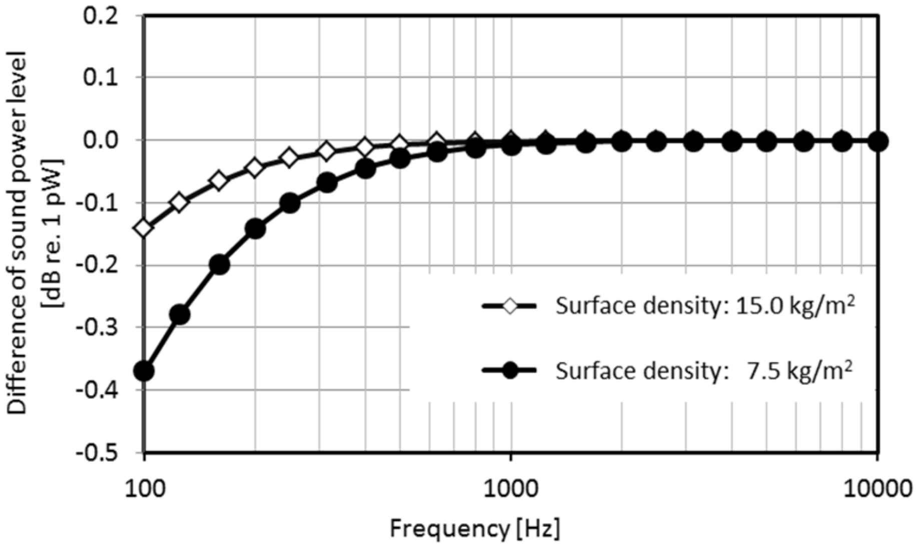

Figure 4 – Difference of sound power level between floor having finite surface density and rigid floor

3.1.3 Experimental Evaluation of Sound Power Transmission

Then, sound power transmission was experimentally examined by using the RSS and changing the thickness of the wooden boards. However, ΔL_w cannot be experimentally determined because we cannot realize sufficiently rigid reflecting plane in our facility. Instead, we determined the difference of sound power level between 7.5 kg/m^2 and 15.0 kg/m^2 in the surface density of wooden boards. For each case, sound power level was measured three times and the average was calculated.

Environmental conditions were 23.3 ± 0.2 C° in temperature and 100.0 ± 0.1 kPa in static pressure for the former case and 23.2 ± 0.2 C° and 100.9 ± 0.1 kPa for the latter case, respectively. The RSS is Brüel & Kjær type 4202 and driven by AC 100 V with 50 Hz.

The difference of sound power level $\Delta L_{\mathrm{w\_density}}$ between 7.5 kg/m^2 and 15.0 kg/m^2 in the surface density [dB] is defined as follows:

$$\Delta L_{w\_\mathrm{density}} = L_{W\_\mathrm{light}} - L_{W\_\mathrm{heavy}} \tag{8}$$

where, L_{w_light} and L_{w_heavy} [dB] are sound power levels for the surface density of 7.5 kg/m^{2}and 15.0 kg/m^2, respectively.

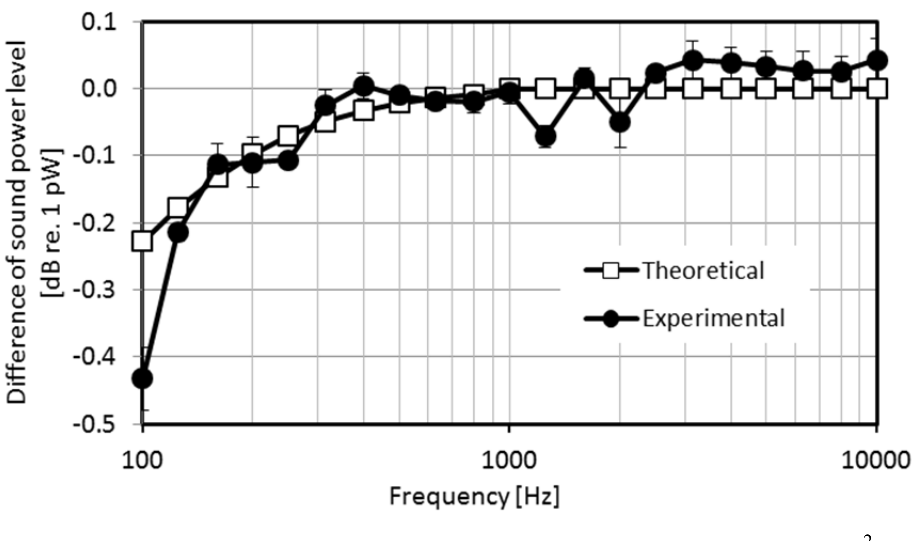

Figure 5 –Theoretical and experimental difference of sound power level between 7.5 kg/m^2 and 15.0 kg/m^2 in floor surface density. Error bars represent standard deviations of experimental difference.

Figure 5 shows $\Delta L_{\mathrm{w\_density}}$ and theoretical result is also plotted for reference. Figure 5 shows that experimental result is in good agreement with theoretical one. The difference between theoretical and experimental result is 0.25 dB at 100 Hz. But except for 100 Hz, they agree within 0.1 dB.

Figure 5 implies that sound power transmission through the floor can be theoretically estimated and corrected. Future study includes the investigation of the difference at 100 Hz.

3.2 Influence of Floor Vibration caused by RSS Operation

Wooden boards are thinner and lighter compared with a concrete floor and may vibrate to some extent when the RSS is operated. To examine the influence of floor vibration, sound power level of the RSS was examined by eliminating the vibration. The RSS was physically isolated from the floor by hanging the RSS from the ceiling of the anechoic room and by using fine steel wires. As a result, the RSS was positioned 1 cm apart from the floor. For conditions with and without floor vibration, sound power level was measured five times and the average was calculated. Environmental conditions during the measurement were 23.3 ± 0.2 C° and 100.8 ± 0.1 kPa.

The difference of sound power levels with and without floor vibration, $\Delta L_{\mathrm{w\_vibration}}$ [dB] is defined as follows:

$$\Delta L_{w\_\mathrm{vibration}} = L_{W\_\mathrm{off}} - L_{W\_\mathrm{on}} \tag{9}$$

where, L_{w_on} and L_{w_off} [dB] are sound power levels with and without floor vibration, respectively.

Figure 6 shows $\Delta L_{\mathrm{w\_vibration}}$. At some frequencies, differences exceed standard deviations of the measurement without floor vibration but still less than 0.1 dB. This result implies that the influence of floor vibration is not significant.

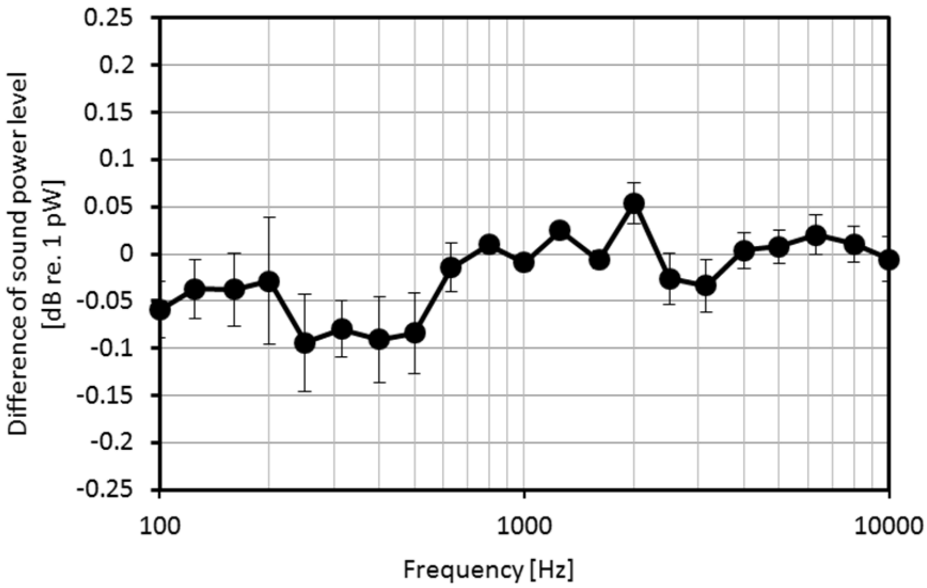

Figure 6 – Difference of sound power levels with and without floor vibration. Error bars represent experimental standard deviations without floor vibration.

3.3 Verification of Inverse Square Law

An inverse square law was experimentally validated in our hemi-anechoic environment to see if its acoustic performance meets the qualification requirements of ISO 3745 Annex A.

Measurement frequencies were from 100 Hz to 10 kHz with 1/3 octave sequences. From 100 Hz to 200 Hz, an omnidirectional loudspeaker (type 4292-L, Brüel & Kjær) was used. Over 250 Hz, a tweeter (type TW-25B, Mitsubishi Electric Corporation) was used by attaching a board with a ϕ13 mm hole on its front to realize spherical wave. Sound pressure levels were measured along five straight paths from the sound source to the room walls. For each path, measurement positions relative to the sound source ranged from 0.5 m to 2.5 m with 0.1 m interval.

The measured sound pressure levels were compared with theoretical values. Theoretical sound pressure level L_p [dB] at the distance of r [m] from the sound source is calculated as follows.

$$L_p(r) = 20\log_{10}\left[\frac{a}{r - r_0}\right], \tag{10}$$

where

$$a = \frac{\left(\sum_{i=1}^{N} r_i\right)^2 - N\sum_{i=1}^{N} r_i^2}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i\, q_i} \quad \text{and} \quad r_0 = -\frac{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} r_i q_i - \sum_{i=1}^{N} r_i^2 \sum_{i=1}^{N} q_i}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i q_i}, \tag{11}$$

where

$$q_i = 10^{-L_{pi}/20} \tag{12}$$

and L_{pi} [dB] is sound pressure level at the ith measurement position. r_i [m] is the distance from the sound source at the ith measurement position. N is the number of measurement positions along each microphone path. For the measured sound pressure L_{pi} at each measurement position, the deviation ΔL_{pi} from theoretical value is defined as follows.

$$\Delta L_{pi} = \left|L_{pi} - L_p(r_i)\right| \tag{13}$$

For each path and each frequency, the maximum of ΔL_{pi} is determined among all the measurement positions and shown in Figure 7. For reference, the allowable deviation by ISO 3745 is also plotted. All the data in Figure 7 are within the allowable deviation. Thus our hemi-anechoic environment satisfies the requirement of ISO 3745 and thus ISO 6926.

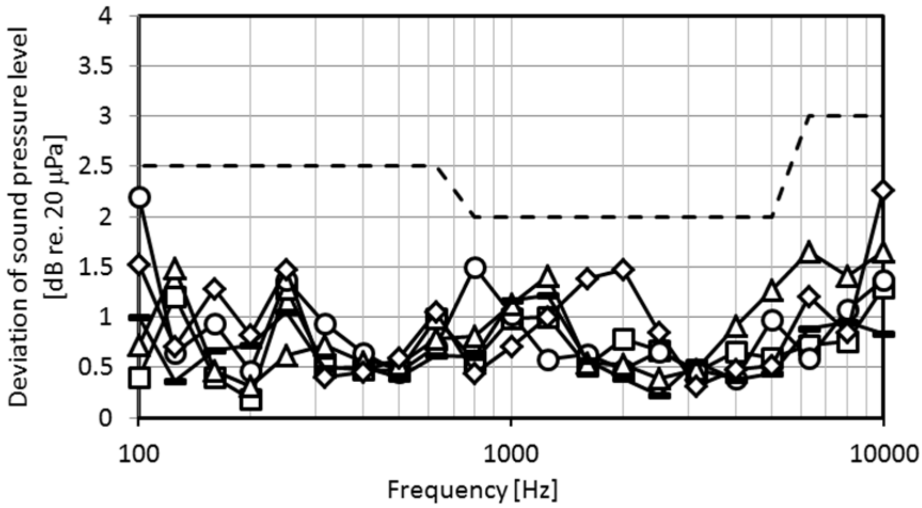

Figure 7 – Maximum deviations of sound pressure level from theoretical values. All the data along five paths are plotted. Dotted line shows the allowable deviation in ISO 3745.

4. INFORMAL COMPARISON WITH CALIBRATION DATA OF ANOTHER LABORATORY

To confirm the validation of our calibration system, sound power level of the RSS by our system was compared with that by another laboratory. The RSS used for the evaluation is Brüel & Kjær type 4204, S/N 2574792. We used the calibration certificate issued by the SP, Technical Research Institute of Sweden . SP carried out the calibration in hemi-anechoic room and adopted a microphone traverse method [8]. Correction for air absorption was applied from ISO 9613-1[9]. Sound pressure level was corrected to the reference environmental conditions.

On the other hand, NMIJ performed the measurement three times and calculated the average. The environmental conditions were 23.2 ± 0.2 C° and 100.9 ± 0.1 kPa. Sound power level was corrected to the reference environmental conditions. Standard deviations were from 0.01 dB to 0.04 dB for all the frequencies. Air absorption correction was also applied.

The difference of sound power level calibrated by NMIJ and SP, $\Delta L_{w\_\mathrm{cal}}$ [dB] is defined as follows:

$$\Delta L_{w\_\mathrm{cal}} = L_{W\_\mathrm{SP}} - L_{W\_\mathrm{NMIJ}} \quad (14)$$

where, L_{w_SP} and L_{w_NMIJ} [dB] are sound power levels calibrated by SP and NMIJ, respectively.

Figure 8 shows $\Delta L_{w\_\mathrm{cal}}$. The differences are within the expanded uncertainty reported by SP for all the frequencies. This result means that calibration data by the two labs. are equivalent within the range of the expanded uncertainty.

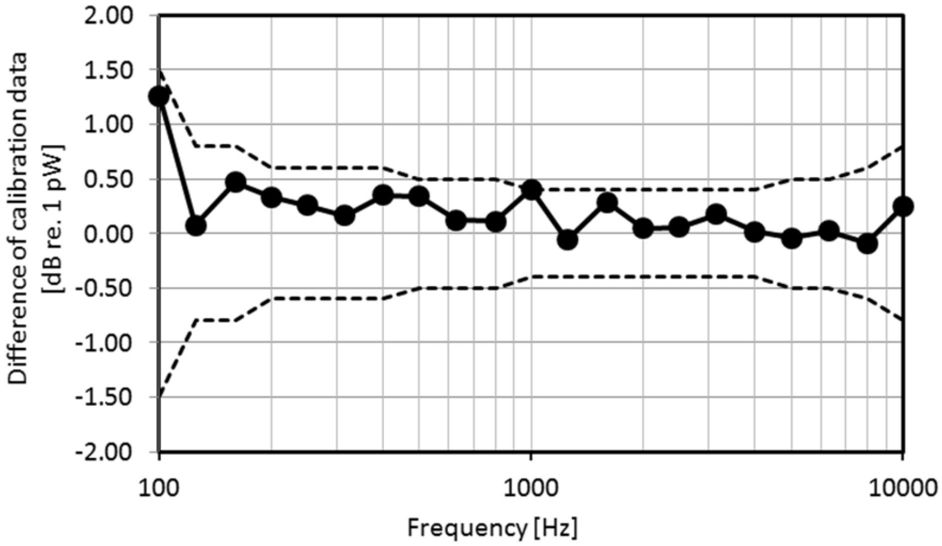

Figure 8 – Difference of sound power levels calibrated by NMIJ and SP. Dotted line shows expanded uncertainty reported by SP.

5. CONCLUSION

This study theoretically and experimentally investigated the influence of using wooden boards as the reflecting plane on sound power level of the RSS. We concluded that our hemi-anechoic environment is satisfactory for the RSS calibration in accordance with ISO 6926.

Sound power transmission through the wooden board floor was theoretically estimated and compared with experimental results. They are in good agreement and it was confirmed that the influence of sound power transmission on sound power level can be corrected theoretically. Furthermore, significant influence of floor vibration caused by the RSS operation was not observed.

We also confirmed that our hemi-anechoic environment satisfies the requirement in ISO 3745 by verifying the inverse square law.

Finally, to confirm the validation of our calibration system, sound power level of the RSS by NMIJ was compared with that by another laboratory. As a result, it was confirmed that they are equivalent within the range of the reported expanded uncertainty.

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