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Sound Strength Calibration Methods

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ABSTRACT

The sound strength G is a room acoustical parameter used to investigate the sound distribution in a hall or to compare the loudness between different halls. ISO 3382-1 describes several methods to measure G. The accuracy of a G measurement depends on the accuracy with which the power level of the sound source can be determined or with which the measurement system can be calibrated. In this research the different available sound strength calibration methods have been compared using a standard omnidirectional (dodecahedron) sound source. Using the same measurement equipment, different (system) calibration methods are compared: 1] free-field measurement in an anechoic room, 2] sound intensity measurement in an anechoic room, 3] diffuse-field measurement in a reverberation room, 4] near-field measurement on stage in a concert hall. For method 1, measurements have been performed in a horizontal plane with white noise and exponential sweeps at various distances from the sound source. For method 2, intensity measurements according to ISO 9614-3 have been performed using white noise while scanning the sound source surface with a two microphone probe. For method 3, the direct method and the comparison method according to the ISO 3741 standard have been used to determine the sound power level using white noise. Also, a system calibration has been performed in the anechoic room and the reverberation room using exponential sweeps. Finally, for method 4, a convenient near-field measurement method at a distance of 1 m has been performed on the stages of a large and a small concert hall using white noise and exponential sweeps. It has been found that the intensity and the diffuse-field calibration methods give substantially equal results. The horizontal-rotation free-field calibration method gives results that differ significantly from those of the diffuse-field and intensity methods. For a survey G measurement in a concert hall it is sufficient to perform an on-site calibration.

INTRODUCTION

Definition

The sound strength G [1][4] is a room acoustical parameter used to investigate the sound distribution in a concert hall or to compare the loudness between different concert halls. G is defined as the sound pressure level caused by an omnidirectional sound source on the stage, measured at a listener position in the hall, with reference to the sound pressure level at 10 m distance from the same sound source in a free field. Using a stationary signal, G can be written as:

$$G = L_{p(listener)} - L_{p(dir,10m)}\ [dB] \tag{1}$$

where:
$L_{p(listener)}$ is the sound pressure level at a listener position
$L_{p(dir,\,10m)}$ is the sound pressure level at 10 m from the same sound source in the free field

Similarly G can also be calculated from impulse responses through their sound pressure exposure levels:

$$G = L_{pE(listener)} - L_{pE(dir,10m)}\ [dB] \tag{2}$$

$$L_{pE(listener)} = 10\lg\left(\int_0^\infty p_{(listener)}{}^2(t)dt\right)\ [dB] \tag{2a}$$

$$L_{pE(dir,10m)} = 10\lg\left(\int_0^\infty p_{(dir,10m)}{}^2(t)dt\right)\ [dB] \tag{2b}$$

where:
$L_{pE(listener)}$ is the sound pressure exposure level of $p_{(listener)}$
$L_{pE(dir,10m)}$ is the sound pressure exposure level of $p_{(dir,10m)}$
$p_{(listener)}$ is the instantaneous sound pressure of the impulse response measured at the listener position
$p_{(dir,\,10m)}$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 m in a free field

Problem and goal

The accuracy of G depends mainly on the accuracy of $L_{p(dir,10m)}$ in equation 1 or $L_{pE(dir,10m)}$ in equation 2. These levels serve as reference and are obtained in a one-off calibration measurement. $L_{p(dir,10m)}$ of an omnidirectional sound source is related as follows to its sound power level L_W:

$$L_{p(dir,10m)} = L_W - 31\,[dB] \qquad (3)$$

where L_W can be obtained through three different precision measurement methods:

- Diffuse-field measurement (ISO 3741)
- Free-field measurement (ISO 3745)
- Intensity measurement (ISO 9614-3)

These precision methods use stationary sound. However, ISO 3382-1 also describes equivalent diffuse-field and free-field methods to arrive at $L_{pE(dir,10m)}$ using impulse responses instead of a stationary signal. Here an intermediate parameter equivalent to L_W is not defined explicitly, but could have been so as the sound power exposure level L_{WE}.

If the calibration and the measurements are carried out using the very same system, it is not necessary to know L_W (from the calibration measurements) and L_p (from the field measurements) in order to calculate G: because G is a relative parameter, it would be sufficient to know the relation between L_W and L_p. Using impulse responses, the same holds for L_{WE} and L_{pE}. However, because stationary signals are usually related to absolute levels, while impulse responses are related to systems and relative levels, the calibration measurements are hereafter assumed to be based on absolute levels for stationary signal measurements (Level Calibration) and on relative levels for impulse response measurements (System Calibration).

Unfortunately precision calibration measurements require special measurement rooms, and are rather time consuming. Therefore common rough but easy on-stage methods are investigated as well, for instance a sound power measurement at a near-field distance of 1 m from the omnidirectional sound source. From experience and earlier student reports [2][3] it appears that differences in G of more than 2 dB can be found using different calibration methods in a laboratory and a concert hall. This investigation is a follow-up study on these differences between precision laboratory calibration techniques and more practical calibration methods, and therefore divided into 2 parts:

- *Precision method* using diffuse-field and intensity measurements
- *Survey (or consultancy) method* using Indicative essentially free-field and free-field measurements

MEASUREMENTS

Measurement equipment

For all measurements the same measurement set was used. The power amplifier had a built-in white noise generator. For every measurement this noise generator was set to exactly the same value, so the sound power level of the omnidirectional sound source was always the same. The sound source was a 12 loudspeaker omnidirectional sound source (dodecahedron) with a diameter of approx 40 cm. The measurement equipment consisted of the following components:

- *sound source:* omnidirectional (B&K Type 4292);
- *signals:* stationary white noise and an exponentially swept sine;
- *input/output:* USB audio device (Acoustics Engineering - Triton);
- *power amplifier:* (Acoustics Engineering - Amphion);
- *turntable:* 80 s for one rotation (B&K Type 2305);
- *reference sound source:* (B&K Type 4204);
- *microphone:* ½” omnidirectional ICP (B&K Type 4189);
- *sound intensity probe:* (B&K Type 3520);
- *software:* DIRAC (B&K Type 7841).

Measurement conditions

For this investigation a precision diffuse-field method and a precision intensity method as described in the standards were used. Regarding the free-field calibration method no standard has been used. Table 1 shows the calibration methods in relation to the sound fields and the measurement signals. The e-sweep was used as stimulus for the impulse response measurements. The anechoic room has been used only to find out if and how accurate the sound power level of a standard dodecahedron can be determined from a horizontal-rotation measurement.

Table 1. Calibration methods and measurement signals

Calibration Method	Measurement Signal	
	Stationary White noise (Level Calibration)	**Non-stationary** e-Sweep (System Calibration)
Diffuse-field *Reverberation room* (ISO 3741)	Direct method and Reference method	Impulse response measurements
Free-field *Anechoic room* SR-distance: 7 m, 1 m *Concert hall, on stage* SR-distance: 1 m	Full rotation	Impulse response measurements Steps: 45°
Intensity Anechoic room (ISO 9614-3)	Sweep Scan measurement	---

- Diffuse-field measurements:
The diffuse-field measurements were carried out in the reverberation room (200 m^3) of the Faculty of Applied Sciences of the Delft University of Technology. All sound power measurements were done according to ISO 3741 [5]. According to this standard two source positions and four microphone positions were used for the direct and the reference method. The last one using a calibrated reference sound source with a known sound power spectrum. For the system calibration measurements (impulse response measurement using e-sweeps and deconvolution) two sound source positions and three microphone positions were used. For each situation the measurement results were averaged over the microphone and sound source positions.

Figure 1. Diffuse-field measurement in reverberation room

- Free-field measurements:

The free-field measurements were carried out in the anechoic room of the Faculty of Applied Sciences of the Delft University of Technology (see figure 3). In this room a measurement is performed at 1 m distance (near field) and 7 m distance from the centre of the omnidirectional sound source. The sound power level or the sound pressure level at 10 m distance in the free field can be calculated from the measured sound pressure level and the microphone-source distance *d* using:

$$L_W = L_{p(dir,dm)} + 10\lg d^2 + 11\,[dB] \qquad (4)$$

And

$$L_{p(dir,10m)} = L_{p(dir,dm)} + 20\lg\left(\frac{d}{10}\right)[dB] \qquad (5)$$

where:

L_W	is the sound power level of the omnidirectional sound source
$L_{p(dir,dm)}$	is the sound pressure level at a distance of d m from the sound source
$L_{p(dir,10m)}$	is the sound pressure level at a distance of 10 m from the sound source
d	is the measurement distance from the sound source

For both distances measurements were performed using stationary white noise and exponential sweeps. For the exponential sweep signal the sound source was rotated around its vertical axis in steps of 45 degrees, where at each step a measurement was performed, while for the stationary white noise signal, continuous rotation measurements were performed using a turntable with a rotation speed of 360^o/80s. Figure 2a and figure 2b show the dodecahedron sound source orientation during the free-field measurements.

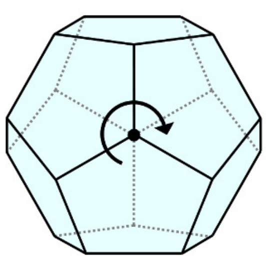


Figure 2a. Top view of vertical rotation axis during free-field and near-field measurements

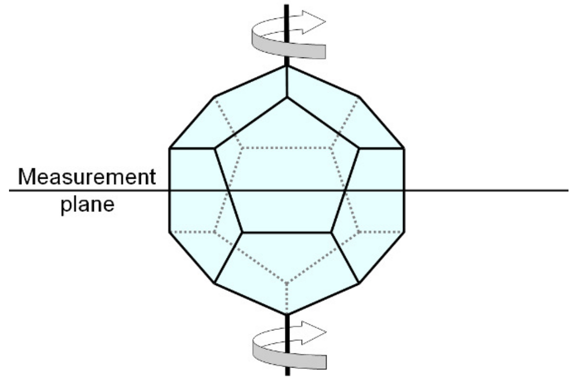


Figure 2b. Side view of vertical rotation axis and horizontal measurement plane during free-field and near-field measurements

Figure 3. Free-field measurement in anechoic room

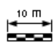
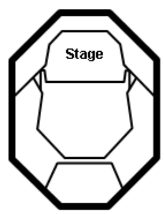
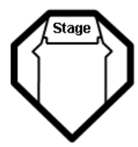
- Stage measurements:

The measurements on stage were carried out in the symphonic concert hall (figure 4) and the chamber music hall of the Frits Philips Muziekcentrum Eindhoven. The room acoustical properties of both halls are given in table 2 and figure 5. The (near-field) measurements are performed at a distance of 1 m from the centre of the omnidirectional sound source. During the measurements the stages were un-occupied. The sound pressure level at 10 m distance in the free field was calculated from the measured sound pressure level and the microphone-source distance *d* using equations 4 and 5.

Figure 4. Near-field measurement on empty stage

As during the free-field calibration measurements in the anechoic room both the stationary white noise signal and the exponential sweep signal were used. For the exponential sweep signal the sound source was rotated again in steps of 45 degrees, where at each step a measurement was performed, while for the stationary white noise signal, one continuous rotation measurement was performed.

Table 2. Concert hall specifications

Hall type	Symphonic music	Chamber music
Floor plan 		
Volume	14400	4000
Number of Seats	1250	385
Stage area [m²]	200	70
T_{avg} [s]	2.0	1.5

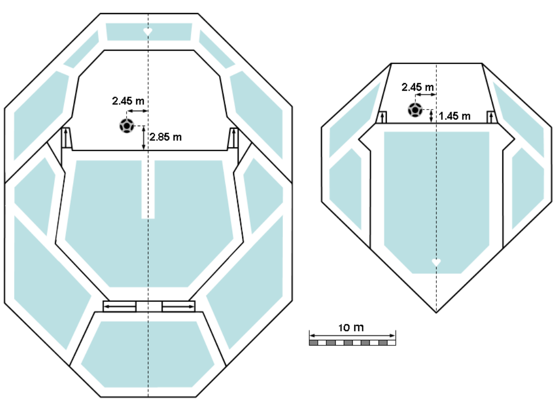


Figure 5. Sound source position in the concert halls

- Sound Intensity measurements:
The sound intensity measurements were also carried out in the anechoic room of the Faculty of Applied Sciences of the Delft University of Technology. See figure 6. The measurements were performed according to ISO 9614-3 [6], using a metal mesh cube with dimensions 1.05 x 1.05 x 1.05 m^3 and a mesh size of 15 x 15 cm^2. Using the sweep scan method all individual surfaces were scanned in two directions and averaged to one intensity measurement. The sound intensity of the bottom surface was determined by turning the omnidirectional sound source upside down. The total sound power level L_W is obtained by summing the 6 separate sound intensity results using:

$$L_W = 10\lg\sum_{i=1}^{6}\left(I_i \cdot A\right)[dB] \qquad (6)$$

where:

L_W is the sound power level of the omnidirectional sound source

I_i is the averaged sound intensity over cube surface i

A is the area of one cube surface

Figure 6. Sound Intensity measurement in anechoic room

RESULTS

The results of all measurements were normalised to G_0, where G_0 is defined as the average over the G values determined from the three precision calibration methods: the direct diffuse-field calibration, the diffuse-field calibration using a reference source and the calibration using the sound intensity method.

Figure 7 depicts the spread in the results from these precision calibration methods. Starting point is the equality of these different measurement techniques. Figure 8 shows the same results as figure 7 but in full octave bands.

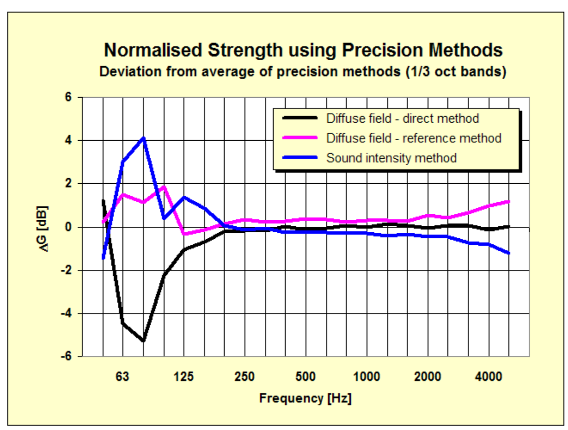


Figure 7. Normalised G obtained from precision calibration methods, presented in 1/3 octave bands

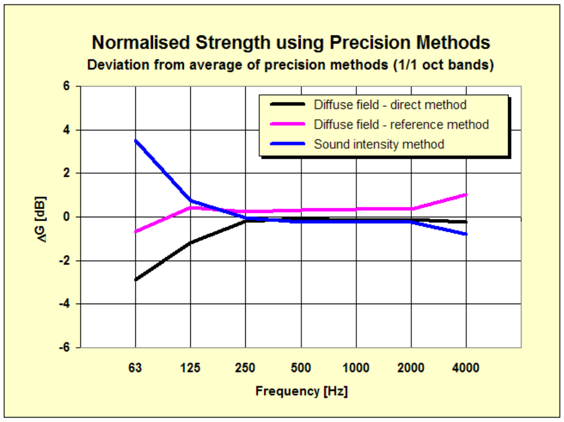


Figure 8. Normalised G obtained from precision calibration methods, presented in full octave bands

Figure 9 shows the normalised G obtained from the free-field (7 m) and near-field (1 m) measurements (using stationary white noise) in an anechoic room and on empty stages of a symphonic concert hall (*Stage B*) and a chamber music hall (*Stage A*). The distances between microphone and omnidirectional sound source used for further calculations are the physical distances between the centre of the omnidirectional sound source and the centre of the microphone, measured with an accuracy of 1 cm in height and radius. For both music halls the sound source and the microphone were placed at a height of 1.5 m above the stage floor.

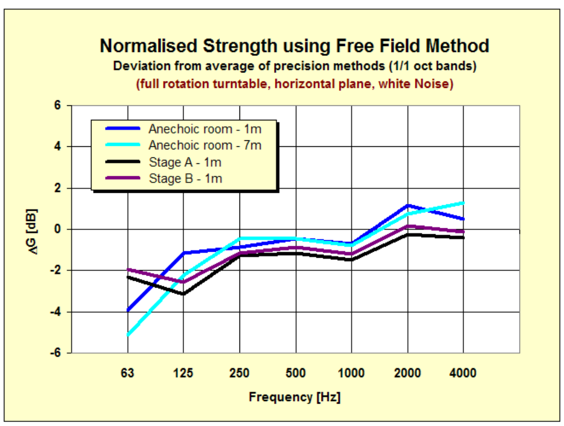


Figure 9. Normalised G obtained from free-field calibration methods using white noise

Figure 10 depicts all normalised G values calculated from impulse response measurements using a system calibration with e-sweeps and deconvolution. Unlike the noise measurements, the distances between microphone and omnidirectional sound source (free-field system calibration) were calculated from the time interval between t = 0 and the starting point (direct sound) of the impulse responses. It should be noted that the source receiver distance derived from this time interval differs from the measured distance between the centre of the microphone and the centre of the 12 loudspeaker omnidirectional sound source. The calculated distance is approx 0.15 m less than the measured distance.

To complete the set of calibration methods, a diffuse-field system calibration has also been performed.

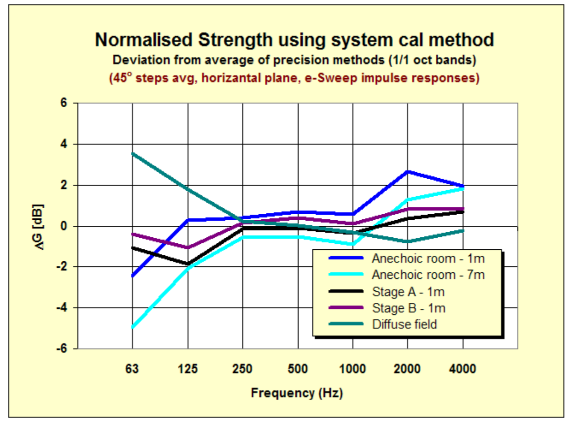


Figure 10. Normalised G obtained from impulse response measurement using e-sweeps and deconvolution

Figure 11, 12 and 13 show an overview of the single number normalised G obtained from all investigated calibration methods. These single numbers values are averages of two octave bands according to the ISO 3382-1 standard. 'Low' is the average of 125 Hz and 250 Hz, 'Mid' is the average of 500 Hz and 1 kHz and 'High' is the average of 2 kHz and 4 kHz. Normally these values are presented together in one graph or one table. The 'Mid'-value can be used as the main single number value, as mentioned in the standard.

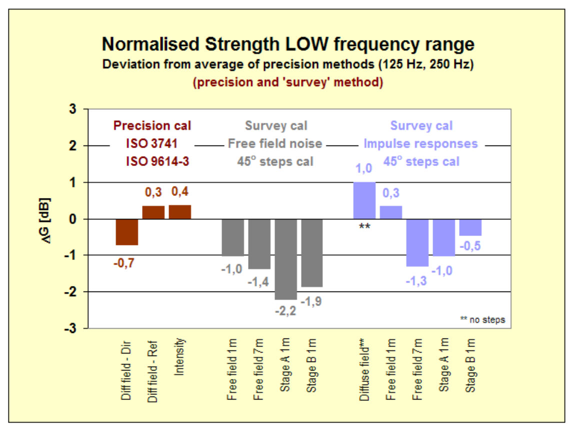


Figure 11. Normalised low frequency (avg 125 - 250 Hz) wide band value of G for all calibration methods

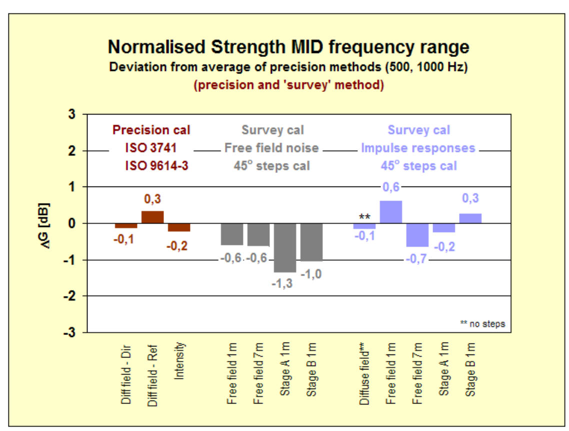


Figure 12. Normalised mid frequency (avg 500 - 1000 Hz) wide band value (= single number value according to ISO 3382-1) of G for all calibration methods

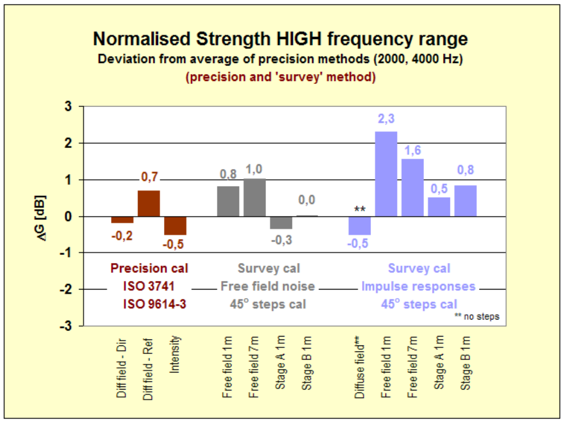


Figure 13. Normalised high frequency (avg 2 kHz - 4 kHz) wide band value of G for all calibration methods

OBSERVATIONS

- G values based on the precision methods used (diffuse field: direct, diffuse field: reference source and sound intensity method) show the following deviations from the precision method average: +/- 0.4 dB over octave frequency range 250 Hz – 2 kHz and +/- 1.2 dB over octave frequency range 125 Hz – 4 kHz

- G values based on a calibration in an anechoic room using a continuous turntable and stationary noise show the following deviations from the precision method average: +/- 1.1 dB over octave frequency range 250 Hz – 2 kHz and +/- 2.3 dB over octave frequency range 125 Hz – 4 kHz*

- G values based on a calibration in a concert hall using a continuous turntable and stationary noise show the following deviations from the precision method average: +/- 1.5 dB over octave frequency range 250 Hz – 2 kHz and +/- 3.2 dB over octave frequency range 125 Hz – 4 kHz*

- G values based on a calibration in an anechoic room using a stepped turntable and measured impulse responses show the following deviations from the precision method average: +/- 2.7 dB over octave frequency range 250 Hz – 2 kHz and +/- 2.7 dB over octave frequency range 125 Hz – 4 kHz*

- G values based on a calibration in a concert hall using a stepped turntable and measured impulse responses show the following deviations from the precision method average: +/- 0.8 dB over octave frequency range 250 Hz – 2 kHz and +/- 1.9 dB over octave frequency range 125 Hz – 4 kHz*

- G values based on measured impulse responses in a reverberation room show the following deviations from the precision method average: +/- 0.8 dB over octave frequency range 250 Hz – 2 kHz and +/- 1.8 dB over octave frequency range 125 Hz – 4 kHz

* These values are likely to depend on the particular loudspeaker used or rather its directivity pattern.

CONCLUSIONS

- The intensity and the diffuse-field calibration methods give substantially equal results.

- The horizontal-rotation free-field calibration method gives results that differ significantly from those of the diffuse-field and intensity methods.

- For G measurements with errors not exceeding the Just Noticeable Difference (JND), a precision calibration method should be applied.

- For a survey G measurement in a concert hall it is sufficient to perform an on-site calibration. There is no need for special sound field conditions or measurement rooms.

- On-site (system) calibrations using impulse responses are more accurate than calibrations performed with stationary noise.

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