Sound Power Measurements Based on ISO 3741 and 3745

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Abstract

In this paper, we present the description and results of experimental study of the sound power measurements based on International Standards ISO 3741 and 3745. The sound power emitted by a calibrated reference sound source was measured in a reverberation room and a free field over a reflecting plane, using the precision methods of International Standards ISO 3741 direct method and ISO 3745, respectively. The sound power measurements carried out in this study give accurate estimation and also show that both methods for determining the sound power levels of a sound source in a reverberation room and a free field over a reflecting plane, according to the ISO 3741 and 3745, respectively, have proved equally good.

I. Introduction

A noise level or sound level is usually a sound pressure level, that is, a measure of the small pressure fluctuations in the air superimposed on the normal atmospheric pressure. Noise levels produced by a machine or a piece of equipment can be easily measured with a sound level meter [1, 2]. The meter shows the sound pressure level at the measurement location. The sound pressure level depends on how far away the meter is from the machine, and on the measuring environment. It relates to the loudness of the sound and to the potential damaging effect on hearing.

A sound power level on the other hand is a measure of the total power of noise radiated by the machine in all directions. It is a property of the machine and essentially independent of the measuring environment. Sound power level data are useful for: (a) calculating the approximate sound pressure level at a given distance from a machine operating in a specified environment, (b) comparing the noise radiated by machines of the same type and size, (c) comparing the noise radiated by machines of different types and sizes, (d) determining whether a machine complies with a specified upper limit of sound emission, (e) planning in order to determine the amount of transmission loss or noise control required under certain circumstances, and (f) engineering work to assist in developing quiet machinery and equipment [3, 4].

In the past, the sound pressure level was commonly used for noise analyses. However, with more complicated noise problems, the sound power has become more and more popular for noise analyses. The sound power, using sound pressure measurements, can be determined either directly or by comparison with a reference sound source. The precision and engineering methods of sound power determination based on sound pressure measurements are governed by the standards ISO 3741 to 3747. Table 1 summarizes the applicability of each of the series of seven basic International Standards specifying various methods for determining the sound power levels of machines and equipment [3].

The principal objective of this paper is to show how the sound power actually can be determined from sound pressure measurements. In this study, we carried out sound power measurements using the precision methods of International Standards ISO 3741 direct method and ISO 3745. For comparison of the accuracy obtainable when determined in accordance with the standards ISO 3741 and 3745, the sound power levels of a reference sound source, which is emitting constant broad-band noise with an adequate sound power level, were determined in special test rooms: reverberation room and hemi-anechoic room [5-7]. They show a well-known, calibrated broad-band sound power spectrum over the frequency range of interest.

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Table 1. Overview of International Standards for determination of sound power levels of machines and equipment.

International Standard No.	ISO 3741	ISO 3743-1	ISO 3743-2	ISO 3744	ISO 3745	ISO 3746	ISO 3747
Classification of method	Precision	Engineering			Precision	Survey	Engineering or survey
Test environment	Reverberation room	Hard-walled room	Special reverberation room	Essentially free field over a reflecting plane	Anechoic or hemi-anechoic room	No special test environment	Essentially reverberant field in situ, subject to stated qualification requirements
Volume of sound source	Preferably less than 2 % of test room volume	Preferably less than 1 % of test room volume		No restrictions; limited only by available test environment	Characteristic dimension less than half measurement radius	No restrictions; limited only by available test environment	
Character of noise from the source	Steady, broad-band, narrow-band or discrete frequency			Any	Any	Any	Steady, broad-band, narrow-band or discrete frequency
Sound power levels obtainable	A-weighted and in one-third octave or octave bands	A-weighted and in octave bands		A-weighted and in one-third octave or octave bands		A-weighted	A-weighted from octave bands
Optional information available	Other frequency-weighted sound power levels			Directivity information and sound pressure levels as a function of time; other frequency-weighted sound power levels		Octave bands sound power levels; other frequency-weighted sound power levels, Sound pressure levels as a function of time	Other frequency-weighted sound power levels

II. Sound power determination based on sound pressure measurements

There are two different methods for sound power determination based on sound pressure measurements: direct method and comparison method [5, 6]. The direct method is primarily used in the free or semi-free field. Its principle is that the measurements of spatially-averaged sound pressure level are made in a known acoustic environment while the sound source is on. Corrections are made for the background noise. The sound power of the source is then calculated from the sound pressure measurements with the known acoustic environment. Two types of acoustic environment are used for such determination, namely, a reverberant field produced by a reverberation room, and a free field produced by an anechoic room or a free field over a reflecting plane by a hemi-anechoic room.

The principle of the comparison method is that a sound source is placed in a reverberant field, together with a known reference sound source [2]. First, the reference sound source is turned on and the spatially-averaged sound pressure levels are measured. Then after the reference sound source is replaced by the source, the spatially-averaged sound pressure levels are measured. It is now very simple to calculate the sound power with measured sound pressure.

The direct method specified in ISO 3741 is for steady broad-band noise sources tested in reverberant conditions. The noise source being measured is placed in a reverberation room. Octave band or one-third octave band spectra of the emitted noise are measured using either a single microphone on a rotating boom or a number of microphones at static positions. The room is characterized by measuring its reverberation times in the relevant frequency bands. The sound power level in these bands is then computed from the noise spectra and the reverberation times. The standard deviation of reproducibility of sound power levels determined in accordance with this International Standard is equal to or less than 0.5 dB for A-weighted sound power levels (for sources which emit noise with a relatively flat spectrum). In one-third octave bands, it is equal to or less than 3 dB from 100 Hz to 160 Hz, 2 dB from 200 Hz to 315 Hz, 1.5

dB from 400 Hz to 5000 Hz, and 3 dB from 6300 Hz to 10000 Hz. In octave bands, it is equal to 2.5 dB for 125 Hz, 1.5 dB for 250 Hz, 1 dB from 500 Hz to 4000 Hz, and 2 dB for 8000 Hz [3, 5].

If the directional information is required, then the measurements must be made under free field conditions. The measurements are carried out in an anechoic room, usually over a reflecting plane, according to ISO 3745. Ten or more microphone positions are used over an imaginary hemispherical measurement surface. Octave or one-third octave spectra are measured at each microphone position and the sound power level is computed. In one-third octave bands, the standard deviation of reproducibility of sound power levels determined in accordance with this International Standard is equal to or less than 1.5 dB from 100 Hz to 630 Hz, 1 dB from 800 Hz to 5000 Hz, and 1.5 dB from 6300 Hz to 10000 Hz for hemi-anechoic rooms. In octave bands, it is equal to 1.5 dB from 125 Hz to 500 Hz, 1 dB from 1000 Hz to 4000 Hz, and 1.5 dB for 8000 Hz [3, 6]. The ISO 3745 standard does not prescribe any standard deviation for A-weighted values.

The sound pressure level is measured directly by a sound level meter. The sound power level is determined by means of the equation

$$L_W = L_P - 10\log\left[\frac{Q(\vartheta,\varphi)}{4\pi r^2} + \frac{4}{R}\right] \text{ dB}, \tag{1}$$

where L_W is the sound power level referenced to 10^{-12} W, L_P is the sound pressure level referenced to 20 μPa, Q is the directivity factor of the sound source in the direction (ϑ,φ), r is the distance from the source to the point of measurement of L_P, in metres, and R is the room constant defined by

$$R = \frac{\overline{\alpha} S}{1-\overline{\alpha}}, \tag{2}$$

where $\overline{\alpha}$ is the average absorption coefficient and S is the total surface area of the room, in square metres [2]. The first term inside the brackets is the direct component of the sound field obeying the inverse square law and the second term is the reverberant component of the sound field governed by the acoustic absorption properties of the room and its contents. This latter component can be determined by measurement of the reverberation time or by calculation using the absorption coefficients of the surfaces and contents of the room and their respective areas.

III. Method for determining the sound power levels of a sound source in a reverberation room according to ISO 3741

3.1. Measurement of sound pressure level

The method described in this section provides a procedure for determining the sound power levels produced by noise sources in a reverberation room according to ISO 3741 direct method. The reverberation room of volume 155 m^3 and of total surface area 177.6 m^2 is qualified in accordance with ISO 3741. Two methods are specified in ISO 3741 as reverberation room technique. The first method is usually called a direct method because it uses directly measured or calculated reverberation times. The second method is a so-called comparison method. A calibrated reference sound source is used, from which the sound power levels of the noise source are determined by comparison. As all two methods require a determination of the average sound pressure level in the reverberant field, instrumentation and basic measurement techniques are the same for both methods.

Sound power measurements were made with a B&K type 4205 sound power source of height 0.345 m and of diameter 0.24 m. The sound pressure level was measured using a B&K type 4418 building acoustics analyzer, a B&K type 3923 rotating microphone boom, and a B&K type 4166 diffuse-field 1/2" microphone with a B&K type 2639S 1/2" microphone preamplifier. A schematic

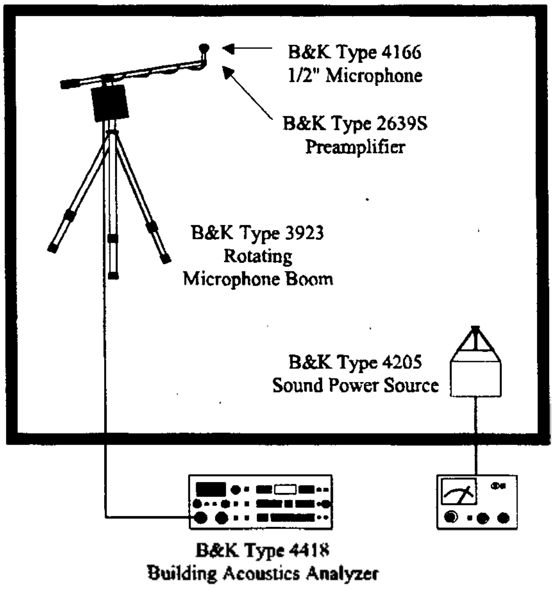

Figure 1. Schematic diagram of the sound power measurements carried out in a reverberation room.

diagram of the sound power measurements carried out in a reverberation room is shown in Figure 1. The microphone was mounted at the end of a rotating boom traversing a circle with a diameter of 2 m. In order to reduce the influence of the direct field on the measured sound pressure level, the microphone was mounted pointing in such a way that the normal to its diaphragm is parallel to the axis of rotation and the microphone faces away from the sound source under measurement. The microphone was traversed at constant speed over a path 2π m in length while the signal was being averaged on a mean-square basis and the period of rotation was 32 s. Longer paths and traversing periods are used to reduce the background noise of the drive mechanism, and to minimize modulation of any discrete tone(s) due to the moving microphone.

A sound source was placed on the floor of the reverberation room, at least 1.5 m from any wall, and 2 m from the point of closest approach of the microphone. Before the measurement of the sound pressure levels, the measurement set-up was calibrated in accordance with ISO 3741. The measurement of the sound pressures levels along the circular microphone path was carried out for each octave band with centre frequencies from 125 Hz to 8000 Hz.

3.2. Measurement of reverberation time

A basic assumption of this method is that the reverberant component dominates the sound field at the microphone positions [8, 9]. The microphone orientation described above significantly reduces the direct field contribution, and, therefore, the measured sound pressure level is determined by the reverberant field. The reverberation time is determined by the absorption in air and by the room surfaces. From the measured reverberation time, the total room absorption is calculated.

The reverberation time of the reverberation room with a B&K type 4224 sound source was determined in those octave bands with centre frequencies from 125 Hz to 8000 Hz using the procedures specified in ISO 354. For each frequency band of interest, nine decays were measured at three locations equally spaced on the microphone path, from which the average reverberation time was determined.

3.3. Calculation of sound power level

Under reverberant field conditions,

$$\frac{4}{R} \gg \frac{Q(\theta,\phi)}{4\pi r^2}$$

and Eq. (1) reduces to

$$L_W = L_p - 10\log\frac{4}{R} \tag{3}$$

or

$$L_W = L_p + 10\log R - 6. \tag{4}$$

The room constant, R is defined by Eq. (2) and, therefore, the sound power level of the sound source, L_W, in decibels, in each octave band with centre frequencies from 125 Hz to 8000 Hz is determined by Eq. (5), using the average sound pressure level determined in the reverberation room and the equivalent absorption area of the reverberation room determined when the source is installed.

$$L_W = \overline{L}_p + 10\log\frac{A}{A_0} + 4.34\frac{A}{S} + 10\log\left(1+\frac{Sc}{8Vf}\right) \\ -25\log\left(\frac{423}{400}\sqrt{\frac{273}{273+\theta}}\cdot\frac{B}{B_0}\right) - 6, \tag{5}$$

where $\overline{L}_p$ is the average sound pressure level in the room in each frequency band of interest, in decibels, A is the equivalent absorption area of the room, in square metres, $A_0 = 1\,\mathrm{m}^2$, S is the total surface area of the reverberation room, in square metres, V is the volume of the room, in cubic metres, f is the centre frequency of the octave band of measurement, in hertz, c is the speed of sound at temperature θ, in metres per seconds, θ is the temperature, in degrees Celsius, B is the atmospheric pressure, in pascals, and $B_0 = 10^5$Pa. In Eq. (5), the term $4.34A/S$ was added to account for air absorption in the test room [10]. The term involving temperature, θ, and the pressure, B, is calculated for the actual meteorological conditions at the measurement location. The term is used to adjust the measured sound power levels to those that would be measured at a meteorological condition corresponding to a characteristic impedance of $\rho c = 400$ N · s/m^3. The equivalent absorption area of the room, A, is calculated, for each frequency band, from the Sabine reverberation time equation

$$A = \frac{55.26}{c}\left(\frac{V}{T_{rev}}\right), \tag{6}$$

where T_{rev} is the reverberation time for a given frequency band, in seconds, and V is the volume of the test room, in cubic metres [8].

The A-weighted sound power level, L_{WA}, in decibels, is calculated from the following equation

$$L_{WA} = 10\log\sum_{j=1}^{j_{max}} 10^{0.1(L_{Wj}+C_j)}, \tag{7}$$

where L_{Wj} is the level in the j th octave band, $j_{max} = 7$ for octave band data, and C_j is given in Table 2.

Table 2. Values of A-weighting, C_j for octave band data.

j	Octave band centre frequency	C_j
	Hz	dB
1	125	- 16.1
2	250	- 8.6
3	500	- 3.2
4	1000	0.0
5	2000	+ 1.2
6	4000	+ 1.0
7	8000	- 1.1

IV. Method for determining the sound power levels of a sound source in a free field over a reflecting plane according to ISO 3745

4.1. Measurement of sound pressure level

The method described in this section provides a procedure for determining the sound power levels produced by noise sources using essentially free field conditions over a reflecting plane as specified in ISO 3745. The measurement was carried out in a hemi-anechoic room of dimensions 6.7 m × 5.3 m × 5.5 m and of volume 194.3 m^3 as qualified in accordance with ISO 3745. For measurement in a free field over a reflecting plane, the sound pressure level was averaged in space and time by moving a single microphone successively along five circular paths as shown in Figure 2. In this arrangement the microphone was rotated. Each path is associated with a zone of the hemisphere. These zones have the same height 0.2 r and thus the same spherical surface area 0.4 πr^2. A B&K type 4155 free-field 1/2" microphone was installed on an imaginary hemisphere, which has its origin in the reflecting plane. The normal to the diaphragm of the microphone passes through the origin of the measurement hemisphere. A rotating boom that moves the microphone along five coaxial circular paths on the imaginary hemisphere was used for the microphone arrangement. The annular areas of the hemisphere associated with each circular path are equal. The microphone was traversed at constant speed and the traversing period was 32 s. Longer periods are suitable to reduce background noise of the drive mechanism.

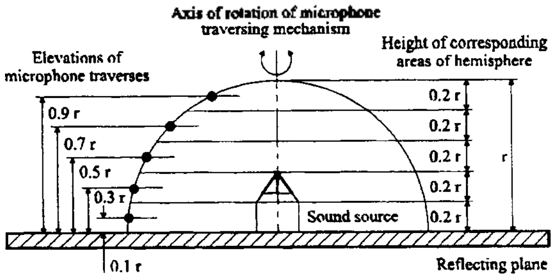

Figure 2. Coaxial circular paths in parallel planes for microphone traverses in a free field over a reflecting plane.

A sound source was placed on the reflecting plane. The projection of the geometric centre of the source on the plane is the origin of the measurement hemisphere with radius r. The radius of the measurement hemisphere was 1 m greater than twice the source dimension. Before measuring the sound pressure levels, the measurement set-up was calibrated in accordance with ISO 3745. The measurement of the sound pressure levels was carried out for each octave band with centre frequencies from 125 Hz to 8000 Hz.

4.2. Calculation of surface sound pressure level

The sound power level of a source is calculated from the surface sound pressure level averaged over the surface of the measurement hemisphere. This surface sound pressure level is calculated from the space average of the mean-square sound pressures over the hemisphere. When the microphone is caused to traverse along five coaxial circular paths, the surface sound pressure level, $\overline{L}_P$, in decibels, is obtained from the following equation

$$\overline{L}_P = 10\log\frac{1}{N}\left(\sum_{i=1}^{N} 10^{0.1L_{Pi}}\right), \tag{8}$$

where L_{Pi} is the average band pressure level measured for the i th traverse, in decibels, and N=5 is the number of measurements.

4.3. Calculation of sound power level

Under essentially free field conditions over a reflecting plane with a directivity of 2, Eq. (1) becomes

$$L_W = L_P - 10\log\left(\frac{1}{2\pi r^2}\right) \tag{9}$$

and simplification yields

$$L_W = L_P - 10\log\left(2\pi r^2\right) \tag{10}$$

To obtain an accurate measure of L_W in each frequency band of interest, it is desirable to use the surface sound pressure level, $\overline{L}_P$ for each of the corresponding bands, referred to a spherically radiating point source. For a free field over a reflecting plane, the sound power level of the sound source, L_W in decibels, in each octave band with centre frequencies from 125 Hz to 8000 Hz is determined from the following equation

$$L_W = \overline{L}_P - 10\log\left(\frac{S}{S_0}\right) + C, \tag{11}$$

where $\overline{L}_P$ is the surface sound pressure level over the measurement hemisphere, in decibels, $S = 2\pi r^2$ is the area of hemisphere of radius r in square metres, $S_0 = 1\text{m}^2$, and C is the correction term, in decibels, for the influence of temperature θ in degrees Celsius, and atmospheric pressure p in millibars, given by

$$C = -10\log\left[\left(\frac{293}{273+\theta}\right)^{0.5} \times \frac{p}{1000}\right]. \tag{12}$$

The A-weighted sound power level, L_{WA} is obtained from Eqs. (7) and (11).

V. Results and discussion

For comparison of the accuracy obtainable when measured in reverberant and hemi-anechoic conditions, the measurements of sound power of a calibrated reference sound source were carried out in a reverberation room and a free field over a reflecting plane, according to ISO 3741 direct method and 3745, respectively. There are two types of sound power outputs emitted by the B&K type 4205 sound power source: (a) octave band noise output in 7 frequency bands: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz, and (b) wide band noise output in the frequency range 100 Hz to 10000 Hz. The accuracy of the emitted sound power when the sound source is calibrated is ± 1.5 dB in 125 Hz band, ± 1.0 dB in the frequency range 250 Hz to 2000 Hz, and ± 1.5 dB in 4000 Hz to 8000 Hz and wide band. In order to examine the accuracy of the measurement of sound power for each octave band and the determination of A-weighted sound power level, not only the sound power levels of octave band noise but also the A-weighted sound power levels of wide band noise were measured. The sound power level of the sound source was set to a value of 75 dB re 1 pW for each octave band with centre frequencies from 125 Hz to 8000 Hz and a value of 75 dB(A) re 1 pW for wide band, respectively, which is at least 15 dB above the background noise level in test rooms. If possible the sound power of the sound source should be set at a level sufficiently high above the background noise that no corrections are necessary.

Before measuring the sound power of the sound source, the background noise level was measured to check whether or not corrections are necessary to the sound power measurements. No corrections due to the background noise were necessary in each octave band and wide band because the background noise level including any noise due to motion of the microphone was at least 15 dB below the sound pressure level to be measured in each frequency band [5, 6].

Figure 3 shows the results obtained from sound power measurements of octave band noise emitted by the sound source in each frequency band. This figure compares the sound power levels measured in a reverberation room and a free field over a reflecting plane, according to ISO 3741 and 3745, respectively. As can be seen in Figure 3, the measured values of sound power are in good agreement with the sound power emitted by the sound source in each of octave bands. Although a small error due to interference caused by the reflecting plane may be introduced, this can be ignored. However, the sound power level for 125 Hz band as measured in a reverberation room according to ISO 3741 is in less agreement with the known value. The major cause of uncertainty in determining sound power levels in a reverberation room is the spatial irregularity of the sound field. At low frequencies, the major problem tends to be the small number of room mode that can be excited at any given frequency [5, 11, 12]. A large reverberation room may be used to reduce uncertainties at low frequencies although the precision of high frequency sound power level determinations may be degraded.

Conversely, a small room may lead to reduced high frequency uncertainties but increased low frequency uncertainties. Thus, if improved precision is needed, and if two reverberation rooms are available, it may be desirable to carry out the low frequency sound power level determinations in the larger room and high frequency determinations in the smaller room.

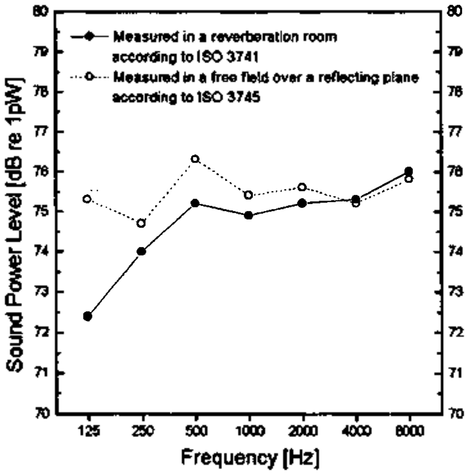

Figure 3. Sound power levels of octave band noise as measured in a reverberation room and a free field over a reflecting plane, according to ISO 3741 and 3745, respectively.

The major cause of uncertainty in determining sound power levels in an anechoic room is the spatial irregularity of the sound field due to the directivity of the source [6]. In a hemi-anechoic room, the spatial irregularity may be increased due to the superposition of the sound field of the actual source and that of the image source. The directivity pattern of a source located above a reflecting plane is generally more complicated than that of the same source in a free field. Moreover, the near field extends to greater distance, and the radius of the test hemispheres is usually larger than the radius of the test sphere that would be required in a free field. The smallest uncertainty in determining sound power levels occurs when measurements are made in a free field. Fore this reason, if no other constraints are present, the free field environment is preferred for laboratory measurements. However, it is difficult to make measurements on some classes of equipment under truly free field conditions. Some sound sources are too large to fit into existing anechoic rooms, some are too heavy to be suspended in the centre of these rooms and others are normally supported by or associated with a hard, reflecting surface. For these reasons, the free field over a reflecting plane is a laboratory environment that is useful for measurements on many different types of equipment.

The sound power spectra of wide band noise emitted by the sound source as measured in octave bands and the A-weighted sound power levels calculated from Eq. (7) are shown in Figure 4 and 5. Figure 4 shows the results measured in a reverberation room according to ISO 3741 and Figure 5 in a free field over a reflecting plane according to ISO 3745. From Figure 4 and 5, it can be seen that the A-weighted values determined from the octave band measurements of wide band noise agree to

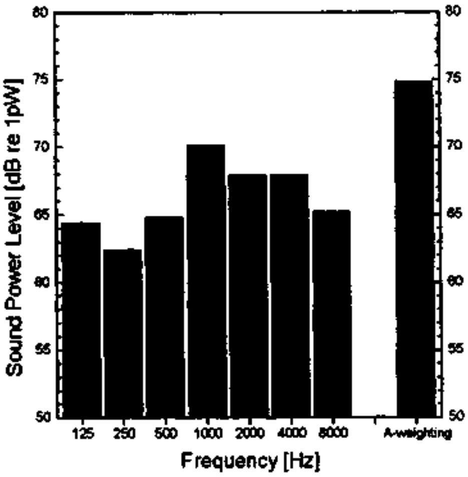

Figure 4. Sound power spectrum of wide band noise as measured in a reverberation room according to ISO 3741 and the A-weighted sound power level obtained from Eqs. (5) and (7).

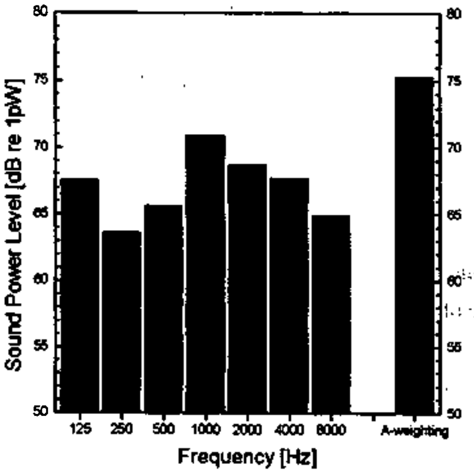

Figure 5. Sound power spectrum of wide band noise as measured in a free field over a reflecting plane according to ISO 3745 and the A-weighted sound power level obtained from Eqs. (7) and (11).

within 0.5 dB. In general, one can say that the highest accuracy of measurement will be obtained when the octave band measurements are used for sources that emit noise with a relatively flat spectrum.

VI. Conclusions

In this study, the sound power measurements were carried out in a reverberation room and a free field over a reflecting plane, using the precision methods of International Standards ISO 3741 direct method and ISO 3745, respectively. For comparison of the accuracy obtainable when determined in accordance with the standards ISO 3741 and 3745, the sound power levels of a calibrated reference sound source, which is emitting constant broad-band noise with an adequate sound power level, were determined from sound pressure measurements. In order to examine the accuracy of the measurement of sound power for each octave band, the sound power levels of octave band noise emitted by the calibrated reference sound source were measured in each frequency band. Also, the A-weighted sound power levels of wide band noise were determined from the octave band measurements. The sound power measurements carried out in this study give accurate estimation and also show that both methods for determining the sound power levels of a sound source in a reverberation room and a free field over a reflecting plane, according to the ISO 3741 and 3745, respectively, have proved equally good.

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