Hans G. Jonasson

Determination of Sound Power Level and Systematic Errors

Swedish Council for Work Life Research 1997-1612
Abstract

Some of the basic international standards for determination of sound power levels contain known systematic errors which are not dealt with. In particular, the standards which base the determination of sound power level on sound pressure level measurements in a more or less free field above a reflecting plane have this weakness. The two errors which are believed to be most important in practical applications are the sampling error and the wave front or angle error. At low frequencies and at short measurement distances the near-field error may also become significant. These problems are discussed, theoretical simulations are carried out and measurements on 5 different machines using different methods are reported. Improvements are proposed.

EN ISO 3745 uses a hemi-spherical measurement surface. The microphone array specified is not optimal. In particular for small machines serious systematic errors will occur due to interference between direct and floor reflected sound. It is possible to improve the measurement accuracy significantly by changing the microphone array to eliminate more than one microphone position from having the same height above the reflecting surface. It is recommended to adopt the 20 points array proposed in the new ISO 6926 for the calibration of reference sound sources.

EN ISO 3744 has the same deficiencies as EN ISO 3745 when a hemispherical measurement surface is used. However, as the measurement uncertainty is greater, it may be sufficient to replace the old 10 points microphone array by a new 10 points array. In addition ISO 3744 has a problem when using a box-shaped measurement surface. This surface will yield systematically too high sound power levels. It seems to be difficult to make accurate corrections but it is recommended to supplement the standard with a 1 dB systematic error and to warn for even greater errors for large machines. The present 9 points array for the key microphone positions is not suitable, in particular for small sources. As for the hemi-spherical array, microphone positions on the same height above the reflecting plane should be avoided.

Key words: sound power level, measurement, systematic error, international standard

SP Sveriges Provnings- och Forskningsinstitut
SP Rapport 1998:39
ISSN 0284-5172
Borås 1998

SP Swedish National Testing and Research Institute
SP Report 1998:39

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Preface

This project has been funded by the Swedish Council for Work Life Research project no 1997-1612.

The measurements have been carried out by Jarl Olofsson, Geir Andresen and Tomas Ström. Tore Bergqvist built the artificial sound sources.

The help of the above organization and individuals is gratefully acknowledged.

Borås 1998-12-18

Hans Jonasson
Conclusions

Some of the basic standards for determination of sound power levels contain known systematic errors which are not dealt with. In particular, the standards which base the determination of sound power level on sound pressure level measurements in a more or less free field above a reflecting plane have this weakness. The two errors which are believed to be most important in practical applications are the sampling error and the wave front or angle error. At low frequencies and at short measurement distances the near-field error may also become significant.

EN ISO 3745 uses a hemi-spherical measurement surface. The microphone array specified is not optimal. In particular for small machines serious systematic errors will occur due to interference between direct and floor reflected sound. It is possible to improve the measurement accuracy significantly by changing the microphone array to eliminate more than one microphone position from having the same height above the reflecting surface. It is recommended to adopt the 20 points array proposed in the new ISO 6926 for the calibration of reference sound sources.

EN ISO 3744 has the same deficiencies as EN ISO 3745 when a hemispherical measurement surface is used. However, as the measurement uncertainty is greater, it may be sufficient to replace the old 10 points microphone array by a new 10 points array. In addition ISO 3744 has a problem when using a box-shaped measurement surface. This surface will yield systematically too high sound power levels. It seems to be difficult to make accurate corrections but it is recommended to supplement the standard with a 1 dB systematic error and to warn for even greater errors for large machines. In addition the present 9 points array for the key microphone positions is not suitable, in particular for small sources. As for the hemi-spherical array microphone positions on the same height above the reflecting plane should be avoided.
1 Introduction

1.1 Background

At present there are 9 different international and European standards for the determination of the sound power level of machines, the ISO 3740 series, [1]-[6], and ISO 9614, [7]. All standards are or will become harmonized European standards.

In each standard the measurement uncertainty is given in terms of the standard deviation of the reproducibility. However, nothing is said about the systematic errors(bias). This means that two standards can have the same random measurement uncertainty although there may be a systematic difference of several dB between the standards. Sometimes these systematic errors are greater than the random errors given as standard deviations relevant for one specific standard. According to ISO and CEN guidelines, [8], different standards with the same random measurement uncertainty should be considered to be equivalent. Depending on the environmental conditions and the practical requirements the most suitable standards can be selected.

The systematic errors are, to a large extent, rather well known but so far there have been few constructive proposals to consider them in the basic sound power standards. An overview of some of the errors is given in [16].

In [11] some comparisons between different methods are reported, see figure 1.

![Graph showing differences between sound power levels determined by various methods.]

**Figure 1.** The difference between the A-weighted sound power level determined by the standards indicated and that of ISO 3741. 4 laboratories and 8 sources.

From figure 1 it is difficult to draw any firm conclusions about systematic errors. However, if we reanalyze the data and take a closer look at ISO 3744 a slightly different pattern appears. The two lowest values, those of Delab, have been obtained using a hemispherical measurement surface while all other results have been obtained using a box-shaped measurement surface. If the Delab results are excluded there is a strong
indication that the sound power level, relative to ISO 3741, is systematically overestimated.

1.2 Aim

The aim of this project is to analyze the systematic errors in sound power determinations and, if possible, propose modifications to the existing international standards in order to decrease the difference in measurement results between the different methods.
2 Test methods - Some preliminary considerations

2.1 EN ISO 9614

This is the most basic method and at the same time the most recent standard. It is basic as it relies on the sound intensity technique, that is the sound power is determined directly from the sound intensity without using the sound pressure in an intermediate step. Mathematically the sound power $P$ is obtained from the equation

$$ P = \iint_{S} I \hat{n} \cdot dS $$

(2.1)

where $S$ is a surface completely enclosing the source, $I$ is the intensity vector from the source and $\hat{n}$ the normal to the surface.

Assuming that the measurements are carried out properly eq. (2.1) is considered to give the true sound power without any systematic errors. Thus we will use this method as reference together with ISO 3745 with a large measurement radius and ISO 3741.

2.2 EN ISO 3741

ISO 3741, [1], is a reverberation method. Apart from the low frequencies this method has been shown to give equivalent results with ISO 3745, see below. In [20] it is concluded "Measurements in hemi-free field rooms and in reverberation rooms produce exactly the same results, except in the frequency ranges below 100 Hz and above 10 kHz". In the latest version the result is normalized to the reference characteristic impedance $R_c = 400$ and a new correction, from [21], is introduced. This correction means that

$$ L_W = L_{W,old} + 4,34 \frac{A}{S} $$

(2.2)

Where $L_{W,old}$ is the sound power level of the old ISO 3741, $A$ is the sound absorption area of the reverberation room and $S$ is the surface area of the room boundaries.

This new correction will, to a large extent, eliminate earlier differences at high frequencies. After these improvements the only known remaining weakness is the low frequencies. However, as these low frequency problems are very closely coupled to room dimensions they will not be dealt with further here.

2.3 EN ISO 3743 and 3747

Part one of ISO 3743 is a comparison method, that is the sound power is determined by comparing the sound pressure levels of the source under test with those of a reference sound source with known sound power output. This standard has no known systematic errors in addition to those associated with the calibration of the reference sound source, which shall be calibrated according to ISO 6926, which allows calibrations according to either ISO 3741 or ISO 3745.
Part two is either a comparison method in a special reverberation room or a method with a standard correction. As this method is no longer used extensively it will not be dealt with further.

ISO 3747 is also a comparison method. However, as it is under revision and not yet finalized it will not be discussed here.

2.4 EN ISO 3744, 3745 and 3746

These standards are all based on measurement of sound pressure levels on a measurement surface surrounding the source under test in a test environment with a more or less free sound field above a reflecting plane. These standards are widely used (ISO 3745 indirectly to calibrate reference sound sources). As they have, as will be shown later, in many practical applications known significant systematical errors this project will concentrate on these standards. However, systematic errors, if any, due to environmental corrections ($K_2$ in the standards) due to an inferior measurement environment outside the laboratory will not be dealt with.

In [9] the systematic errors under free-field conditions are analyzed. In [12] and [13] there are some constructive proposals to eliminate the wave front or angle error but these proposals have not been considered in the present international standards. Sampling errors and interference effects are discussed in [14] and [17]. In [15] some measurements are reported indicating that boxshaped measurement surfaces result in sound power levels up to 2 dB greater than those obtained using a hemispherical measurement surface.

In ISO 3744 and 3745 there is one important rule which, as will be shown later, are very questionable. It is that, when using a hemi-spherical measurement surface, and more positions are required because the maximum difference between two microphone positions exceed the number of microphone positions additional positions are to be obtained by rotating the original 10 p array around the vertical axis. Thus the heights of the microphone above the floor will remain the same and no new information about interference effects will be gained.

As to ISO 3744 nothing is said about the systematic differences between a hemi-spherical and a box-shaped measurement surface. Although there is a requirement to use the same type of measurement surface on similar machines this is not very helpful when other standards can be applied as an alternative.
3 Theoretical considerations

3.1 Mathematical simulations

For measurements on a measurement surface in a free field above a reflecting plane mathematical simulations have been made. The procedure is outlined in the following.

If the near field error, see clause 3.2, is ignored we can assume having a point source generating the following sound pressure

\[ p = \frac{e^{\alpha r}}{r} \]  \hspace{1cm} (3.1)

where \( k \) is the wave number and \( r \) the distance. For reasons of simplification the amplitude has been normalized. Putting \( r=R_1 \) for the direct sound wave, that is the distance between the point source and a microphone position, and \( r=R_2 \) for the floor reflected sound wave, that is the distance between the image point source and the microphone position, yields the following expression for the total sound pressure

\[ |p| = \frac{1}{R} \sqrt{1 + \left( \frac{R_1}{R_2} \right)^2 + \frac{2R_1}{R_2} \cos(k(R_2 - R_1))} \]  \hspace{1cm} (3.2)

(3.2) is valid for tones. Following [19] averaging over third octaves transforms (3.2) into

\[ |p| = \frac{1}{R} \sqrt{1 + \left[ \frac{R_1}{R_2} \right]^2 + \frac{2R_1}{R_2} \sin \left[ \frac{k(R_2 - R_1) \Delta f}{2f} \right] \cos \left( \frac{k(R_2 - R_1)}{2f} \sqrt{1 + \left( \frac{\Delta f}{2f} \right)^2} \right) \] \hspace{1cm} (3.3)

For third octave bands

\[ \frac{\Delta f}{2f} = \frac{2^{1/6} - 2^{-1/6}}{2} = 0.1158 \] \hspace{1cm} (3.4)

According to ISO 3744

\[ L_w = 10 \log \left( \frac{P_r^2}{P_0^2} \right) + 10 \log(S) \] \hspace{1cm} (3.5)

where \( S \) is the area of the measurement surface, \( P_0 = 2 \cdot 10^{-3} \) and \( P_r^2 \) is the mean pressure-squared over the measurement surface.

The "true" sound power necessary to generate the sound pressure of eq. (3.1) is given by
\[ L_{\text{Wtrue}} = 10 \log \left( \frac{W_{\text{true}}}{10^{-12}} \right) = 10 \log \left( \frac{p^2 S}{\rho c \cdot 10^{-12}} \right) \]  

(3.6)

In (3.6) \( S \) is the area of a sphere at any distance \( r \), \( 4\pi r^2 \), and \( p \) the sound pressure at this distance. \( \rho c \) = characteristic impedance of air = 400. Using \( r=R_f \) thus yields the "error" 

\[ L_{W} - L_{\text{Wtrue}} = 10 \log (p^2) + 10 \log (S) - 10 \log \left( \frac{4\pi R_f^2 \cdot 4 \cdot 10^{-10}}{400 R_f^2 \cdot 10^{-12}} \right) = \]

(3.7)

\( p^2 \) in (3.7) is the energy average of all microphone positions for which \( p^2 \) is evaluated from (3.3) and \( S \) is the area of the measurement surface.

It should be observed that the true sound power level above is not an unambiguous definition as we do not consider the effect of nearby reflecting surfaces.

### 3.2 Measurements in a free field above a reflecting plane

#### 3.2.1 General

Measurements according to ISO 3744 and 3745 are based on the assumption that the sound intensity is approximated by the squared sound pressure over the characteristic impedance of air and that the sound power is obtained by integration of the sound intensity over a surface completely surrounding the source under test. The first assumption is valid only when the sound pressure and the particle velocity is in phase, something which is not the case at distances short compared to the wavelength. The actual integration over the surface assumes that the wavefront is perpendicular to the surface. This is approximately true for a hemispherical surface far from the source but never for a boxshaped surface close to the source. In the following these two errors will be called near-field error and wavefront error(also often called angle error) respectively. As has been shown in [9] these two errors will always lead to an overestimate of the true sound power. Another source of error, the sampling error, is the averaging error on the measurement surface. If an inadequate number of microphone positions are used the estimate of the mean sound pressure level will be wrong.

Examples of the wavefront error are given in [13] and [15]. For small machines it is not unusual to get an overestimate of the sound power level of the order 2 dB which may be doubled or even more for large machines.

The sampling error is dealt with in the standards by requiring more microphone positions if the maximum sound pressure level difference between two positions is greater than the total number of positions. However, this is not enough. [17] and [14] show that interference effects have a significant effect on the measurement result. This problem will be dealt with in detail in the following.
3.2.2 Hemi-spherical measurement surface - Sampling error

![Diagram of RSS measurement using a hemi-spherical measurement](image)

Figure 2. A RSS measured using a hemi-spherical measurement.

Measurements on a hemi-spherical measurement surface according to ISO 3744 or 3745 are carried out using the microphone array shown in figure 2. In [14] a new microphone array is proposed as a better alternative to the one recommended in ISO 3745. The new version of ISO 6926, [18], also contains a new 20 points array for the calibration of reference sound sources. The coordinates for the different arrays are given in table 1. A theoretical simulation of these three arrays is shown in figure 3 for a 0.2 m high point source. The results confirm that the new arrays are better than that of ISO 3745. They both avoid the deep dip around 2500 Hz. The result is similar if the point source is raised from 0.2 m to 0.8 m, see figure 4, the dip then moves downwards in frequency but it is still there.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Different arrays on a hemispherical measurement surface</th>
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<tr>
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<tr>
<td></td>
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<td>0.38</td>
</tr>
<tr>
<td>20</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Figure 3. A comparison between the ISO 3745 10 points microphone array (full line), the one proposed in [14] (dashed line) and the new 20 points array in ISO 6926 (++++) with a point source 0.2 m above a reflecting plane. \( r = 2 \) m. The 3 upper curves indicate the maximum level difference between two microphone positions.

Figure 4. A comparison between the ISO 3745 10 points microphone array (full line), the one proposed in [14] (dashed line) and the new 20 points array in ISO 6926 (++++) with a point source 0.8 m above a reflecting plane. \( r = 3 \) m. The 3 upper curves indicate the maximum level difference between two microphone positions.
Figure 5.  New ISO 6926 20p array (full line), reduced ISO 6926 10p array (---) and present ISO 3745 10p array (+++). Figure 5 shows that even a reduced ISO 6926 array from 20 to 10 positions is very good and considerably better than the present ISO 3745 array.

Figure 6 and 7 show what happens if we have a larger source. Figure 6 indicates that the new arrays are significantly better when the measurement radius is small, in this case it is twice the largest dimension (or twice the highest point source) while figure 7 indicates a smaller difference when the measurement radius increases to four times the largest dimension or four times the height of the highest source.

Figure 6.  A comparison between the ISO 3745 10 points microphone array (full line), the one proposed in [14] (dashed line) and the new 20 points array in ISO 6926 (+++) for the large chip board box described in clause 4.2. Measurement radius 4 m. The 3 upper curves indicate the maximum level difference between two microphone positions.
Figure 7. A comparison between the ISO 3745 10 points microphone array (full line), the one proposed in [14] (dashed line) and the new 20 points array in ISO 6926 (+++) for the large chip board box described in clause 4.2. Measurement radius 8 m.

3.2.3 Box-shaped measurement surface - Sampling error

Figure 8. Key microphone positions of a box-shaped measurement surface according to ISO 3744.

Measurements on a box-shaped measurement surface according to ISO 3744 are carried out using the microphone array (9 key positions only) shown in figure 8. For large or highly directive sources additional positions are required. As is shown in figure 9, this array often causes serious interference problems. The coordinates of the ISO array are
given in table 2 together with a proposal for a new array avoiding the most serious interference problems. The theoretical simulation of the two arrays for a 0.2 m high point source is shown in figure 9. The results confirm that the new array, at least for the geometry tested, is better than that of ISO 3744. The result is similar if the point source is raised from 0.2 m to 0.8 m, see figure 10. The comparison is not quite 100% fair as ISO 3744 prescribes additional microphone positions whenever the difference in sound pressure level between two microphone positions is greater than 9 dB (for the 9 key positions). However, it is interesting to note that the new array is better despite a greater max level difference (14 dB versus 12 dB in figure 9).

Table 2  Key microphone positions of ISO 3744 and a proposal for new key positions. lx, ly and lz are the dimensions of the measurement surface.

<table>
<thead>
<tr>
<th></th>
<th>ISO 3744</th>
<th>New proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
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<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>0.5 lx</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.5 ly</td>
</tr>
<tr>
<td>4</td>
<td>-0.5 lx</td>
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<tr>
<td>5</td>
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<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-0.5 lx</td>
<td>-0.5 ly</td>
</tr>
<tr>
<td>7</td>
<td>0.5 lx</td>
<td>-0.5 ly</td>
</tr>
<tr>
<td>8</td>
<td>0.5 lx</td>
<td>0.5 ly</td>
</tr>
<tr>
<td>9</td>
<td>-0.5 lx</td>
<td>0.5 ly</td>
</tr>
</tbody>
</table>

Figure 9.  3 different arrays on a boxshaped measurement surface. Point source at 0.2 m, d= 1 m. 37p according to ISO 3744(full line), 9p according to ISO 3744 (dashed line), new array according to table 2 (++++).
Figure 10. As figure 8 but with the source height 0.8 m.

In figure 11 and 12 a larger source, the large chipboard box shown in figure 20, is simulated as two point sources at about 1 m and 2 m respectively. In these cases the differences between the different arrays are less pronounced than is the case for the single point source close to the floor.

Figure 11. 3 different arrays on a boxshaped measurement surface. Two point sources at the holes of the large chipboard box, see figure 20. d= 1 m. 37p according to ISO 3744(full line), 9p according to ISO 3744 (dashed line), new 9p array (+++).
Figure 12. As figure 10 but with d=2 m.

Figure 13. A point source with height varying from 0.1 to 2.0 m in steps of 0.1 m. Full line indicates 9p box array at 1 m according to ISO 3744. (+++ ) indicates the new 9p array.

In figure 13 and 14 a point source is simulated moving upwards in steps of 0.1 m. The figures indicate that the new array is considerably better without any significant interference effects and that the new 9p array is a good alternative to the old 37p array.
3.2.4 **Box-shaped measurement surface - wave front error**

Even if the sampling error is eliminated the wave front error will still remain. In figure 15 and 16 two examples are shown. At low frequencies all levels above +3 dB are due to the wave front error and at high frequencies this is approximately the case above 0 dB. Figure 15 indicates that, for a point source, the wave front or angle error is 1.2 - 1.7 dB for a 37p array. Figure 16 which refers to a larger machine with two dominating point sources at the edges indicates that the wave front error increases with the size of the machine. It should be observed that the 37p simulated array is not always in 100% compliance with the standards, some small areas may be oversampled. However, the practical consequences of the deviations which take place are small.
Figure 16. Box shaped measurement surface with 37 microphone positions at \( d = 1 \text{ m} \) around a 3 m by 1 m by \( h(i) \text{ m} \) machine with two point sources with heights \( h(i) \) and \( 0.5h(i) \) respectively on two diagonal corners in steps of 0.1 m.

3.3 Discussion

The simulations in 3.2 clearly confirms the following:

- the standard microphone array used in ISO 3745 and 3744 for a hemispherical measurement surface and in 3744 and 3746 for a box-shaped measurement surface is not as good as it could be, in particular not for sources with one dominating small sound emitting part
- a boxshaped measuremnt surface always overestimates the sound power level
- a hemi-spherical measurement surface is preferable to a box-shaped

As to constructive proposals for improvements the results indicate the following possible solutions:

- for a hemispherical measurement surface in ISO 3745 adopt the new 20 points array in ISO 6926.
- for a hemispherical measurement surface in ISO 3744 adopt either the microphone array according to [14] or [18]
- for a box-shaped measurement surface adopt either the array proposed or something similar and, as a consequence of a better array, loosen the requirements on maximum permissible differences between two microphone positions
- include the bias in future versions of ISO 3744 when using a box-shaped measurement surface
4 Description of measurements

4.1 Measurement procedures

4.2 Sources tested

Five different sources have been used for the tests:

A B&K 4204 reference sound source with the size (reference box) 0.300 m x 0.300 m x 0.315 m, see figure 17.

Figure 17. B&K 4204 reference sound source

An electric compressor with the size 0.90 m x 0.57 m x 1.21 m, see figure 18.

Figure 18. The compressor

A small chip board box with the size 0.900 m x 0.615 m x 0.810, see figure 19. The box had two open holes, one in the middle of the top side and one in the middle of one of the small sides and inside the B&K reference sound source was located.
Figure 19. The small chip board box.

A large chipboard box, see figure 20, with the dimensions (reference box) 2,0 m x 0,65 m x 2,14 m. The lower part of the box had the height 1,15 m and inside there was the reference sound source.

Figure 20. The large chipboard box
A circular saw with the size 1,02 m x 1,38 m x 0,88 m, see figure 21. The saw was idling during the measurements.

Figure 21. The circular saw
5 Measurement results - Comparisons with theoretical simulations

5.1 The reference sound source

![Graph showing sound power level vs frequency for different measurements.]

**Figure 22.** B & K reference sound source. A comparison between different precision methods. The "Hemi,scan" measurement is the PTB calibration measurement.

Figure 22 indicates that the agreement between different precision methods is rather good with two exceptions: the low frequencies and ISO 3741 and the interference frequency 2500 Hz. As has been shown in clause 3 the latter problem will be eliminated if another microphone array is used. The example in figure 22 refers to the present array.

Figure 23 illustrates the near field error. The error is small at 1 m above 100 Hz. However, at shorter distances and lower frequencies the error quickly becomes quite significant. It should be observed that only 9 microphone positions have been used also at the shortest distances. According to the standard more positions are required so close to the source, at least for some frequencies, see figure 24 for all frequencies where the level difference between two microphone positions exceeds 9 dB. However, the basic result would have been the same in this case for the low frequencies. (see figure 26 for an example at 1 m).
Figure 23. Illustration of the near field error. Measurements on a boxshaped measurement surface around a B&K aerodynamic reference sound source.

Figure 24. Maximum difference between two microphone positions on the measurement surfaces used for the reference sound source.

The great sound pressure level differences at low frequencies shown in figure 24 is due to the near field error.
Figure 25. Theoretical simulation with point source at h=0,2 m. Measurement distance d = 0,25 m (+--), d= 0,5 m (----), d = 1,0 m (-----) and d= 2,0 m (-.-.-). 9 microphone positions in each case. The three upper curves indicate the maximum level difference between two microphone positions.

Figure 25 is a theoretical simulation of the measurements shown in figure 23 and figure 24. As can be seen the agreement is rather good considering the fact that the reference sound source has been modelled as one single point source at the height 0,2 m.

Figure 26. Illustration of the sampling error.
Figure 27. Measurement on a B&K 4204 reference sound source using a box-shaped and a hemi-spherical measurement surface respectively.

Figure 28 is a theoretical simulation of the measurements accounted for in figure 27. The principal agreement is good. In both cases the box-shaped surface overestimates the sound power level about one dB at low and high frequencies. Because of interference effects around 1000 Hz the box-shaped surface does, in this specific case, not yield the same overestimate.

Figure 28. Theoretical comparison between hemisphere, \( r = 2 \text{ m} \) and \( 20 \text{ p} \) according to ISO 6926 (full line), and box, \( d = 1 \text{ m} \) and \( 37 \text{ p} \) (++). Effective height of point source \( 0.2 \text{ m} \).
5.2 The electric compressor

The electric compressor was tested according to the different methods shown in figure 29. Unfortunately only the ISO 3745 10 p array was used on the hemi-spherical measurement surface. It is difficult to draw any firm conclusions. However, the results indicate that the basic arrays for both the hemi-spherical and the box-shaped measurement surface are not optimal. It is also a little surprising that the 20p box-shaped array does not give a more systematic overestimate in relation to ISO 3741.

Figure 29. Sound power level of the compressor

Figure 30. Maximum difference between two microphone positions on the measurement surfaces used for the compressor.
5.3 The small chip board box with two holes

For the small chipboard box, the sound power level, determined using several different standards, is accounted for in figure 31. As can be seen the box-shaped measurement surface yields systematically higher values, at least above 630 Hz. At 200 Hz it yields the lowest values. However, this is most likely due to interference effects. As can be seen in the simulation shown in figure 32 the box surface has a minimum at this frequency. It should be noted that the hemispherical array has not been exactly the same during the measurement and the simulation. During the measurement the ISO 3745 array of table was used, positions 11-20 being obtained after a rotation of 180° of the original array. The simulation used the new ISO 6926 array.

![Graph showing sound power level vs frequency for different standards.](image1)

**Figure 31.** Sound power level of the small chipboard box determined according to three different standards.

![Graph showing theoretical simulation.](image2)

**Figure 32.** Theoretical simulation of small chipboard box. Hemi, 2 m, 20p according to ISO 6926 = full line, box, 1 m, 37p = (+ + +).
In figure 33 the box-shaped measurement surface with three different measurement distances is shown. There is no clear distinction between the cases. However, as is shown in figure 35, the theoretical difference between the three cases is less than 0.5 dB. It is difficult to measure such small differences.

**Figure 33.** The small chipboard box. Three different measurement distances.

**Figure 34.** Maximum difference between two microphone positions on the measurement surfaces used for the small chipboard box.
5.4 The large chipboard box

For the large chipboard box, see figure 20, figure 36 indicates a good agreement between ISO 3741 and 9614 apart from the high frequencies. As expected ISO 3744 with a boxshaped measurement surface yields systematically higher values. In figure 37 a simulation shows a similar behaviour.

Figure 35. Theoretical simulation of the small chipboard box. Box shaped measurement surface with 9 p and measurement distance d = 0.5 m (+++), d = 1 m (--), d = 2 m (---)

Figure 36. The sound power level of the large chipboard box determined according to four different standards.
Figure 37. Simulation of the large chipboard box using two point sources ISO 6926 20p array at r = 8 m (full line), boxshaped 37p array according to ISO 3744 at d = 1 m (---) and d = 0.5 m (++) respectively.

Figure 38. Maximum difference between two microphone positions on the measurement surfaces used for the large chipboard box.
5.5 The circular saw

For the circular saw, see figure 21, figure 39 indicates, as expected, that ISO 3744 and a boxshaped measurement surface yields systematically higher values than ISO 9614-2. Figure 40 indicates very little difference between different arrays. These small differences are confirmed by the theoretical simulation in figure 42.

![Graph](image1)

**Figure 39.** Comparison between the intensity method ISO 9614-2 and a 37 p array on a boxshaped measurement surface at d= 1 m.

![Graph](image2)

**Figure 40.** The sound power level determined according to different boxshaped measurement surfaces.
Figure 41. The maximum sound pressure level difference for different arrays around the circular saw.

Figure 42. Simulation of the circular saw using four point sources (the saw blade and three other openings) and a boxshaped measurement surface at 1 m using 37p (full line) and at 0.5 m (----) respectively.

5.6 Discussion

In general, the measurements support the conclusions drawn from the theoretical simulations in clause 3. Some additional information is also obtained. Figure 23 illustrates the near-field error which was not simulated. ISO 3744 allows measurements down to 50 Hz and a measurement distance down to 0.25 m. In the example given in figure 23 the near-field overestimate is 10 dB at 0.25 m! The standard should inform about this kind of error at short measurement distances.
The measurements also indicate how difficult it is to correct for the systematic overestimate of the sound power level due to a box-shaped measurement surface. As an example figure 27 indicates, for the reference sound source, that other measurement errors, for some frequency bands, may cancel this overestimate. Another example is the compressor measurements in figure 29 where the agreement between ISO 3741 and a box-shaped measurement surface is quite good for many frequency bands. In other cases, e.g. figure 36 and the large chipboard box and figure 39 and the circular saw, the overestimate is quite clear all over the frequency range. As has been shown in [12] by numerous calculation the overestimate increases with the size of the machine. For large machines 3 dB is not unusual. It seems to be reasonable to account for this by introducing a size dependent bias. However, this is not an easy task as the correction will not only depend on the size but also on the distribution of sources. It has not been possible to propose such corrections within this project. However, it might be possible to introduce a conservative correction which would be a step in the right direction.

Some of the theoretical conclusions are very well supported. Figure 26 comparing the 9p and the 37p array on a box-shaped measurement surface around the reference sound source clearly shows the inadequacy of the present 9p array.
6 Proposals

EN ISO 3744

As to the measurement uncertainty a systematic error should be introduced. This error should be zero for the hemi-spherical measurement surface and 1-3 dB for the box-shaped measurement surface. In addition a near-field bias should be included at low frequencies and for small measurement distances.

For small sources only hemispherical measurement surfaces should be used. Both the microphone array for the 10 key positions and for the additional positions should be changed to include more variations in the height above the floor. If box-shaped measurement surfaces are allowed for small machines the key microphone positions should be changed to include more variations in the height above the floor.

EN ISO 3745

No 10p array should be allowed. Introduce in stead the 20p array used in the new ISO 6926. Also in this standard a warning for the near field error should be issued for low frequencies whenever the measurement radius is smaller than 2 m.
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Under revision, 2nd WD nov 1997

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