PRACTICAL CONSIDERATIONS IN SOUND POWER MEASUREMENT

D Simmons Acoustics Group, National Physical Laboratory, UK
R Payne Acoustics Group, National Physical Laboratory, UK

1 INTRODUCTION

There are many practical considerations to be taken into account when making a sound power determination on a machine. For example, the choice between making sequential measurements using a single microphone, or using a fixed array, or power requirements for the machine and the instrumentation, and maintaining and monitoring the machine operating conditions. When conducting measurements outdoors there may be additional practical considerations to be taken into account, such as site security, weatherproofing of the instrumentation, and choice of site location. Even if a test code or measurement protocol is used, the user will have to use experience and expertise to make judgments on practical considerations affecting the balance between the often conflicting requirements for desired measurement accuracy, and measurement effort (and associated cost).

The focus of this paper is on two particular practical considerations brought to our attention from within the noise emission measurement community, as a result of a recent study, conducted by NPL that involved an industry survey. The particular measurement issues are given further analysis, and practical solutions to these particular problems are proposed.

2 BACKGROUND

Accurate measurements of noise emission from many different machines and products are required by regulations that refer industry directly to international specification standards. The EU Directive on noise from machinery used outdoors, 2000/14/EC[1] for example, requires in many cases, that measurements be conducted in accordance with the ISO 3740 series of standards, (entitled 'Determination of sound power level of noise sources using sound pressure').

In order to assess the suitability of the standards, there is a need to identify and assess the limitations and failings of currently used standard methods as experienced by industry. This was addressed in a recent study[2] commissioned by the U.K. National Measurement System (NMS), and conducted by NPL. The objective of the study was achieved by conducting a survey eliciting the views and experiences of industrial sectors involved in noise emission measurement, focusing especially on measurement of sound power of machinery. The output of the study will assist a long-term radical revision and simplification of the ISO 3740 series of standards, based on the principle that the selection of a measurement method and configuration is based upon the degree of accuracy desired.

The feedback from the industry survey identified several broad problem areas, namely meteorological conditions, measurement uncertainties, machine operating conditions, test site, and number of microphones. The specific problems discussed in this paper fall into the 'test site' and 'number of microphones' categories, and are referred to below, as 'problem 1' and 'problem 2' respectively.

3 PROBLEM 1: PREDICTION OF GROUND PLANE ABSORPTION COEFFICIENT FROM MEASUREMENT OF K_2

3.1 Background and methodology

Questions arose during the industrial survey regarding the reflecting ground plane for measurements conducted in hemi-anechoic conditions, especially, in connection with its approximation to acoustic characteristics of 'real' floors. The assessment of the reflecting (or absorption) properties of a floor is complicated and usually requires the use of a reverberation chamber.

Here, the possibility of defining a simpler measurement procedure that describes the reflection properties of a ground plane, in a clear and simple way, is assessed. This proposed method requires only the measurement of k_2, the environmental correction factor specified in ISO 3744[3], and assumes that the acoustic environment is essentially free-field over a partially reflecting ground plane.

This paper reports upon an experimental study involving the measurement of k_2 using ground covering materials exhibiting a variety of absorption coefficients. The feasibility of a simple method for estimating absorption coefficient of the ground plane, from measurement of k_2, is investigated.

3.2 Experimental procedure

A variety of ground plane materials and constructions were used for this study. The materials were chosen on the basis of ease of construction and variety of absorption characteristics. The surface area of the floor coverings varied between 14 and 17 square meters. The materials are reported, together with approximate material depth, in Table 1 below.

Table 1 Floor coverings

Material code	Material Description	Approx surface area (m^2)	Approx depth (mm)
A	Carpet tiles	15.6	15
B	Hardboard panels	13.5	8
C	Low density fibreglass	13.5	100
D	Felt underlay	16.7	15
D	*B* over sound absorbent foam in wooden slat frame	13.5	108
E	*D* over sound absorbent foam in wooden slat frame	13.5	108
F	*A* over sound absorbent foam in wooden slat frame	12.0	200
G	*C* over sound absorbent foam in wooden slat frame	13.5	115

The environmental correction factor, *k2(mat)* for each floor covering, was determined in a hemi-anechoic room. The sound power level, *Lw(mat)* from which $k_2(mat)$ was calculated, was determined using a Reference Sound Source (RSS) B&K type 4204, placed over the floor covering. The measurements were conducted in accordance with the requirements of ISO 3744, using the 10 key microphone positions distributed over a 1.5 m radius hemispherical measurement surface. k_2(mat) for each material covering was calculated in 1/3 octave frequency bands from the following expression:

$$k_2(mat) = Lw(mat) – Lw(ref)$$

Where *Lw(ref)* is the sound power level of the RSS, measured directly over the concrete ground plane, with no absorbent material present. The sound absorption coefficient for each material covering was measured in a reverberation chamber using the interrupted noise method, as specified in ISO 354[4]. Reverberation times were acquired in 1/3-octave bands between 100 Hz and 10 kHz. For both chambers, the permanent floor, on which the coverings were laid, consisted of 50 cm thick concrete having negligible sound absorption.

3.3 Measurement results for k2(mat)

The measured values for k_2 for ground plane materials are shown in Figure 1. The legend indicates the covering material label (see Table 1).

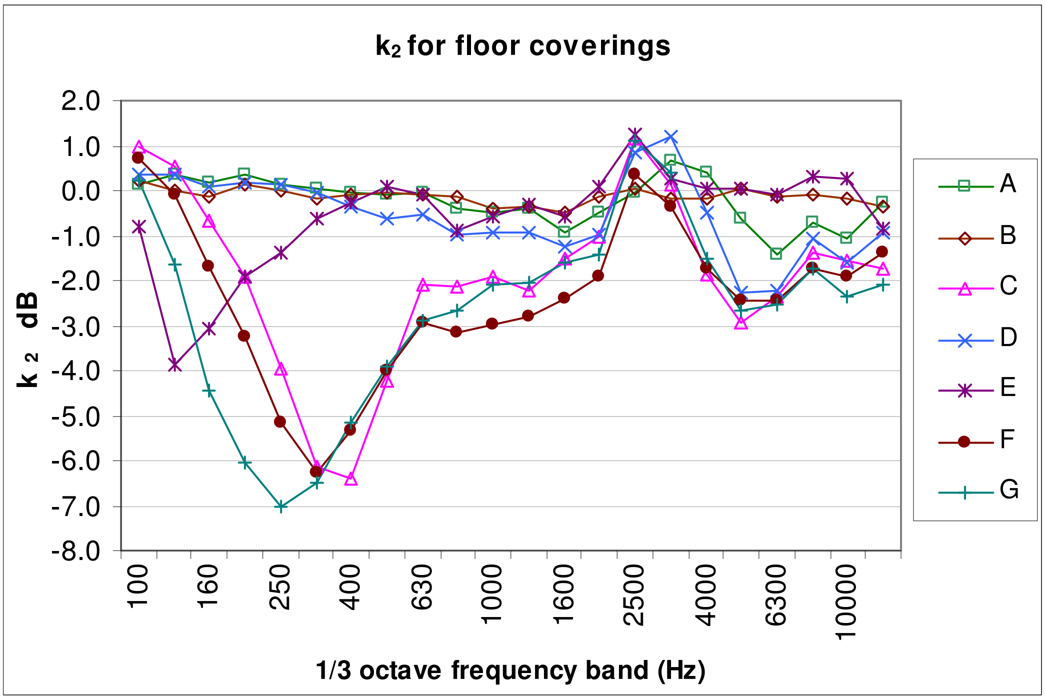

Figure 1 Measured values of k_2 for floor coverings

The large low frequency 'dip' observed for many material coverings, present in the 200 Hz to 500 Hz frequency region may be largely explained by a reduction of constructive interference. If it is assumed, for modelling purposes, that the sound at the microphone is the sum of two waves, one direct path originating from a point on the RSS surface at half the height of the RSS and the other path emitted from an imaginary source, originating from a reflection in the ground plane, then as the ground plane becomes more absorbent, the overall sound power level will appear to decrease. At lower frequencies, the direct and reflected signals are correlated and therefore a potential maximum difference of 6 dB is possible, as a result of pressure doubling. At higher frequencies, the direct and reflected signals are no longer correlated and therefore combine on an energy basis, resulting in a change of up to 3 dB. The frequency of the first constructive interference, for the microphones at the middle height, 0.68 m (for a 1.5 m radius hemisphere), occurs at approximately 400 Hz. For the higher microphone positions, at height 1.15 m, there is a slightly larger path difference hence the constructive interference peak will occur at a slightly lower freq, and for the lower microphone position, at height 0.23 m, a slightly higher frequency.

It can also be observed in Figure 1 that *D*, *E*, *F* and *G*, and to a lesser extent, material *A*, exhibit a 'peak' at approximately 3 kHz. These materials had a depth exceeding 100 mm. It is therefore concluded that the peak corresponds to a change in interference resulting from the modified path difference between direct and reflected sound due to the change in height relative to the concrete ground.

3.4 Measurement results for sound absorption

The measured sound absorption coefficient for each floor covering, is shown below in Figure 2. The legend indicates the floor covering material label.

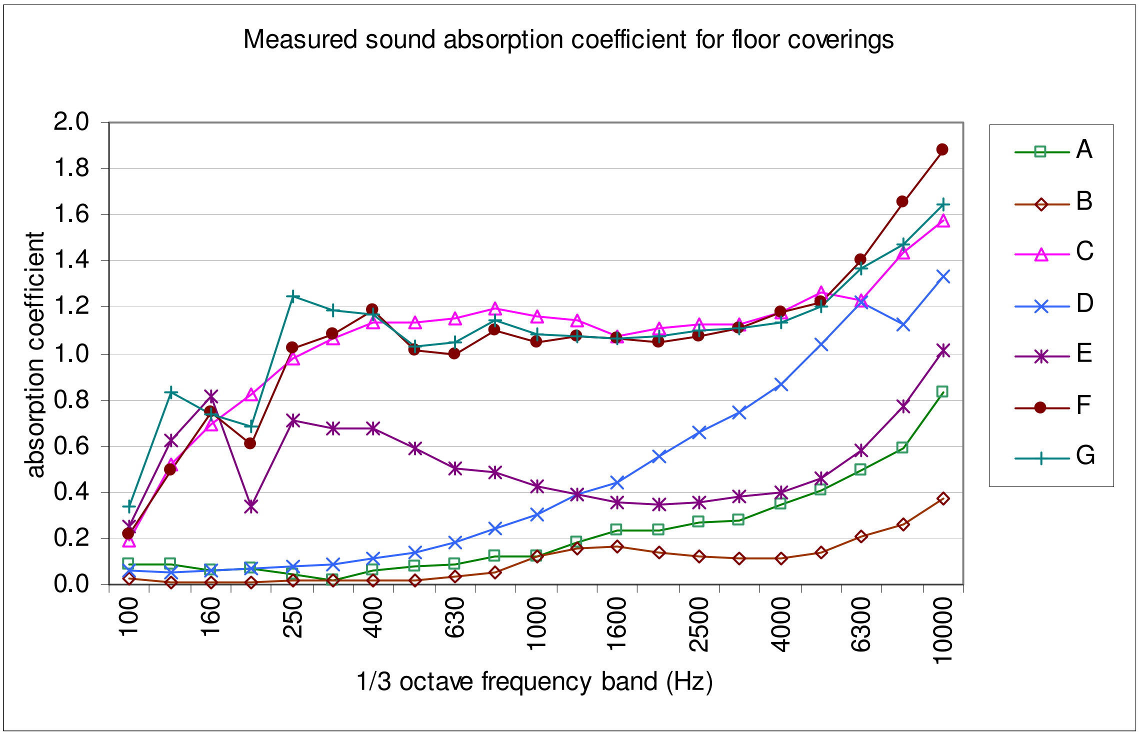

Figure 2 Absorption coefficient for floor coverings

It may be observed that many of the materials have an absorption coefficient greater than 1. One reason for this is the error resulting from estimation of surface area in the case of materials *E*, *F*, and *G*, there is partial absorption from the sides of the material sample and from areas around the edge where the top layer did not coincide with the edge of the sound absorbent foam filled frame.

In general, considering a point source above a ground plane, the attenuation of the signal reflected from the ground plane, is related to the absorption coefficient, α. However, the value for α using ISO 354 is for random incidence, whereas the required α, for the purposes of this study is for specific angles of incidence associated with the receiver (microphone) height. This is therefore a source of uncertainty in the measurement of α, for this application. Also, it should be noted that sound not absorbed by the material is reflected back into the material from the concrete floor below, and therefore the measurement results discussed in this study are not necessarily applicable to materials covering ground planes having a greater absorption than concrete.

3.5 Data analysis and discussion

For practical purposes, it is assumed that the relationship between k_2, and absorption coefficient, *a*, may be modelled by a linear best-fit line, using the least squares statistical method. For this model, it is assumed that for a totally reflective ground plane, such as the concrete floor used in a hemi-anechoic chamber, the measured $k_{2,ref}$ should be exactly 0, and the corresponding absorption coefficient of that material should also be exactly 0. This constraint forces the best-fit line to pass through the origin, (0,0). It is proposed that the absorption coefficient of the ground plane material under test, a(f), in frequency band f, may be estimated from the following expression:

$a(f) = -k2(f) \cdot m(f)$

Where $k_2(f)$ is the environmental correction factor, in octave band *f*, measured over the ground plane under test, and *m(f)* is the gradient of the best-fit line, obtained from a plot of k_2 against a, as measured in this investigation. For practical reasons, the measured data was combined into octave bands.

An examination of the goodness of fit associated with each line is summarised, along with line gradient, *m*, for each frequency band, in Table 2, below. The quantity used to assess goodness of fit is the coefficient of determination, R^2. This represents the proportion of the variation of the data explained by the best-fit model. In this case, the model is a linear fit passing through (0,0).

Table 2 Values of gradient m(f) and coefficient of determination, R^2

Octave band centre frequency (Hz)	$m_{(f)}$	Goodness of fit,'(R^2')
125	-0.27	-0.17
250	-0.20	0.82
500	-0.28	0.79
1000	-0.45	0.87
2000	-0.81	0.46
4000	-0.85	0.33
8000	-0.70	0.46

In the 250 Hz, 500 Hz, 1000 Hz frequency bands, the high values of R^2 indicates that there is reasonably strong evidence that there is a linear relationship between $k_2(f)$ and *a(f)*. The low value for R^2 in the remaining frequency bands indicate that there is no strong evidence for a linear relationship between $k_2(f)$ and *a(f)*.

However, for the purposes of application of this procedure to noise emission declaration, an A-weighted quantity for *a*, is required. An 'A-weighted' absorption coefficient, *a(A)*, has been calculated from octave band reverberation time values. It is assumed for the purposes of this study, that the initial average sound pressure level, used for the reverberation time tests, in each frequency band, is the same. This flat spectral shape is reasonably representative of the actual spectral shape of the RSS used for determination of $k_2(A)$, and of the noise source used for the reverberation time measurements required for the calculation of *a(A)*. The scatter plot and associated best-fit line, showing the variation of k_2, with *a(A)*, is shown in Figure 3, below. Also displayed on Figure 3 is the equation of the line and the corresponding value for R^2.

It can be seen from Figure 3, below, that the value of R^2 is 0.9. This high value indicates that there is reasonably strong evidence that the data fits this best fit model, and that the gradient *m*, for A-weighted *a*, having a value of –0.6, is reliable.

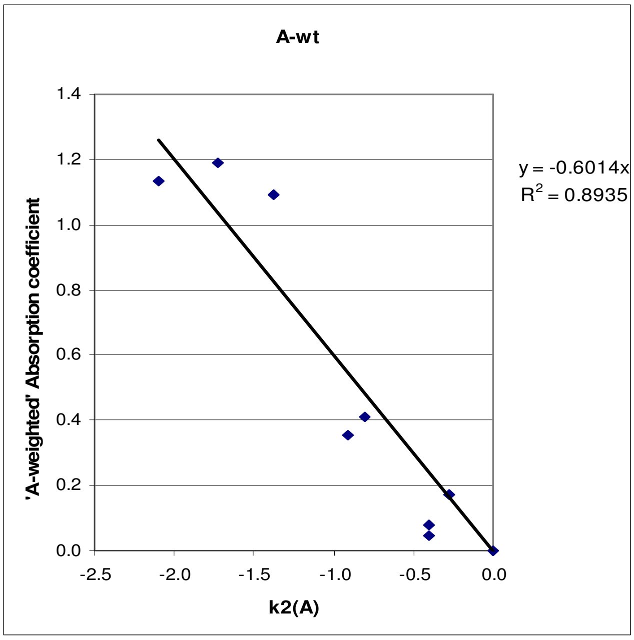

Figure 3 Variation of k_2, with $\alpha_{(A)}$

3.6 Conclusion and proposed solution for problem 1

It may be concluded that although octave band values of m have been determined, they are not all reliable enough for the purposes of prediction of a. A value for *m*, based on A-weighted *a*, however, has been calculated, and shown to be reliable.

It is therefore proposed that, for the purposes of this guide, A-weighted sound absorption coefficient of a ground covering material, *a(A)*, may be estimated from a measurement of $k_2(A)$, using the following expression:

$a(A) = -0.6\ k_2(A)$

The high value of R^2 for A-weighted values indicates that there is reasonably strong evidence that the data fits this best fit model, and that the gradient *m*, for A-weighted *a*, having a value of –0.6 is reliable.

4 REQUIREMENT FOR ADDITIONAL MICROPHONE POSITIONS FOR DIRECTIONAL NOISE SOURCES

4.1 Background

A potential problem was raised in the survey regarding the requirement to increase the number of microphone positions for directional noise sources. ISO 3744, for instance, requires that the number of microphone positions on a hemispherical surface be doubled from 10 to 20 if the range of the sound pressure levels (difference between the maximum and minimum) from the 10 positions is greater than 10 dB (i.e. the number of positions). Cases were cited where the difference is only just above 10 dB for a hemisphere and it is suggested that the value of the result obtained by doubling the number of positions is not significantly different and does not have a significantly reduced measurement uncertainty. It is not clear where this requirement originated but what is evident is that it needs to be validated to ensure that undue restrictions and increased measurement effort together with the associated financial penalty are not being imposed.

In order to examine the need to double the number of microphone positions when using a hemispherical measurement surface, an experimental programme of sound power determinations has been carried out at NPL. The noise sources, acoustic environments and instrumentation used are described below.

4.2 Experimental results

Two measurement sites at NPL were used: one outdoors that consists of a large flat concrete covered surface, approximately 50 m square with no sound-reflecting objects, and a hemi-anechoic room, for indoor measurements.

The sound power levels of 19 noise sources were determined and are listed as follows: Diesel powered electrical power generator; Reference sound source (RSS), Floor buffing machine, Hand held jig saw, Hair drier, Electric garden shredder, Electric Hedge trimmer, Electric razor, Handheld vacuum cleaner, Personal computer base unit, Dot matrix printer, Mainframe computer cabinet, Box 1, Box 2, Box 3, Box 4, Box 5, Box 6, and Box 7.

Of these, the generator, shredder and hedge trimmer were used on the outdoor site. Of the remaining 16 sources, nine were actual machines and seven (described as boxes) were specially constructed. These seven sources used the RSS as a noise source fixed in the bottom of a variety of boxes formed using two individual boxes. The two boxes were of 40 cm square section, 29 cm and 46 cm long made using 2 cm thick MDF material. The shape, size and orientation of each box was chosen to increase the range of A-weighted Directivity Index. The configuration of each box source is described as follows: Box 1 smaller box top face open, Box 2 larger box both ends open, Box 3 both boxes joined both ends open, Box 4 larger box top open, Box 5 both boxes joined top open, Box 6 larger box one end open, Box 7 both boxes joined one end open.

Measurements were performed in accordance with ISO 3744 using a hemispherical surface. For the outdoor measurements and for the computer cabinet, all measurements were carried out with a radius that was twice the characteristic distance as defined in ISO 3744. All other measurements were carried out using a 1.5 m diameter hemispherical surface in the NPL hemi-anechoic room. Sound power level determinations carried out in the NPL hemi-anechoic room used the 20-microphone array of ISO 3744 on a hemispherical enveloping surface. Sound power level determination was repeated three times in order to assess measurement repeatability. In addition to the sound power determinations, the difference between the maximum and minimum sound pressure levels using the 20-microphone array and for the 10-key microphone positions were observed and the Directivity Index of each noise source was calculated from the 20-microphone array.

The results of the series of measurements are summarised in Table 3, below, where “Range (1 to 10)” is the difference between the maximum and minimum sound pressure level (SPL), when using the 10-key positions specified in ISO 3744, and “Range (1 to 20)” is the difference between the maximum and minimum SPL when using all 20 microphone positions (also specified in Table B.1 of ISO 3744. Also displayed is the difference between the sound power levels determined using the 20-position microphone array and the 10-key microphone array, here referred to as “Diff (20–10)”.

Table 3 Range of sound pressure levels and sound power level differences

Machine	'Range (1 to 10)'	'Range (1 to 20)'	'Diff (20 –10)'
Generator	1.8	5.3	0.4
RSS	2.3	2.5	-0.1
Floor buffing machine	3.5	4.5	0.2
Jig-saw	4.0	4.5	0.1
Hair drier	4.5	5.3	0.1
Garden shredder	5.0	5.7	0.1
Hedge trimmer	5.3	5.3	0.2
Box 1	5.6	5.9	0.0
Electric razor	5.8	6.4	0.1
Hand-held vacuum cleaner	5.9	9.3	0.3
PC base unit	7.1	8.7	0.0
Dot matrix printer	7.7	9.5	0.6
Box 2	9.7	9.7	0.0
Box 3	11.6	12.0	0.0
Box 4	12.2	12.3	0.0
Mainframe computer cabinet	14.3	14.6	-0.1
Box 5	16.3	16.3	0.0
Box 6	17.6	19.1	-0.3
Box 7	19.2	19.2	-0.4

It can be seen from Table 3 that when using the ten key microphone positions, 13 of the noise sources had a difference between maximum and minimum sound pressure levels that was less than 10 dB (ranging from 0.8 dB to 9.7 dB). For these noise sources, ISO 3744 does not require a doubling of microphone positions. For 6 of the noise sources, the difference was greater than 10 dB ranging from 11.6 dB to 19.2 dB. For these noise sources compliance with ISO 3744 requires that the number of measurement positions is increased from 10 to 20. In order to assess the effect of increasing the number of microphones, the sound power levels were re-determined including the additional microphone positions, making a total of 20 in total, for all noise sources. It can be seen that the difference between maximum and minimum sound pressure levels using 20 microphone positions was less than 20 dB (ranging from 2.5 dB to 19.2 dB). So, sound power determinations now all comply with the requirements of ISO 3744. It can be seen from Table 3 that the differences between sound power levels determined using 10 microphones with those using 20 microphones is relatively small for all noise sources, ranging from -0.4 dB to zero for noise sources that require 20 microphone positions and an even larger range of 0.6 dB to -0.1 dB for noise sources that only require 10 microphone positions. The average difference for the 13 sources requiring only 10 microphones is 0.15 dB and for the 6 noise sources requiring an increase to 20 microphone positions is -0.13 dB. Although there is a change of polarity, neither of these differences is significant. It is concluded, therefore, that the ISO 3744 requirement to double the number of microphone positions does not result in a significant improvement in sound power level determination.

4.3 Conclusion and proposed solution for problem 2

It is concluded that the ISO 3744 requirement to double the number of microphone positions does not result in a significant improvement in sound power level determination. However it is acknowledged that the Directivity Index of the vast majority of machines is not sufficient to require the implementation of the ISO 3744 requirement to double the number of microphones and so it may be that this is a problem that rarely occurs.

Despite the similarity between the sound power levels determined using 10 microphones with those determined using 20 microphones there still remains the problem of the assessment of the associated measurement uncertainty. The seven standards in the ISO 3740 series are currently all being revised by ISO in what is described as a short-term revision. In the long term it is the intention of ISO to provide a new series of international standards to replace the current ISO 3740 series. The new series will cover the same variety of test environments, but comprise only four standards instead of the present seven. Two will require the use of qualified reverberant and free-field rooms. The others will be for use in-situ, intended to give working methods for everyday use in declaring and verifying sound power levels. The latter two will give information on how to tailor the reproducibility of the results to the amount of measurement effort (i.e. the number of measurement positions). This will mean that the current ISO 3744 requirement to double the number of microphone positions will become redundant. It is important that this long-term revision progresses with some urgency especially regarding a “floating uncertainty” working standard.

5 MAIN SUMMARY AND CONCLUSIONS

Two specific practical measurement problems have been assessed and measurement solutions for each have been proposed. In the case of estimation of ground plane sound absorption, an expression for estimation of A-weighted sound absorption from a measured value of k_2 has been proposed. For the issue of doubling of microphone positions, it has been shown that, in practice, this does not result in a significant improvement in sound power determination. However, this issue will be addressed by the long-term revision of ISO 3740 series of sound power standards.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the National Measurement System Programmes Unit of the UK Department for Innovation, Universities and Skills".

7 REFERENCES

1. Council Directive 2000/14/EC of 8 May 2000 on the approximation of the laws of the Member States relating to noise emission in the environment by equipment for use outdoors. Official Journal of the European Communities N°L162, Volume 43
2. D. Simmons and R Payne, “Problems in the industrial application of procedures for measurement of machinery noise emission", National Physical Laboratory Report DQL-AC 017; 2007
3. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 3744:1994, Acoustics - Determination of sound power levels of noise sources using sound pressure - Engineering method in an essentially free field over a reflecting plane.
4. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 354:2003, Acoustics - Measurement of sound absorption in a reverberation room.