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ASSESSMENT OF REPRODUCIBILITY UNCERTAINTIES FOR USE IN AN INTERNATIONAL STANDARD

Richard Payne **National Physical Laboratory, Teddington, UK**

1. INTRODUCTION

In recent years a large number of European Directives have been published, containing requirements for determining the sound power levels of machines. The forerunner was Directive 79/113/EEC[1], which included a general method of determining the sound power level of construction plant and equipment. This was implemented by Directive 84/532/EEC[2] and several subsequent related directives, which imposed sound power limits on a wide range of machines used on construction sites. Separately from these, Directive 86/594/EEC[3] made provision for labelling household appliances with their A-weighted sound power level on a voluntary basis, and this was followed by Directive 92/75/EEC[4] which made the noise labelling mandatory. Directive 89/392/EEC[5] (the Machinery Directive) covers the safety of a wide range of machinery types, and it requires manufacturers to give information on the sound power level if the A-weighted sound pressure level at the work station of a machine exceeds 85 dB. In addition to all these, there is another new directive which addresses the noise emitted by machinery used outdoors[6]. It concerns some sixty machine types and will include some new noise limits and requires that all machines are labelled with a guaranteed A-weighted sound power level. The guaranteed level is defined as a sound power level that includes uncertainties due to production and measurement procedures.

The measurement procedures called up in the proposed new Directive are taken from the series of international standards that are concerned with the determination of sound power. In particular those that require measurements of sound pressure level around the machinery over a hypothetical surface surrounding the source. These standards are considered by many users as being too complicated and time consuming to use. The usefulness of a sound power measurement standard depends on the speed and accuracy with which results are obtained. The shape and size of the hypothetical surface and the way in which the sound field is sampled affects the accuracy and speed of the measurement. Generally, the more samples that are taken, the higher the grade of accuracy and the longer the measurement takes.

In a recent Report[7] it was proposed that a new series of sound power standards should be produced, ultimately to replace all the existing ones. The measurement method would be to relate the number of measurements of sound pressure level to the measurement uncertainty associated with the resultant sound power determination, allowing the number to be increased in order to achieve improved accuracy if required. The report provided data on measurement uncertainty based on <u>repeatability</u> standard deviations. However, the measurement uncertainty required for inclusion in these standards is revealed by the <u>reproducibility</u> of results when a given method is applied by different organisations, by different operators, using different equipment.

This paper describes a programme of inter-laboratory measurements designed to obtain estimates of the standard deviation of reproducibility. These values of reproducibility uncertainty are compared with the values obtained by Reference 7, based on repeatability data, with a view to providing uncertainty values suitable for inclusion in the proposed new series of standards.

2. EXPERIMENTAL PROGRAMME

2.1 Reproducibility testing

The objective of the project was to acquire data on the uncertainties in the determination of sound power levels, expressed in terms of standard deviations of reproducibility. To obtain reproducibility uncertainties it is necessary for the noise emission levels of a particular noise source to be measured,

by the same method,
by different laboratories (in different locations),
by different personnel,
using different measurement apparatus,
at different times.

The test programme was drawn up, following the guidance of ISO 5725-2[8] which deals with experiments to determine reproducibility of measurements, to provide the best balance between the number of repeated measurements (**three**) and number of laboratories (**four**) performing the tests with statistical confidence and measurement effort.

2.2 Noise source considerations

Thirty-two noise sources (actual machines and specially constructed devices) were used in reference 7 with a range of Directivity Index from 0.8 dB to 8 dB and an estimate of measurement uncertainty was associated with each. The purpose of the current series of measurements is to assess how these estimates compare with reproducibility values. However, because of the logistical difficulties involved with using such a large number of noise sources, it was decided to limit the number of noise sources to just three: a reference sound source with an A-weighted Directivity Index of 0.8 dB and a specially constructed source with Directivity Index of 6.9 dB, to examine the extremes of the Directivity Index range and a diesel-engined electrical power generator (Directivity Index of 1.3 dB) to include data for a real machine.

2.3 Measurement methods

The Standard generally used as the basis for all sound power determinations is ISO 3744:1994[9], and the proposed EC Directive concerning the noise from equipment used outdoors generally requires the use of a hemispherical enveloping surface. So, it was decided to concentrate the measurement effort on sound power levels determined according to ISO 3744 using a hemispherical surface. For the purposes of this paper only A-weighted sound pressure levels are considered. The number of measurement positions used for each hemispherical measurement surface was twenty and each sound power level determination was repeated three times in order to assess measurement repeatability. Sound power levels determined using this 20-microphone array were used as reference levels to which data from other arrays and configurations (see sub-Section 2.4) are compared and furthermore, are assumed to be true values. Measurements were made on all three noise sources by each Laboratory over a two week period with an overall measurement period of about two months. Measurements were also carried out by one of the Laboratories on all noise sources at each laboratories test site as soon as practicable after each had completed the required measurements. These measurements were performed to check on the long term stability of the noise sources and also permitted an estimation of uncertainties associated with the differing measurement sites. These uncertainties are a half way house between repeatability- and reproducibility-conditions and should provide information as to the contribution of variations resulting from differing sites and differing measurement laboratories to the final reproducibility variance. In this paper these uncertainties are termed "intra-site" repeatability.

2.4 Spatial sampling

From the sound pressure level measurements made using the twenty microphone positions, values of sound power level may be calculated for several microphone position sub-sets. Seven microphone position sub-sets were used in Reference 7 and may be briefly described as follows:

Twenty positions — The key and additional positions of ISO 3744
One array

Ten positions — The 10-key positions or the 10-additional positions of ISO 3744
Two arrays

Six positions — Six positions on each of the three complete hemispherical arcs
Three arrays, described as 6 (opp)

Four positions — All four positions at different heights
Six arrays

Three positions — All three positions at different heights
Six arrays, described as 3 (120)

Three positions — Three positions, two on one half-hemispherical arc and one on the opposite half-hemispherical arc
Six arrays, described as 3 (opp)

One position — Each of the twenty ISO 3744 positions
Twenty arrays

3. EXPERIMENTAL RESULTS

3.1 repeatability uncertainties

The average of the four Laboratories A-weighted repeatability uncertainties are shown in Table 1 for each sound source.

Table 1 Standard deviations of A-weighted repeatability uncertainties (expressed in dB).

	Number of measurement positions						
Machine	20	10	6 (opp)	4	3 (opp)	3 (120)	1
RSS	0.04	0.04	0.05	0.07	0.07	0.07	0.11
Generator	0.04	0.06	0.07	0.06	0.10	0.08	0.14
Box	0.06	0.08	0.10	0.13	0.15	0.14	0.16

An examination of these average values shows that repeatability uncertainties are generally less than 0.2 dB and for the reference 20-microphone array are of the order 0.05 dB. Values for all three noise sources tend to increase as the number of microphone positions is reduced. However, it can be seen that this increase is only of the order 0.1 dB when the number of microphones is reduced from twenty to one.

3.2 Intra-site uncertainties.

There is a variation in sound power determination between sites, with a range of 0.59 dB, 0.68 dB and 0.94 dB for the reference sound source, generator and box source respectively. If it is assumed that the variations in sound power level for the reference sound source are the result of differing values of K_{2A} and data is corrected relative to the site 1 value, the range of the variation in sound power determinations for the generator is reduced to 0.31 dB and for the box source to 0.35 dB. Standard deviations of intra-site uncertainties are shown in Table 2, with data in shaded areas calculated after applying K_{2A} corrections.

Table 2 Standard deviations of A-weighted intra-site repeatability uncertainty (expressed in dB)

	number of microphones in the array						
source	20	10	6 (opp)	4	3 (opp)	3 (120)	1
RSS	0.29	0.29	0.35	0.42	0.33	0.36	0.73
Generator	0.35	0.38	0.42	0.39	0.47	0.42	1.16
Generator	0.15	0.21	0.25	0.26	0.33	0.43	1.12
Box source	0.42	0.52	2.41	1.81	2.42	1.61	7.30
Box source	0.14	0.35	2.37	1.77	2.37	1.61	7.30

For the 20-microphone array, standard deviations of intra-site repeatability for generator and the box source are reduced to 0.15 dB and 0.14 dB respectively when corrected to account for differences in measured values of K_{2A}. It is clear that, for the 20-microphone array, although the four sites used were all in the category described in ISO 3744 that may be considered as having values of K_{2A} that may be neglected, an adjustment for the actual values of K_{2A} reduces the measurement uncertainty.

It is interesting to compare these values of intra-site repeatability with the repeatability data shown in Table 1. This comparison indicates that, for the 20- and 10-position arrays, there is a residual contribution to the measurement uncertainty of approximately 0.1 dB that can not be attributed to variations in the value of K_{2A}. This residual is small and similar to the standard deviations of repeatability and so is unlikely to be statistically significant.

The standard deviations of intra-site repeatability show a marked increase as the number of measurement positions is reduced to one. The magnitude of this increase in value is dependent on the noise source, being smallest for the reference sound source and largest for the box source. In fact, the increase is dependent on the directivity index of the source which is largest for the box source (6.9 dB) and smallest for the reference sound source (0.8 dB).

It is clear that once the number of microphones is reduced below ten, the major contribution to intra-site repeatability is from variations in sound power determination resulting from inadequate spatial sampling with minimal contribution from repeatability uncertainties and from variations resulting from using different measurement sites.

3.3 Reproducibility uncertainties

There is a variation in sound power determination between sites, with a range of 0.81 dB, 1.00 dB and 0.53 dB for the reference sound source, generator and box source respectively. If it is assumed that the variations in sound power level for the reference sound source are the result of differing values of K_{2A} and data is corrected relative to the Laboratory 1 value, the range of the variation in sound power determinations for the generator is reduced to 0.81 dB and for the box source to 0.28 dB. Standard deviations of reproducibility uncertainties are shown in Table 3, with data in shaded areas calculated after applying K_{2A} corrections.

Table 3 Standard deviations of A-weighted reproducibility uncertainty (expressed in dB)

	number of microphones in the array						
source	20	10	6 (opp)	4	3 (opp)	3 (120)	1
RSS	0.34	0.34	0.37	0.40	0.38	0.37	0.64
Generator	0.44	0.48	0.44	0.54	0.49	0.46	1.12
Generator	0.15	0.21	0.25	0.26	0.33	0.43	1.12
Box source	0.26	0.42	2.42	1.91	2.64	1.69	7.49
Box source	0.16	0.37	2.42	1.91	2.63	1.69	7.48

It can be seen from a comparison of these data with those in Table 2 that the reproducibility standard deviations are very similar to those for intra-site repeatability. The conclusion that may be drawn from this similarity between intra-site and repeatability data is, that when several Laboratories carry out a sound power determination using a specified procedure, the measurement uncertainties involved are not statistically significantly different from those associated with measurements carried out by a single Laboratory so the major contributor to measurement uncertainty are variations resulting from differing site conditions and spatial sampling.

These standard deviations of reproducibility are similar to values based on intra-site repeatability from Reference 7. The average difference, relative to Reference 7, across the seven arrays considered was - 0.1 dB, 0.17 dB and 0.39 dB for the RSS, generator and box source respectively. So, values from Reference 7 are generally larger. It is concluded therefore that for A-weighted sound power levels, standard deviations of reproducibility based on data from Reference 7 may over-estimate actual values and so, considering the application of measurement uncertainties in providing a guaranteed sound power level, will be suitable for inclusion in international sound power standards.

Although the value of reproducibility standard deviations is dependent on the number of microphones in the array, it can be seen from the data for the two 3-microphone arrays for the highly directional box source, that it is also dependent on the distribution of the microphones. The data from reference 7 obtained for machine noise sources has, therefore, been analysed using only arrays that have, as far as practically possible, microphones positions evenly distributed on the measurement surface, as these provide the smaller reproducibility uncertainties. Six arrays are considered comprising 1, 3, 4, 6, 7 and 10 microphone positions.

The standard deviations of reproducibility for all six configurations are shown in Figure 1, plotted as a function of Directivity Index. A least squares linear best fit line has been calculated for each data set. As an indication as to the goodness of fit of this line, the standard deviation of the differences of each data point from this line has been calculated and the line shown in Figure 1 is the best fit line plus two standard deviations. For the purpose of providing reproducibility data suitable for inclusion in an international standard it is this plus two standard deviation line that is of interest as statistically 95% of data points would be expected to lie beneath it. These lines can, therefore, be used with a high level of statistical confidence to assess the reproducibility uncertainty associated with a particular measurement arrangement.

It can be seen from Figure 1 that there is an increase in reproducibility uncertainty as the number of microphones in the array is reduced and as the Directivity Index is increased. It is clear that the 10-

microphone array provides the lowest values of reproducibility uncertainty and, for this array, values are essentially independent of Directivity Index. As the number of microphones in the array is progressively decreased, the value of the reproducibility uncertainty increases in the order of the number of microphones in the array, with the single microphone data resulting in the largest reproducibility uncertainty.

It can be seen that the best fit lines overlap for low values of Directivity Index. While this may be a little confusing, the values of reproducibility associated with all arrays for these low values of Directivity Index are small and so a decision regarding the use of an array with a larger number of microphones to improve the level of uncertainty will not need to be made.

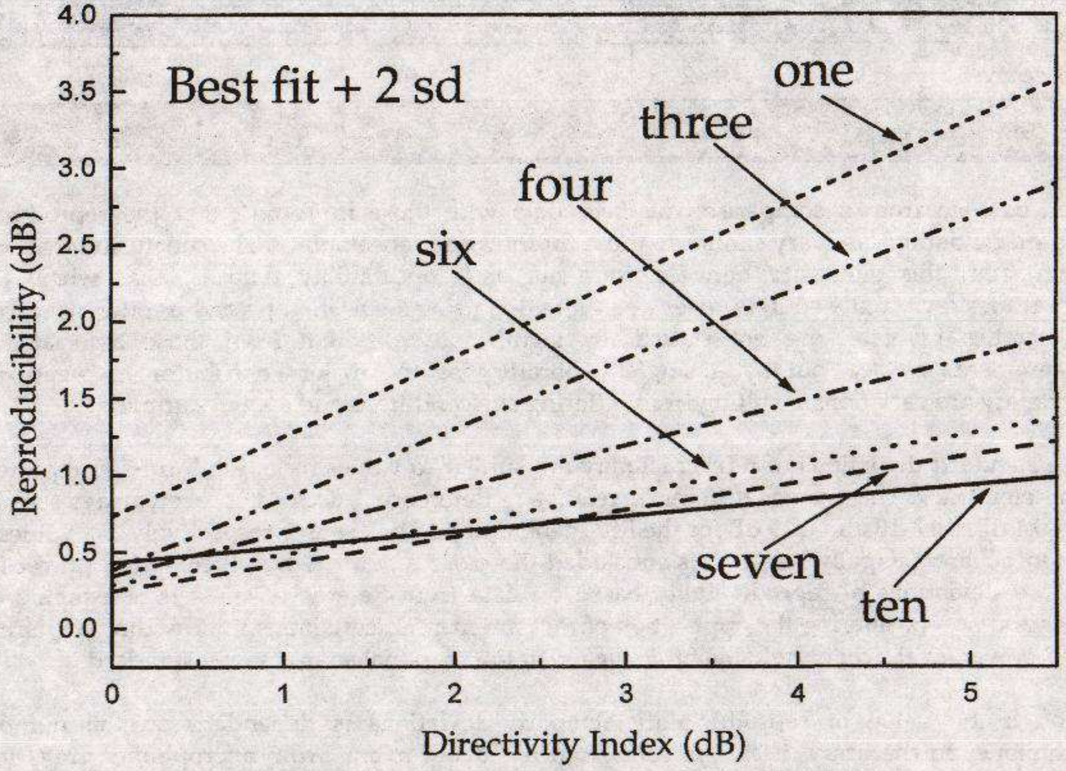

Figure 1 *Variation of reproducibility uncertainty as a function of Directivity Index for the plus two standard deviation lines with the number of microphones in the array as a parameter.*

It is concluded that for the purposes of inclusion in an international standard that is concerned with the determination of sound power level and which will be used with actual machines as a noise source that reproducibility data should be based on the results shown in Figure 1.

4. REPRODUCIBILITY FOR AN INTERNATIONAL STANDARD

It is interesting to examine more closely the distribution of Directivity Index across the machines used. To achieve this, a histogram shown as Figure 2, has been constructed by counting the number of machines with a Directivity Index within 0.5 dB bands from 0.5 dB - 1 dB to 4.5 dB - 5 dB across the range.

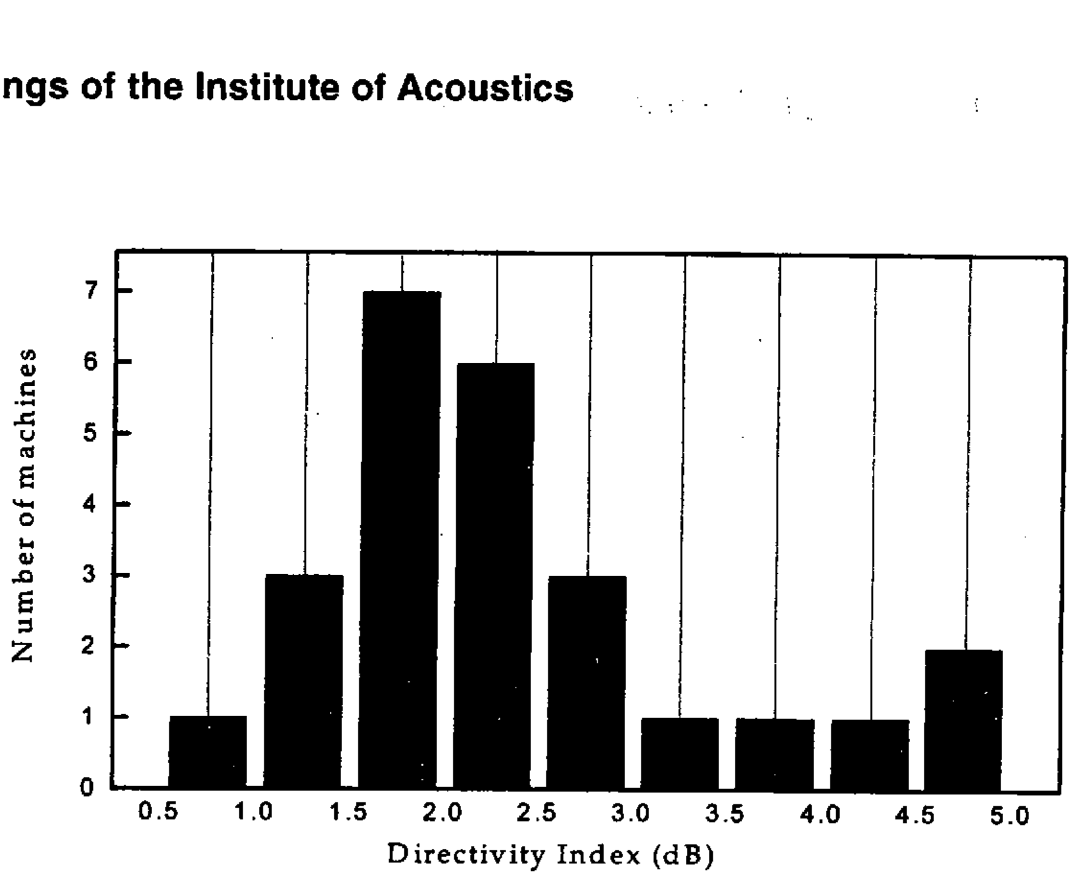

Figure 2 *Histogram of machine Directivity Index*

It can be seen that the majority of machines have a Directivity Index between 1 dB and 3 dB, in fact 19 machines out of a total of 25 machines considered. From these data it seems that if a machine has a particularly low value of Directivity Index (this is probably confined to devices such as a reference sound source) then reproducibility values corresponding to a Directivity Index of 1 dB may be assumed. If on visual inspection the machine is not obviously highly directional (the case for the vast majority of machines) then a medium value of reproducibility corresponding to a Directivity Index of 3 dB may be assumed. If the machine has some obvious directionality components then high reproducibility values corresponding to a Directivity Index of 5 dB may be assumed. For inclusion in an international standard reproducibility data may be most usefully be displayed in tabular form as a function of the number of microphones in an array with Directivity Index as a parameter. Values of reproducibility corresponding to these broad categories are listed in Table 4.

Table 4 Proposed values of reproducibility (dB) for an international standard

Number of microphones	Directivity Index (dB)		
	1	3	5
10	0.4	0.7	1.0
7	0.4	0.8	1.1
6	0.5	0.9	1.3
4	0.6	1.2	1.8
3	0.9	1.8	2.7
1	1.3	2.3	3.3

5. REFERENCES

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3. Council Directive 86/594/EEC of 1 December 1986 on airborne noise emitted by household appliances. Official Journal of the European Communities, N° L 344, 6.12.86, page 24.

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5. Council Directive 89/392/EEC of 14 June 1989 on the approximation of the laws of the Member States relating to machinery. Official Journal of the European Communities, N° L 183, 29.6.89, page 9.

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