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MEASUREMENT UNCERTAINTIES IN THE DETERMINATION OF THE SOUND POWER LEVEL OF MACHINES

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1. INTRODUCTION

The EC Machinery Directive 89/392/EEC requires manufacturers to declare certain basic noise information about the noise emission of their products. Underpinning the Directive is a range of ISO/CEN standards specifying agreed methods of measuring sound power level and emission sound pressure level. Most of these standards have been subject to extensive revision over the past few years, and some are completely new. The standards make it clear that measurements are subject to an uncertainty which is reflected in the reproducibility of results when the standard is applied by different organisations, by different personnel, using different equipment. This paper describes a programme of measurements undertaken by four laboratories on each of four different machines to test the validity of the estimates of reproducibility given in the sound power standards ISO 3744, ISO 3746 and ISO 9614-1.

This paper examines: the intra-laboratory repeatability of the measurements (the ability of each laboratory to produce repeatable results); the intra-standard repeatability (the repeatability of measurements made by each laboratory to each standard over a range of different conditions within the bounds permitted by the standards); and the reproducibility of the measurements (the overall dispersion of measurements made by the four laboratories). The paper also analyses differences between results obtained using hemispherical and parallelepiped measurement surfaces of different sizes in different acoustical environments, and finally inter-compares results obtained using the three standards. A fuller report is available [1].

2. EXPERIMENTAL PROGRAMME

Tests were conducted on four machines: an electric drill, a diesel-engined

electrical power generator, a two-stroke petrol-engined lawnmower and a diesel-engined air compressor. Approximate overall sizes are shown in Table 1. Measurements were made using the hemispherical surfaces listed in Table 2 where the number of measurement positions was typically 10 for ISO 3744 and 4 for ISO 3746, and on parallelepiped surfaces with measurement distances of 0.25 m, 1 m, 1.5 m and 2 m, involving between 5 and 61 measurement positions depending on machine and standard. Measurements according to ISO 9614-1 were made on one parallelepiped surface using between 10 and 50 probe positions depending on machine. One acoustical environment, with an environmental correction factor, K_2, less than 2 dB, was used for ISO 3744; two environments were used for ISO 3746, with K_2-factors of approximately 2.5 dB and 5 dB, and two environments for ISO 9614-1 with K_2-factors of less than 2 dB and approximately 5 dB. In all cases each laboratory conducted three independent sound power determinations.

Table 1. Approximate machine dimensions

Machine	Dimensions (m)		
	Width	Length	Height
drill	0.3	0.05	0.3
mower	0.5	0.7	0.7
generator	0.5	0.7	0.4
compressor	1.2	1.6	1.2

Table 2. Measurement radii, r

Machine	r_1 (m)	r_2 (m)	r_3 (m)
drill	1.0	1.25	1.5
mower	2.0	4.0	6.0
generator	2.0	4.0	6.0
compressor	4.0	6.0	8.0

3. INTRA-LABORATORY REPEATABILITY

Standard deviations were calculated from the three repeat measurements carried out by each laboratory. These show the ability of one laboratory to carry out three nominally identical measurements to a specified standard, using a specified measurement surface and distance, in a specified environment. These standard deviations represent what we shall term the "intra-laboratory repeatability" of the measurements.

The intra-laboratory repeatability standard deviations exhibited a slight dependence on frequency, generally increasing at lower and higher frequencies. However, the standard deviations were generally less than 0.5 dB and the majority were less than 0.3 dB. Standard deviations of the

A-weighted measurements had an overall mean of 0.18 dB, distributed such that about half the means were less than this value. It is interesting at this point to consider the magnitude of the difference, at each laboratory, between sound power levels determined using hemispherical surfaces and those obtained using parallelepiped surfaces. Differences, averaged across all measurement distances, varied between machine and laboratory with an average of just over 0.5 dB.

For measurements to ISO 3746, values of standard deviation averaged across distance were similar for both environments and for all four machines with an overall average of 0.15 dB. This value is comparable with the value of 0.18 dB for ISO 3744. The difference between sound power evaluations using hemispherical measurement surfaces and those using parallelepiped surfaces varied between machine and laboratory and was just over 0.6 dB, averaged across both environments (cf. 0.5 dB for ISO 3744).

For ISO 9614-1, the intra-laboratory repeatability standard deviations were essentially independent of frequency, but there was a slight increase at low frequencies. However, the standard deviations were generally less than 0.5 dB, very similar to the ISO 3744 data. Considering only standard deviations of A-weighted levels, the overall mean, averaged across both environments, was 0.22 dB distributed such that about half were less than this mean value.

4. INTRA-STANDARD REPEATABILITY AND REPRODUCIBILITY

The results of the raw repeated measurements could be combined, for each standard and each laboratory, to yield overall means and standard deviations, taken over all measurement surfaces, distances and environments. These standard deviations show the robustness of the standard and represent what we shall term the "intra-standard repeatability" of the measurements: they are an indication of the variability of sound power determinations that result from the numerous measurement configurations that are permitted and not just a reflection of the precision of the laboratory carrying out the measurements (as is the case for the intra-laboratory repeatability standard deviations). The raw results could also be combined to give grand mean levels and standard deviations, taken over all laboratories. In this case, the standard deviations show the extent to which measurements on a given machine, carried out to a given standard, can be reproduced in different laboratories. Thus, they represent the reproducibility of the measurements.

For ISO 3744, the intra-standard standard deviations were generally around 1 dB in each one-third octave frequency band, with lower values of the order 0.5 dB and values approaching 2 dB not uncommon. This represents a considerable increase when compared with the data discussed in Section 3. This increase is the result of the range of measurement

distances and surfaces involved in the averaging process. The average of the standard deviations of A-weighted values is 0.8 dB, which is a considerable increase over the corresponding value of 0.18 dB for the data in Section 3.

Reproducibility standard deviations for each machine obtained from sound power levels averaged across all laboratories, all measurement distances and both surfaces were generally around 2 dB. However, the standard deviations increased with frequency above about 4 kHz to approximately 4 dB at 10 kHz. The average value for A-weighted levels was 1.1 dB. To permit a clearer view of these general trends and to facilitate a comparison with the estimates of reproducibility standard deviation published in ISO 3744, the data are displayed in Figure 1. The shaded area represents the ISO 3744 estimates; all data points are expected to lie in this area. *It can be seen that at frequencies below about 400 Hz measured values are below the ISO estimates, between 400 Hz and 4 kHz it is machine dependent, but data are generally greater than the values in ISO 3744, and at higher frequencies the ISO limits are clearly too low.*

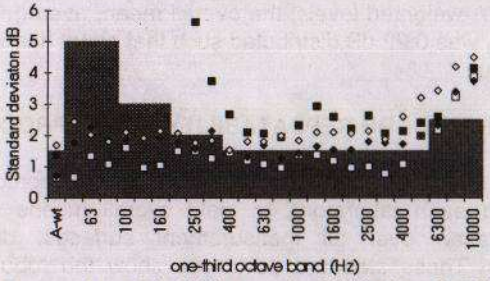

Figure 1 Measured reproducibility standard deviations for ISO 3744.
Data key - ■...Drill, □...Generator, ♦... Mower, ◇...compressor

The large reproducibility standard deviations may result from the relatively large range of K-factors that are deemed acceptable in ISO 3744. The only requirement is that measurements are made in an acoustical environment with a K_2-factor less than or equal to 2 dB. No corrections to measured data to take account of the K_2-factor are required. Values of K-factor for one-third octave bands and A-weighting were determined by the laboratories involved in the measurement programme and showed values ranging from 0.2 dB to 1.6 dB. Such large differences will result in variations in the determination of sound power level and an increase in measurement uncertainties. *It is recommended, therefore, that corrections to allow for variations in acoustical environment should be required by ISO 3744.*

For ISO 3746, the intra-standard repeatability standard deviations had an average value of 0.98 dB compared to 0.15 dB in Section 3.

Reproducibility standard deviations for each machine obtained by combining sound power levels across all laboratories, all measurement distances and surfaces and both environments had an average value of 1.3 dB. The estimated standard deviation of reproducibility published in ISO 3746 for noise sources of the type used in this study is 4 dB. *Thus the measured values are well below the ISO estimate.* The text in the standard makes it clear that standard deviations are dependent on machine type and environment and so it may turn out that if very large machines with time variable and/or impulsive noise attributes are considered the reproducibility standard deviations are larger. However, the results obtained from measurements according to this standard are impressive when compared to those obtained using ISO 3744.

For ISO 9614-1 the intra-standard standard deviations in each one-third octave frequency band were generally around 1 dB with lower values of the order 0.5 dB and higher values approximately 2 dB (similar to the data for ISO 3744). This represents a considerable increase when compared with the data discussed in Section 3 where values were generally around 0.5 dB. The standard deviations for A-weighted levels had an average value of 0.44 dB compared to 0.22 dB in Section 3. Reproducibility standard deviations for each machine were again around 1 dB, although they increased slightly at low frequencies. The average value for A-weighted levels was 0.6 dB. To permit a clearer view of these general trends and to facilitate a comparison with the estimates of reproducibility published in ISO 9614-1 the measured data are displayed in Figure 2.

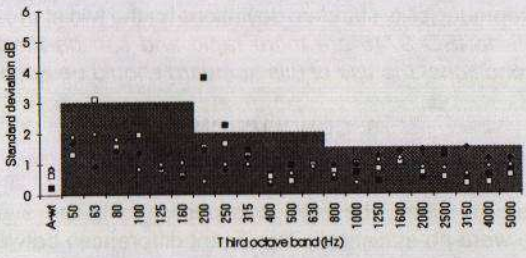

Figure 2 Measured reproducibility standard deviations for ISO 9614 compared with the ISO estimates (shaded mask). Data key as Figure 1.

It can be seen that with only two exceptions the measured data is within the ISO estimates. It must be borne in mind that these reproducibility data are calculated from only one measurement surface and distance. However, measurements carried out according to ISO 3744 indicate that the magnitudes of reproducibility standard deviations do not necessarily increase with an increase in the number of measurement configurations.

5. COMPARISON OF STANDARDS

Differences between A-weighted sound power levels determined using ISO 3744 and those determined according to ISO 9614-1 were calculated from ISO 3744 data using parallelepiped surfaces, averaging over all measurement distances and ISO 9614-1 data from the environment with a K_2-factor less than 2 dB. Thus both sets of data relate to measurements made using a parallelepiped surface in an environment of K_2-factor less than 2 dB. The differences between sound power levels (ISO 3744 data minus ISO 9614 data) were machine and laboratory dependent and ranged from -0.34 dB to 3.34 dB, with an average of 1.2 dB. However, only half the differences were statistically significant at the 95% confidence level so *there is no clear indication of a systematic difference between the standards.* Differences for one-third octave band levels showed a wider scatter of data, with the ISO 3744 data generally providing the larger sound powers.

The difference between ISO 3744 and ISO 3746 calculated from the average A-weighted sound power levels were, -0.96 dB, -0.12 dB, -0.03 dB and -0.46 dB for the drill, mower, generator and compressor respectively. These differences are small compared with the reproducibility standard deviations discussed in this report. *We conclude that ISO 3746 provides sound power levels that agree with those from ISO 3744,* despite differences in acoustic environment and the use of fewer microphone positions than ISO 3744. However, if the data are split into individual measurement configurations and laboratories the differences range up to ±3 dB. Nevertheless, the differences are still consistent with the experimental reproducibility standard deviations for the two standards. *Since measurements to ISO 3746 are more rapid and can be made in semi-reverberant conditions, the use of this standard should be encouraged.*

6. CONCLUSIONS

With the exception of ISO 3744, the experimental reproducibility standard deviations were all within the estimates published in the standards. In general, there were no statistically-significant differences between results obtained using different measurement surfaces and distances. Inter-comparison of the three sound power standards, showed agreement fully consistent with the experimental reproducibilities of the standards.

7. REFERENCES

1. Payne R C and Simmons D J, 1996. Measurement uncertainties in the determination of the sound power level and emission sound pressure level of machines. National Physical Laboratory Report CIRA(EXT)007.