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REPORT

Assessment of Sound Power Levels and Associated Measurement Uncertainties of Construction Equipment

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ABSTRACT

In recent years a large number of European Directives have been published containing requirements for determining the sound power levels of machines. In particular, Directive 2000/14/EC concerns machines for use outdoors and covers fifty-seven machine types and requires that all are labeled with their sound power level and includes new noise limits for twenty-two machine types. The sound power level on the label includes the uncertainties due to production variation and measurement procedures. Thus, it is of prime importance that the sound power level is accurately determined and the level of measurement uncertainty is carefully specified. Included in this limit category are several machines used on construction sites, for example dozers, dumpers and excavator-loaders.

The Directive is a global approach directive, which contains some detailed test codes but still refers to ISO B- and C-type harmonized international standards that may be used by machinery manufacturers in order to demonstrate compliance with its requirements. For construction plant equipment the Type-B standard is ISO 3744 and the Type-C standards are ISO 6393, ISO 6395 and ISO 4872.

The measurement procedures described in these standards determine sound power levels in approximately hemi-anechoic conditions from measurements of sound pressure level around the machine by carrying out a series of measurements over a hypothetical surface surrounding the source. The surface shape required by Directive 2000/14/EC for construction plant is a hemisphere centred on the machine and terminating on a reflecting plane. The distribution and number of measurement positions on this enveloping hemispherical surface vary between the various ISO standards. However, it is assumed that absolute sound power levels and associated measurement uncertainties are the same for all measurement configurations. Because of the requirement on the manufacturer to affix a label to each machine that displays a guaranteed sound power level that may have to withstand some form of verification procedure, it is important that the sound power level and measurement uncertainty is not affected by the choice of measurement configuration.

This report describes an experimental programme, using procedures based on those described in the ISO standards listed above, designed to assess the effect on sound power determination and associated measurement uncertainties, of the number of measurement positions and their distribution on the hemispherical enveloping surface.

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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. Directive 89/392/EEC[3] (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 these, there is another new Directive relating to the noise emission in the environment by equipment for use outdoors, Directive 2000/14/EC[4]. This Directive will supersede some of the earlier directives, it concerns fifty-seven machine types and will require that all are labelled with their sound power level and will include new noise limits for twenty-two machine types. Included in this limit category are several machines used on construction sites, for example dozers, dumpers and excavator-loaders.

Directive 2000/14/EC is a global approach directive, which contains some detailed test codes but still refers to harmonised international standards that may be used by machinery manufacturers in order to demonstrate compliance with its requirements. In order to produce the necessary standard noise test specifications, CEN and ISO are working closely together on various methods of measurement, to suit different acoustical conditions. The standards of interest for present purposes are all type B within the CEN hierarchy, that is, they apply in principle to the noise of a wide range of machinery types. Type C standards, giving detailed machinery-specific methods will be based on these, and they will select and refer to individual type B standards for the appropriate method of noise measurement. For construction plant equipment the Type B standard is ISO 3744[5] and the Type C standards concerned are ISO 6393[6] and ISO 6395[7] and ISO 4872[8] together with Directive 79/113/EEC.

The sound power level on the label is defined as a "guaranteed sound power level", which is determined in accordance with the relevant international standard and which includes the uncertainties due to production variation and measurement procedures. It may be that the increase in the as-measured sound power level resulting from the addition of this uncertainty will affect sales of a particular machine or, for machines that are subject to noise limits, it may result in the machine having to be withdrawn from the European market. Thus, it is of prime importance that the sound power level is accurately determined[9, 10] and the level of measurement uncertainty is carefully specified.

The measurement procedures called up in Directive 2000/14/EC are taken from international standards that are concerned with the determination of sound power and in particular those that determine sound power levels in approximately hemi-anechoic conditions from measurements of sound pressure level around the machinery by carrying out a series of measurements over a hypothetical surface surrounding the source. The surface shape required by the Directive for construction plant is a hemisphere centred on the machine and terminating on a reflecting plane. The distribution and number of measurement positions on this enveloping hemispherical surface vary between the various standards. However, it is assumed that absolute sound power levels and measurement uncertainties are the same for all measurement configurations. Because of the requirement on the manufacturer to affix a label to each machine that displays a guaranteed sound power level that may have to withstand some form of verification procedure, it is important that the determined sound power level is not affected by the choice of measurement configuration.

The Standard generally used as the basis for all sound power determinations is ISO 3744:1994. This standard requires the use of hemispherical or parallelepiped measurement surfaces and is 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 recent reports[11, 12] an efficient standardised measurement technique to obtain rapid and accurate sound power measurements suitable for presentation of noise information in accordance with the various EC directives was identified. It was proposed[13, 14] 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.

This report describes an experimental programme, using procedures based on those described above, designed to assess the effect on sound power determination of the number of measurement positions and their distribution on the hemispherical enveloping surface.

2 RELEVANT INTERNATIONAL STANDARDS

The Standards that are of interest for the purposes of this study are ISO 3744, ISO 4872, together with Directive 79/113/EEC and ISO 6393 and ISO 6395. These documents address hemi-free-field test environments, using similar measurement methods in all cases.

2.1 BRIEF DESCRIPTION OF ISO 3744

ISO 3744 is an engineering-grade method for a hemi-free field environment and forms the basis of methods used for the purposes of noise labelling. An environmental correction, K_2, is defined to allow for deviations of the test conditions from the ideal ones specified, and this is not allowed to exceed 2 dB. For open test sites consisting of a hard, flat ground surface, such as asphalt or concrete, and with no sound-reflecting objects nearby, the standard assumes that K_2 is less than or equal to 0.5 dB and is negligible. There are no restrictions, nor corrections for atmospheric conditions.

A minimum of ten measurement positions is required for a hemispherical enveloping surface. The ten positions are described in ISO 3744 as "the key microphone positions" and are associated with equal areas of the measurement surface. Their coordinates in x, y, z form are listed as a function of the hemisphere radius (r) in Table 1.

Table 1 Coordinates of microphone positions according to ISO 3744

microphone position	x/r	y/r	z/r
1	-0.99	0	0.15
2	0.50	-0.86	0.15
3	0.50	0.86	0.15
4	-0.45	0.77	0.45
5	-0.45	-0.77	0.45
6	0.89	0	0.45
7	0.33	0.57	0.75
8	-0.66	0	0.75
9	0.33	-0.57	0.75
10	0	0	1.0

2.2 BRIEF DESCRIPTION OF ISO 4872 AND DIRECTIVE 79/113/EEC

Both ISO 4872 and Directive 79/113/EEC contain methods based on ISO 3744. Two possibilities of measurement position distribution are given in ISO 4872 one identical to the 10-point array of ISO 3744 and an alternative using a 12-point array. Directive 79/113/EEC only contains the 12-point array. For both documents, the requirements on acoustical environment and atmospheric conditions are the same as for ISO 3744.

The coordinates in x, y, z form of the twelve measurement positions required for a hemispherical enveloping surface are listed as a function of the hemisphere radius (r) in Table 2.

Table 2 Coordinates of microphone positions according to ISO 4872 and Directive 79/113/EEC

Microphone position	x/r	y/r	z
1	1.0	0	1.5 m
2	0.7	0.7	1.5 m
3	0	1.0	1.5 m
4	-0.7	0.7	1.5 m
5	-1.0	0	1.5 m
6	-0.7	-0.7	1.5 m
7	0	-1.0	1.5 m
8	0.7	-0.7	1.5 m
9	0.65	0.27	0.71 r
10	-0.27	0.65	0.71 r
11	-0.65	-0.27	0.71 r
12	0.27	-0.65	0.71 r

It is interesting to note from Table 2 that unlike the 10-point array the location of measurement positions is not always a function of the radius of the hemisphere. For measurement positions 1 to 8 the microphone is placed 1.5 m above the ground plane regardless of the hemisphere radius. This will result in errors for radii that are small compared to the size of the noise source. This is discussed in Section 4.

2.3 BRIEF DESCRIPTION OF ISO 6393 and ISO 6395

These two standards address the measurement of exterior noise from earth moving machinery and are essentially similar to each other but ISO 6393 deals with stationary test conditions and ISO 6395 with dynamic test conditions. In the former the machine is stationary in the centre of the hemisphere and in the latter the machine is driven through the array along the x-axis. Both standards use a sound power determination based on the 12-point array of ISO 4872. However, for these two standards only six measurement positions are required. These six are a sub-set of the ISO 4872 array and the coordinates in x, y, z form of the measurement positions required for a hemispherical enveloping surface are listed as a function of the hemisphere radius (r) in Table 3.

Table 3 Coordinates of microphone positions according to ISO 6393 and ISO 6395

Measurement position	x/r	y/r	z
1	0.7	0.7	1.5 m
2	-0.7	0.7	1.5 m
3	-0.7	-0.7	1.5 m
4	0.7	-0.7	1.5 m
5	-0.27	0.65	0.71 r
6	0.27	-0.65	0.71 r

It can be seen from Table 3 that some measurement positions are independent of the hemisphere radius. For measurement positions 1 to 4 the microphone is placed 1.5 m above the ground plane regardless of the hemisphere radius.

2.4 SUMMARY OF METHODS

The methods of measurement are essentially similar in Directive 79/113/EEC and all four ISO standards. However, it can be seen from an examination of Tables 1, 2 and 3 that the number of microphones and their distribution over the hemispherical enveloping surface varies considerably. Despite this, it is assumed that the sound power determined using each method is the identical within the constraints of measurement uncertainty. However, only ISO 3744 specifically provides information on measurement uncertainties and this is in the form of standard deviations of reproducibility. The inclusion of reference to ISO 3744 in other standards may be taken as implying similar values for all measurement configurations.

It is clear from the coordinates listed in Tables 2 and 3 that the measurement positions are not always on the surface of the hemisphere, (unlike those listed in Table 1). For instance, position 1 in Table 2 is 1.5 m high, on the x-axis and one-radius along the y-axis. This means that this position will always lie just outside the enveloping hemispherical surface. When the radius is much greater than 1.5 m, measurement position 1 will be only just outside and any error due to an increase in propagation distance above that equal to the magnitude of the radius will be small, but as the radius is reduced this error will become significant. For instance, if it is assumed that we have a point source on the reflecting plane at the centre of the hemisphere, then when the radius is equal to 1.5 m the propagation distance is 2.12 m, which will result in a reduction in measured sound pressure level of 1.5 dB. Some initial measurements were carried out to assess the variation in sound power level determined using the measurement positions listed in Table 2, resulting from changes in hemisphere radius. However, the main series of measurements described in this report were designed to provide evidence as to the similarity of sound power level data provided from the various standards outlined above.

3 GENERAL PROGRAMME DESIGN CONSIDERATIONS

3.1 OUTLINE OF THE EXPERIMENTAL WORK PROGRAMME

Because of the relatively large radius used, a considerable amount of time was required to set up the microphone arrays, which involved positioning some microphones at 7.1 m above the ground for ISO 4872 and for ISO 3744, 7.5 m and 4.5 m as well as one positioned at 10 m directly above the machine. To carry out both sets of measurements at the same time would require a 22-microphone array together with the necessary data capture and storage facilities and so it was necessary, in practice, to perform the two sets of measurements at different times, in fact on different days. As a check on the stability of the machine a fixed monitor microphone (see sub-section 3.2.3) was used during all measurements.

3.1.1 Initial hemi-anechoic measurements

As briefly described above, the measurement positions for ISO 4872 are not always on the surface of the hemisphere, (unlike those for ISO 3744). To assess the effect of this location error on the determination of sound power level some initial measurements have been carried out using a range of hemisphere radii, with a reference sound source as a noise source on an outdoor hemi-anechoic site.

3.1.2 Main series of measurements

The prime objective of the experimental work programme was to assess the effect on the determination of sound power level of the number of measurement positions and their distribution over a hemispherical enveloping surface. This experimental objective was achieved by an analysis of sound power level data obtained for a large item of construction plant operating in an outdoor hemi-anechoic environment (see Sub-section 3.2). Sound power determinations were carried out for both stationary and dynamic test conditions.

The absolute sound power levels are not of interest for the purposes of this report, only differences resulting from differing measurement configurations. So, as all measurements were conducted using an enveloping hemispherical surface with a radius of 10 m, sound power levels in this report are expressed after the application of a constant instead of a true area correction.

Sound power levels were determined according to each of the standards outlined in Section 2. These Standards purport to provide engineering (grade-2 accuracy) methods for hemi-free-field test environments. There are now many laboratory rooms or outdoor test sites in the UK that conform with these Standards and they are currently used to test a very wide range of machine types in addition to construction plant and together the methods are by far the most commonly used ones for sound power determinations, certainly in the UK and probably throughout the world.

The sound power levels determined using techniques based on sound pressure measurements were evaluated using a hemispherical enveloping surface. The standards permit measurements to be made employing a range of surface sizes. There is however, a minimum surface area, which is governed by the dimensions of the machine. The dimensions of the machine are described in ISO 3744 and ISO 4872 in terms of the size of the "reference box", the "characteristic dimension", d_o or the maximum dimension of the reference box, d_m . The reference box is a hypothetical surface, which is the smallest rectangular parallelepiped that just encloses the source and terminates on the reflecting plane. The characteristic dimension is half the length of the diagonal of the box consisting of the reference box and its images in adjoining reflecting planes. The radius, r of the hemispherical measurement surface must be greater than or equal to twice the characteristic dimension. While ISO 6393 and ISO 6395 both follow this same general principle they do impose a further requirement for the radius, which is:

- if the basic length of the machine is less than 1.5 m, then the radius shall be 4 m,
- if the basic length of the machine is greater than 1.5 m, but less than 4 m, then the radius shall be 10 m,
- if the basic length of the machine is greater than 4 m, then the radius shall be 16 m.

3.1.3 Real-time pass-by measurements

In addition to the measurements outlined above sound power levels were also determined from one-second values of L_{Aeq} under the dynamic test conditions at one-second intervals during the drive-pass. From these data a comparison between the sound power determined from the L_{Aeq} obtained over the time taken for the machine to traverse the noise measurement zone and the one-second L_{Aeq} values obtained during this time interval, may be made. These time dependent data were readily available from the multi-channel real time data acquisition and analysis system (see sub-section 3.2.3) used for the measurements.

3.2 MEASUREMENT SITE AND NOISE SOURCE

3.2.1 Measurement sites

The initial measurements outlined in sub-section 3.1.1 were carried out on a hemi-anechoic outdoor site that consists of a large flat surface covered with 10 mm thick steel plate and approximately 15 m by 40 m with no sound reflecting objects.

The main series of measurements (see subsection 3.1.2) were carried out using one outdoor hemi-anechoic site. The site was specially constructed for making noise emission measurements on various items of construction plant. The site consisted of a 12.5 m radius circular noise test pad constructed in an open grass covered area. The pad is a large flat surface consisting of concrete on a bed of compacted hardcore to a depth of 0.5 m. Abutting the pad along one axis was a 4 m wide road providing access for the machine under test and also facilitating movement of the machine across the test pad for dynamic noise testing. The pad was permanently marked with lines indicating its centre and the extent of the extent of the noise measurement zone required for dynamic testing to ISO 6395.

3.2.2 Noise source

The noise source was a medium size item of construction plant, a backhoe loader, that required an enveloping hemisphere radius of 10 m. The machine was manufactured by JCB and was powered by a Perkins turbo diesel engine type EL12S11. For the stationary tests the engine was run at maximum rpm and for the dynamic test at the same engine rpm with first gear engaged. The engine rpm for the measurements made according to ISO 3744 was measured as 2292 rpm and for measurements according to ISO 4872 it was 2296 rpm.

3.2.3 Instrumentation

There is an inherent requirement for all instrumentation to adhere to the specifications described in the various standards under examination. The instrumentation used to carry out the basic noise measurements discussed in this report complied with these specifications and where necessary had current traceable calibration certificates. Brief details of the instrumentation used are listed below.

Acoustical instrumentation for sound power determination:

microphones (up to 12)	Brüel & Kjær; type 4165,
microphone preamplifiers (up to 12)	Brüel & Kjær; type 2639,
microphone power supplies (up to 12)	Vinculum; type M591,
windscreen (up to 12)	Brüel & Kjær; type UA0237
pistonphone	Brüel & Kjær; type 4228.

NPL data acquisition and analysis system:

PC running windows 95	Dell; type Optiplex GX1 PIII,
8-channel outboard A/D converters (2)	Aardvark type; Aark24
multi-track audio capture software	Syntrillium type; Cooledit Pro' v1.2,
Signal & frequency analysis software	01dB type; DBFA32, v4.031.

Monitor microphone system:

sound level meter	Norsonic; type 116,
microphone preamplifier	Norsonic; type 1201,
microphone	Norsonic; type 1220,
sound calibrator	Norsonic; type 1250.

4 INITIAL HEMI-ANECHOIC MEASUREMENTS

As outlined in sub-section 2.4 it is possible that the sound power level determined according to ISO 4872 may be dependent on the radius of the enveloping surface used for the measurements. To assess this possibility the sound power level of a reference sound source (Brüel & Kjær; type 4204) was determined on the hemi-anechoic site described in sub-section 3.2.1 using hemispherical enveloping surfaces with radii ranging from 1 m to 10 m in 1 m steps. The maximum dimension, d_m of the reference sound source is 0.3 m so this range can be expressed as from approximately three times d_m to thirty-three times d_m. To reduce the considerable measurement effort involved in carrying out ten sound power determinations (mainly in the setting up of the measurement arrays with microphone heights up to 7 m) it has been assumed that the omni-directional characteristics of the source permit a reasonable assessment of sound power to be made using only two measurement positions. The positions used were one at a height of 1.5 m and one at a height of 0.71 times the hemisphere radius with the appropriate x-and y-coordinates. The reference sound source is particularly omni-directional in the horizontal plane and so the sound pressure level measured at a fixed height above the ground and at a fixed slant distance from the source will be essentially independent of the x- and y-coordinates. So, the sound power level may be determined from the surface average calculated from eight times the sound pressure level measured at the 1.5 m height plus four times the sound pressure level measured at a height above the ground of 0.71 times the radius. The sound power levels determined in this way are shown as a function of hemisphere radius in Figure 1.

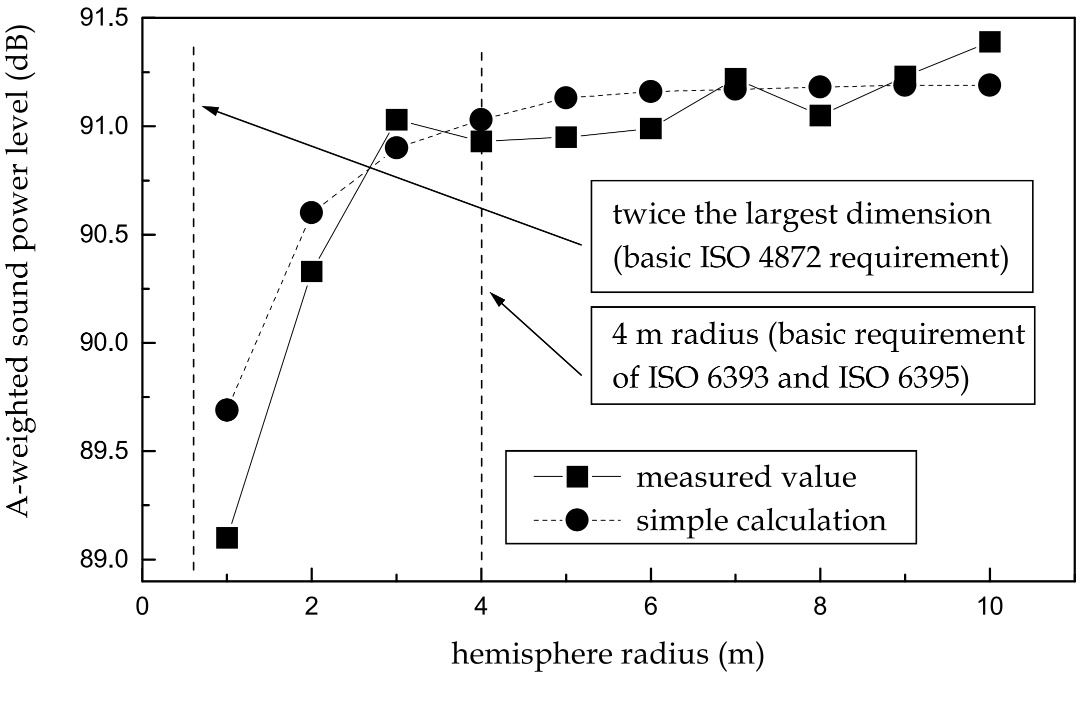

Figure 1 Effect of radius on sound power level determination according to ISO 4872

Also shown in Figure 1 is an indication of the minimum radii required by ISO 4872 ISO 6593 and ISO 6395.

It can be seen from Figure 1 (square symbols) that the determined sound power level decreases as the radius decreases, being most apparent for the smaller values of the radius. This is a direct result of the propagation distance for the 1.5 m high microphones being relatively larger for the smaller radii because they do not lie on the surface of the hypothetical hemisphere (as discussed in sub-section 2.4) thus providing smaller measured sound pressure levels.

The round symbols are the result of a simple prediction using the actual propagation distances involved. For the four measurement positions at a height of 0.71 times the radius it is assumed that the propagation distance is always equal to the radius. For the other eight positions at a height of 1.5 m the actual propagation distance is always larger than the radius value and has been calculated for each radius, and the reduction in sound pressure level obtained assuming an inverse square relationship relative to the value of the radius. The sound power level was then determined by calculating the surface sound pressure level as discussed above. It can be seen that this simple calculation procedure predicts the measured results quite well.

The effect of this error in placement for the 1.5 m high microphones can be seen from Figure 2.

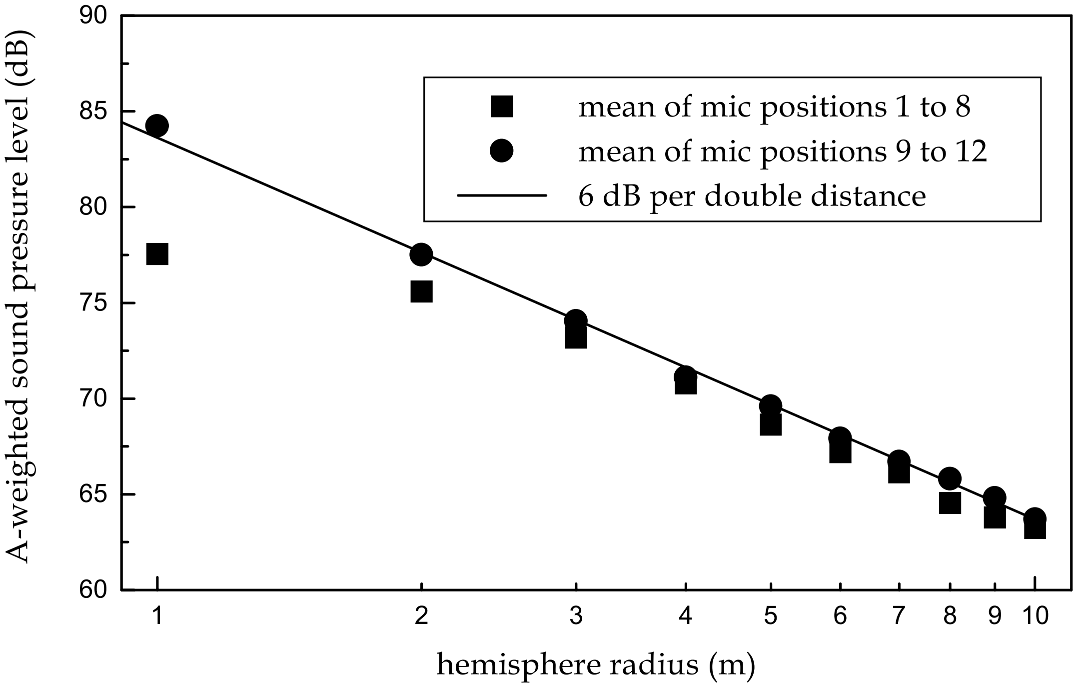

Figure 2 *A-weighted sound pressure levels as a function of distance*

Here the variation of sound pressure level as a function of hemisphere radius is shown for the 1.5 m high microphones (positions 1 to 8) and those at a height of 0.71 times the hemisphere radius (positions 9 to 12). It can be seen from a comparison with the 6 dB per double distance line that the 1.5 m high microphones do not appear to follow this relationship at the smaller radii giving sound pressure levels that are too low. In fact the problem here is that the propagation distance is not equal to the hemisphere radius, as discussed in sub-section 2.4.

It is clear that the requirement given in ISO 4872 for the radius to be at least twice the maximum dimension of the reference box is inadequate, a value approaching four- times would seem to be necessary. The requirement on radius given in ISO 6393 and ISO 6395, that the radius shall be 4 m if the basic length of the machine is less than 1.5 m and 10 m if the basic length of the machine is greater than 1.5 m but less than 4 m and 16 m if the basic length of the machine is greater than 4 m may also be too small. For instance, if the length is just less than 1.5 m then the radius is less than three times the length and if the length is just less than 4 m the radius is approximately two and one-half times the length. Clearly care has to be taken when using the 12- or 6-microphone array to determine sound power levels, especially with regard to assessing a "guaranteed value", as the determined levels may be too low. This may in due course present difficulties if a machine is subjected to some form of verification process.

5 STATIC MEASUREMENTS

Sound power determinations made during the main series of measurements according to the standards outlined in Section 2 were carried out in the hemi-anechoic outdoor space described in sub-section 3.2.1, which fulfilled the acoustic environment requirements of all the standards. Sound pressure levels were measured with frequency weighting A and in one-third octave-bands at centre frequencies from 50 Hz to 10 kHz on a hemispherical measurement surface with a radius of 10 m. Each set of measurements was repeated three times to obtain a value for the standard deviation of repeatability. In fact between successive sets of measurements the machine was not moved, nor were the microphones. The only change, apart from a short period of time between tests, was that the engine was stopped and then run-up again for the next measurement. Two arrays were used, the ten measurement positions from Table 1, for ISO 3744, and the twelve from Table 2, for ISO 4782 (the ISO 6393 array is a six position sub-set of this twelve position array). From the results of these measurements a comparison may be made of sound power levels determined according to ISO 3744 with those from ISO 4872 and also a comparison between the ISO 4872 data and the six-position sub-set of ISO 6393. It must be remembered that measurements according to ISO 3744 were performed on a different day from those according to the other standards (see sub-section 3.1).

5.1 A-WEIGHTED RESULTS FOR STATIC TESTS

The A-weighted sound power levels determined according to ISO 3744, ISO 4872 and ISO 6393 are listed in Table 4 together with standard deviations of repeatability.

Table 4 A-weighted sound power levels for static tests

	A-weighted sound power level (dB)		
	ISO 3744	ISO 4872	ISO 6393
First determination	107.95	107.28	107.33
Second determination	108.01	107.31	107.36
Third determination	107.93	107.34	107.41
Mean	107.96	107.31	107.37
Standard deviation	0.04	0.03	0.04

It can be seen from Table 4 that the variation between determinations is very small resulting in standard deviations of repeatability of less than 0.1 dB.

The mean difference between sound power levels determined using ISO 3744 and those using ISO 4872 can be seen from Table 4 to be 0.65 dB such that ISO 4872 provides the smaller value. This result (ISO 4872 providing the smaller value) is as would be expected from the consideration of microphone positions discussed above in Section 4.

However, the A-weighted sound pressure level data from the fixed position monitor microphone showed a difference of 0.7 dB again with ISO 4872 providing the smaller value. Here the measurements were associated with a standard deviation of up to 0.43 dB. So, it may be assumed that the difference of 0.65 dB between methods (ISO 3744 and ISO 4872) is due to small differences in the machine operating conditions and / or small changes in atmospheric conditions between the two measurement days. However, it seems unlikely that small changes in atmospheric conditions would have a measurable effect over such a small propagation distance and the rpm of the diesel engine was monitored for each test and only ranged from 2292 rpm to 2296 rpm, which will result in a negligible change in sound power level. So, to examine this difference between the two series of tests further it is interesting to examine the sound pressure levels measured at individual microphones in each of the two arrays whose locations were reasonably close together. There are three microphone pairs that are within a metre or two of each other and these are shown in Table 5 together with mean measured differences.

Table 5 Differences between A-weighted sound pressure levels for individual microphone positions

	Position number from Tables 1 and 2 and (height)		
ISO 3744	8 (7.5 m)	2 (1.5 m)	3 (1.5 m)
ISO 4872	11 (7.1 m)	8 (1.5 m)	3 (1.5 m)
Mean difference (dB)	0.4	1.3	0.1

It can be seen that there is a variation of mean differences with an average of 0.6 dB. Even though the measurement locations are not in exactly the same locations, it is not clear why there is this range of differences especially considering the small value of Directivity Index and the negligible values of standard deviations of repeatability. However, the average value is approximately the same as the differences in sound power levels obtained using the two standards and also that observed from the monitor sound level meter readings. It must be concluded that differences in sound power level determinations between those using ISO 3744 and those using ISO 4872 may not be attributed to differences in the measurement methods.

The mean difference between sound power levels determined according to ISO 4872 and those determined according to ISO 6393 can be seen to be only 0.06 dB. Even considering the very small values of repeatability standard deviations this mean difference is not statistically significant and so it may be assumed that there is no difference between the two determinations. This result is perhaps surprising considering the difference in the number of measurement positions involved. It has been shown[11, 12] that values of reproducibility standard deviation are dependent on the number of measurement positions used and on the Directivity Index of the noise source. However, the main contribution to standard deviations of reproducibility is from variations in sound power determination resulting from differing measurement sites. So, it is likely that sound power determinations performed on the same site using differing numbers of measurement positions may be similar to each other, especially if the noise source is not highly directional. The A-weighted Directivity Index of the backhoe loader used in this report was measured as 2.3 dB. This is an indication that the source is not highly directional and is a fairly typical value for machinery[13, 14].

5.2 ONE-THIRD-OCTAVE-BAND STATIC TEST RESULTS

Sound power levels determined according to ISO 3744 for one-third-octave-bands from 80 Hz to 10 kHz and those determined according to ISO 4872 for one-third-octave-bands from 63 Hz to 10 kHz are shown in Figure 3. Background noise levels for the one-third-octave-bands centred on frequencies lower than 63 Hz for ISO 4872 and 80 Hz for ISO 3744 were within 6 dB of noise levels measured with the machine operating and so have been disregarded.

It can be seen that the frequency distribution is such that at low frequencies the sound energy increases to a peak at 400 Hz (associated with the engine speed) and then there is a gradual roll-off at higher frequencies.

It can be seen that for bands centred at 500 Hz and above the results from the two standards are very similar, as would be expected from consideration of the A-weighted data discussed above in sub-section 5.1. There are differences at some lower frequencies where sound power determinations made according to ISO 4872 are generally higher. There is large difference in the 400 Hz band with the ISO 3744 determination providing the higher value. As stated above there is a peak in the spectrum at 400 Hz resulting from tones that are dependent on the engine speed. Because of the tonal nature of the energy in this band measured sound pressure levels will be dependant on the exact microphone position and hence differences in sound power determinations between the two arrays used may be expected. To examine these effects in more detail, the differences between the sound power levels determined according to ISO 3744 and those determined according to ISO 4872 are shown in Figure 4. It can be seen that at low frequencies ISO 4872 provides sound power levels that are approaching 2 dB higher, while at 400 Hz over 3 dB lower and at higher frequencies both standards provide similar results.

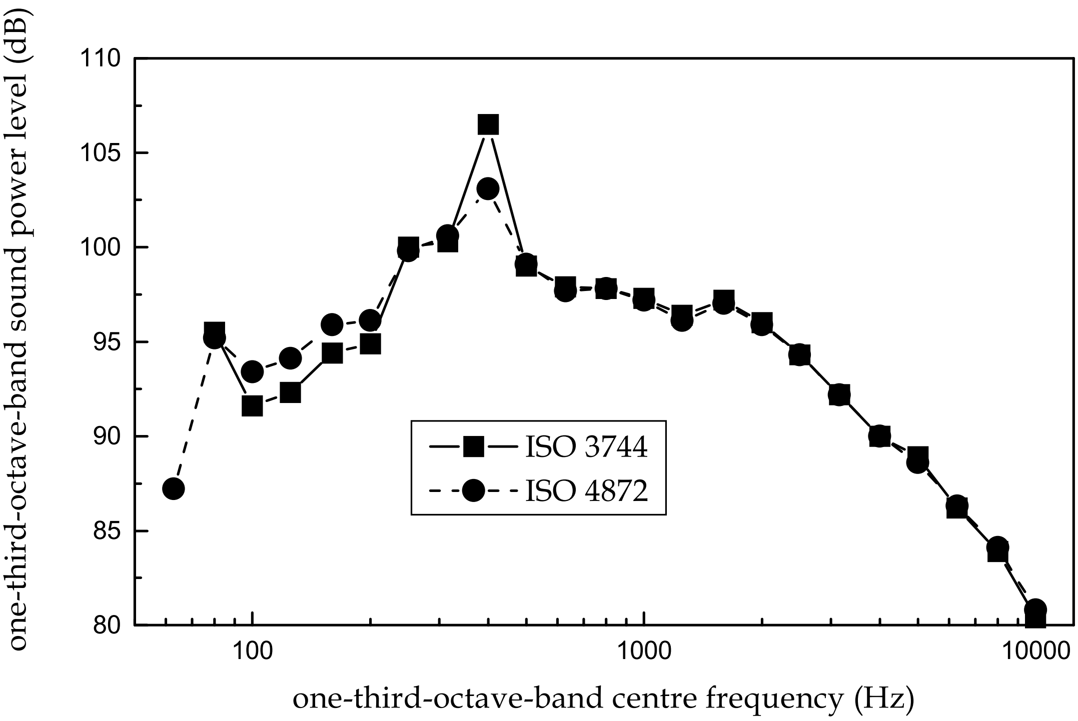

Figure 3 One-third-octave-band sound power levels for static tests

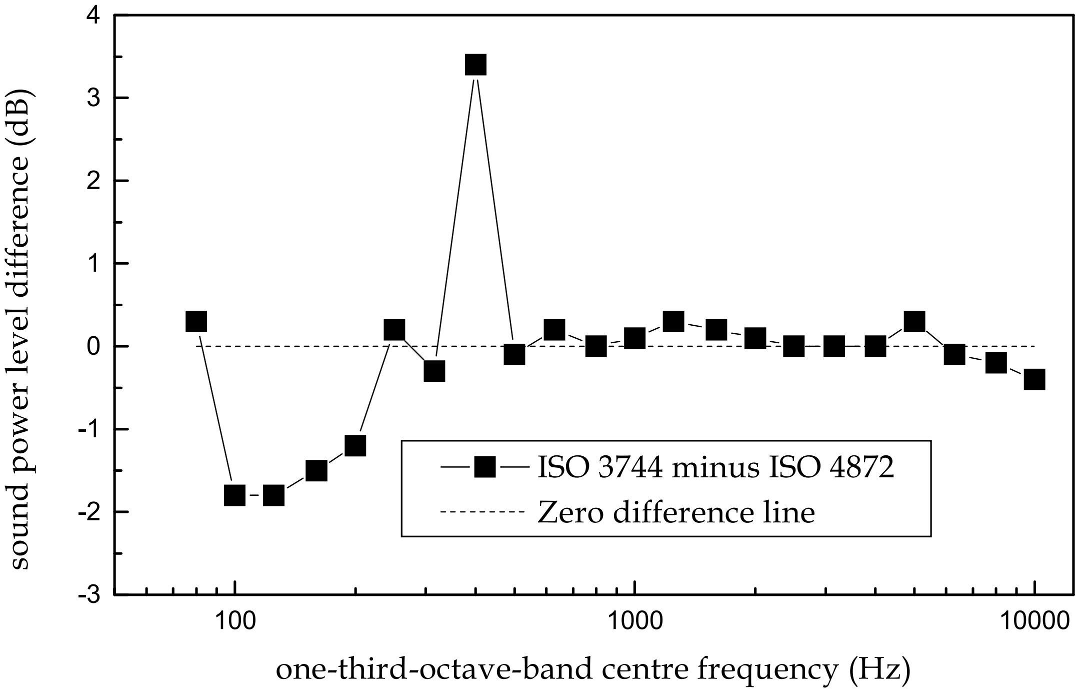

Figure 4 *Differences between ISO 3744 and ISO 4872 one-third-octave-band sound power levels for static tests.*

To assess these differences in more detail it is interesting to consider the effects of interference between direct and ground reflected sound waves. ISO 3744 has microphones positioned at 1.5 m, 4.5 m, 7.5 m and 10 m above the ground and these are associated with first interference cancellations at frequencies of 383 Hz, 127 Hz, 76 Hz and 57 Hz respectively. ISO 4872 has microphones positioned at 1.5 m and 7.1 m above the ground and these are associated with first interference cancellations at 390 Hz and 81 Hz. The difference in the cancellation frequency associated with the 1.5 m-high microphones, between that calculated for ISO 3744 and that for ISO 4872, is because of differences in the x- and y-axis coordinates (see Tables 1 and 2).

The large difference in the 400 Hz band shown in Figure 4 occurs in a frequency region where there are strong interference effects (390 Hz and 383 Hz). These interference effects are associated with the 1.5 m–high microphones. Now, for ISO 3744 there are 3 microphones at a height of 1.5 m, out of a total of 10, whilst for ISO 4872 there are 8 microphones at a height of 1.5 m, out of a tota1 of 12. Because of this distribution of microphone heights, it is reasonable to assume that the interference cancellations will have a greater effect on the sound power level determined according to ISO 4872 than on that determined according to ISO 3744. The sound power levels determined according to ISO 4872 may, therefore, be lower than those determined according to ISO 3744. It can be seen from Figure 4 that ISO 4872 provides sound power levels approximately 3.5 dB lower than ISO 3744. In addition, the effect of interference on measured noise levels is greater for sound that has a tonal content than for sound that is, in effect, random noise, hence the large difference in the 400 Hz frequency band shown in Figure 4.

The interference cancellation at approximately 80 Hz is associated with the 7.5 m-high microphones (for ISO 3744) and the 7.1 m-high microphones (for ISO 4872). The distribution of these microphone heights in the appropriate array is similar for each standard, with 3 out of 10 in ISO 3744 and 4 out of 12 in ISO 4872. The effect of ground interference on the determination of sound power may, therefore, be expected to be similar for each of the two standards. In fact, from an examination of the result for the 80 Hz band shown in Figure 4 it can be seen that the difference is approximately zero.

ISO 3744 has three microphones located 4.5 m above the ground with an associated interference cancellation at 127 Hz. It is likely, therefore, that the sound power level determined according to ISO 3744 may be lower than that determined using ISO 4872. An examination of Figure 4 shows that the sound power levels in the one-third octave-bands around 125 Hz determined according to ISO 3744 are between 1 dB and 2 dB less than those determined according to ISO 4872.

Although there is only one microphone at 10 m above the ground (position 10 for the ISO 3744 array) the interference cancellation at 57 Hz, associated with this microphone, may result in a lower sound power level in the 63 Hz band determined using ISO 3744 than that determined according to ISO 4872. Although because of high background noise levels, data for the 63 Hz band is not shown for ISO 3744, when corrected for these high background noise levels, the ISO 3744 one-third-octave-band sound power level for 63 Hz is 1.6 dB less than that determined according to ISO 4872.

Although these differences in determined sound power levels at low frequencies have little effect on A-weighted sound power levels, (these are generally required for the purposes of reporting or declaring noise levels), it is clear that for research and development purposes care must be taken when interpreting lower frequency data.

6 DYNAMIC MEASUREMENTS

As discussed in Section 2.3, ISO 6395 addresses the assessment of sound power level under dynamic conditions. The standard requires the use of the same six-position microphone array as used for the ISO 6393 static tests described in Section 5. These six positions are a sub-set of the 12 position array described in ISO 4872, so sound power levels have been determined using an array based on (see below) the 12-microphone array of ISO 4872 and, for comparison purposes, the 10-position array of ISO 3744. ISO 6395 relates to mobile machinery and requires that the machine travels through the array from, and to, a given distance from the centre of the hemisphere, such that the centre line of the machine travel is along the x-axis of the array. To facilitate this travel path, two microphones from the 12-position, ISO 4872 array (positions 3 and 7 from Table 2) have to be removed. However, these two are not part of the 6-microphone position array required for ISO 6395.

The sound power determinations made according to the standards outlined above were carried out in the hemi-anechoic outdoor space described in sub-section 3.2.1, which fulfilled the acoustic environment requirements of all the standards. Sound pressure levels were measured with frequency weighting A and in one-third octave-bands at centre frequencies from 50 Hz to 10 kHz on a hemispherical measurement surface with a radius of 10 m with the machine traversing the array according to the requirements of ISO 6395. Three traverses were performed through each array to obtain three complete sets of measurements in order to permit a calculation of a value for the standard deviation of repeatability. Between successive traverses for each of the arrays the microphones were not moved. However, it must be remembered that measurements according to ISO 3744 were performed on a different day from those according to the other standards (see sub-section 3.1).

Sound power levels were calculated strictly according to ISO 6395 and also as a function of the machine position during the traverse. The latter determinations required the use of the multi-channel data acquisition system developed at NPL as data were required from all microphones in real-time. Data obtained according to ISO 6395 require the measurement of the equivalent continuous sound pressure level $L_{peq,T}$, that may be obtained from the following equation:

$$L_{peq,T} = 10\lg\left[\frac{1}{T}\int_0^T \frac{p^2(t)}{p_0^2}dt\right] \qquad \ldots\ldots (1)$$

where:

T is the measurement period in seconds, i.e. the time taken for the machine to cover the required part of the travel path. The length of the travel path over which measurements are taken is defined in ISO 6395 as 1.4 times the radius of the enveloping hemisphere (in this case 14 m) positioned such that there is 7 m either side of the centre of the hemisphere. Referring to Table 2, this corresponds to a path between a ground-plane line joining microphone positions 4 and 6 and a line joining positions 2 and 8,

p is the instantaneous sound pressure of the noise signal,

p_0 is the reference sound pressure (20 μPa).

So, here the output of each microphone is "averaged" as the machine passes through the array and the sound power is determined from a quasi-surface sound pressure level calculated from these averages. There will, therefore, be one sound power level determination for each of the three traverses through each of the two arrays.

For the case of measurements made as a function of the machine position during the traverse there will be several sound power level determinations for each traverse. Here the output of each of the microphones was investigated at one-second intervals during each traverse. In effect this involved carrying out the process in equation 1 with T equal to one-second at one-second intervals throughout the time taken for the machine to cover the required part of the travel path. This will result in several sound power determinations that, unlike the case above where measurements are made continuously as the machine travels through the array, are in effect, a series of measurements made as the array moves continuously past the machine.

It will be interesting to compare the results from these two ways of determining sound power level to see what differences exist between data averaged during the passage of a moving source and those obtained at specific times during the travel.

6.1 A-WEIGHTED RESULTS ACCORDING TO ISO 6395

The A-weighted sound power levels determined according to ISO 3744, the modified version of ISO 4872 and ISO 6395 are listed in Table 6 together with standard deviations of repeatability.

Table 6 A-weighted sound power levels according to ISO 6395

	A-weighted sound power level (dB)		
	ISO 3744	"ISO 4872"	ISO 6395
First determination	108.37	107.98	107.98
Second determination	108.26	108.03	108.06
Third determination	108.26	108.11	108.08
Mean	108.30	108.04	108.03
Standard deviation	0.06	0.07	0.04

It can be seen from Table 6 that the variation between determinations is very small resulting in standard deviations of repeatability of less than 0.1 dB.

The mean difference between sound power levels determined using ISO 3744 and those using the modified ISO 4872 could be seen from Table 6 to be 0.26 dB, such that ISO 4872 provides the smaller value. This result (ISO 4872 providing the smaller value) is as would be expected from the consideration of microphone positions discussed above in Section 4 but is smaller than observed for the static tests (see sub section 5.1). Unfortunately the corresponding average difference provided by the monitor microphone is 1 dB. However, this is a result obtained for a single microphone position and perhaps should be treated with some care. It does, however, tend to indicate that differences between the sound power levels determined according to the two standards are not statistically significantly different.

It is interesting to compare the average data in Table 6 (108.30 dB and 108.04 dB) with the corresponding values of 107.96 dB and 107.31 dB obtained for the static tests displayed in Table 4 - a difference of 0.34 dB and 0.71 dB for ISO 3744 and ISO 4872 respectively. This is a good agreement considering that, although the engine rpm was the same for both static and dynamic tests, in one case the machine was stationary in the centre of the hemispherical measurement surface and in the other, with first gear engaged, the machine was travelling though the measurement surface. Although regulatory requirements may stipulate a dynamic test, these results indicate that sound power data from static tests may be sufficient during the machine development process.

The average difference between sound power levels determined according to the modified ISO 4872 and those determined using the six-microphone array according to ISO 6395 can be seen to be 0.01 dB. Considering the very small values of repeatability standard deviations and the difference in the number of measurement positions involved this small difference is surprising but the levels listed in Table 4 are the result of calculations performed on the as-measured data and so it must be assumed that there is no significant difference between the two determinations.

6.2 ONE-THIRD-OCTAVE-BAND RESULTS ACCORDING TO ISO 6395

Sound power levels determined according to ISO 3744 for one-third-octave-bands from 80 Hz to 10 kHz and those determined according to the modified ISO 4872 for one-third-octave-bands from 63 Hz to 10 kHz are shown in Figure 5. Background noise levels for the one-third-octave-bands centred on frequencies lower than 63 Hz for ISO 4872 and 80 Hz for ISO 3744 were within 6 dB of noise levels measured with the machine operating and so have been disregarded. The data from the 6-microphone array of ISO 6395 are very close to the ISO 4872 data so, for clarity they are not shown in Figure 5.

From Figure 5, it can be seen that the frequency distribution is very similar to the static test results shown in Figure 3 where at low frequencies the sound energy increases to a peak at 400 Hz (associated with the engine speed) and then there is a gradual roll-off at higher frequencies.

It can also be seen that the differences between the two sound power spectra are similar to those for the static test shown in Figure 3 and discussed in sub-section 5.2.

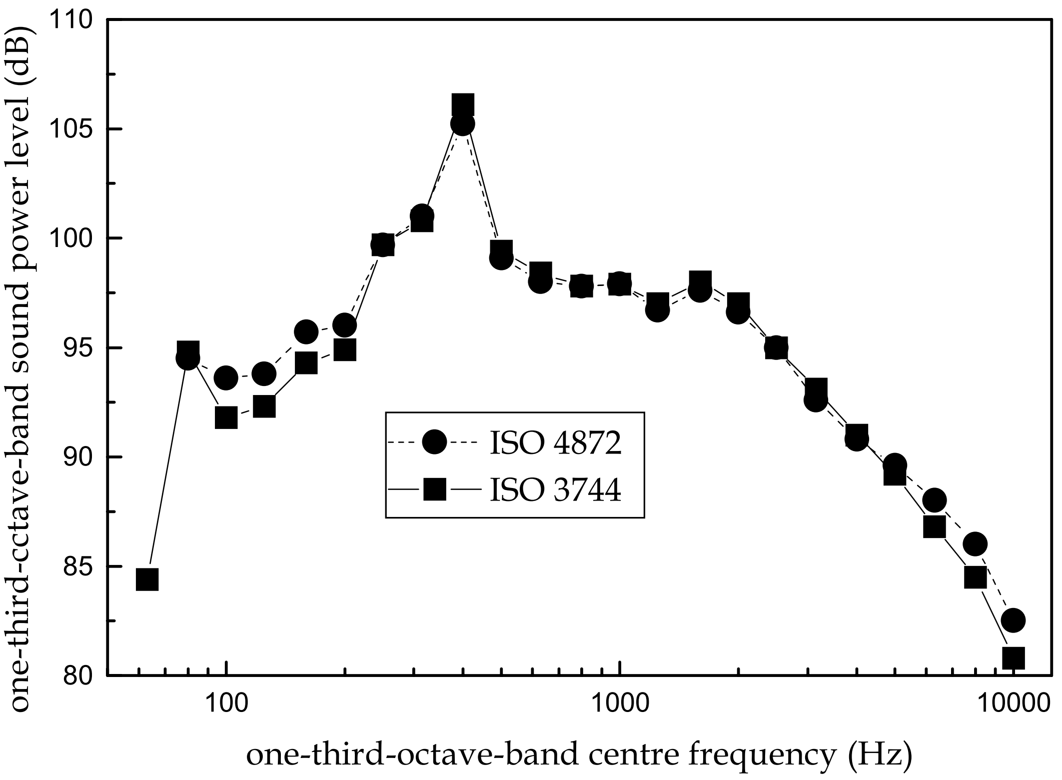

Figure 5 *One-third-octave–band sound power levels for dynamic tests*

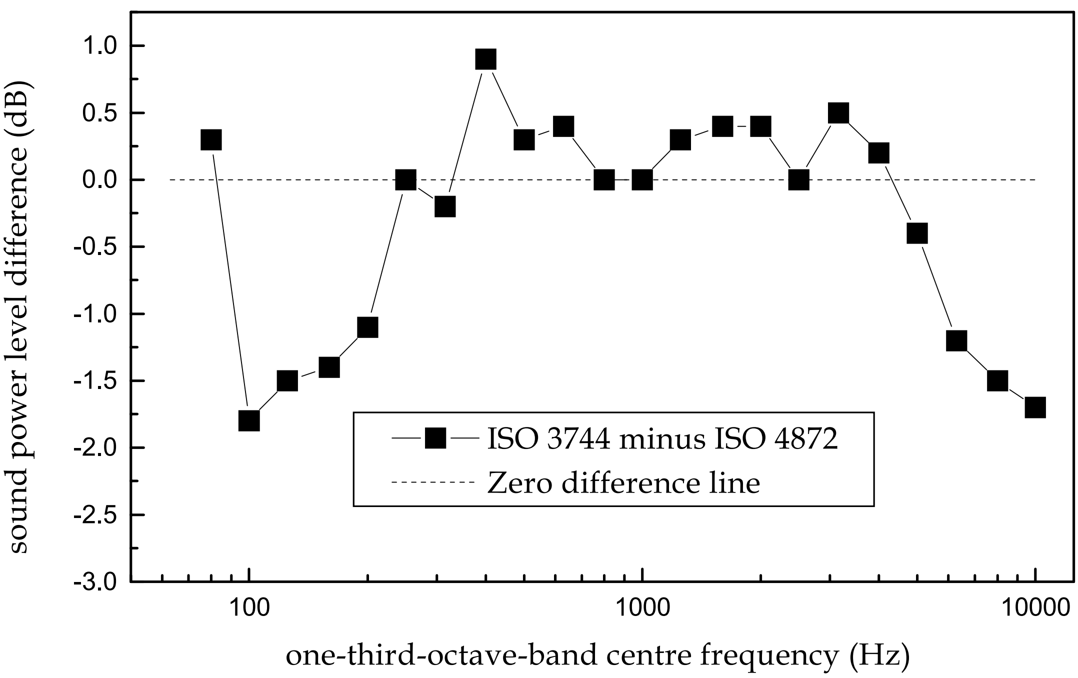

Figure 6 *Differences between ISO 3744 and ISO 4872 one-third-octave-band sound power levels for dynamic tests.*

The differences between the sound powers determined according to ISO 3744 and those determined according to ISO 4872 are shown in Figure 6. It can be seen that at low frequencies ISO 4872 provides sound power levels that are generally between 1 dB and 2 dB higher, while at 400 Hz approximately 1 dB lower and at frequencies above 5000 Hz again between 0.5 dB and 2 dB higher.

The differences at the lower frequencies and at 400 Hz are similar to those obtained for the static tests (see Figure 4) but are smaller. The reduced size of the differences is a result of the averaging process required to obtain a value for $L_{peq,T}$ during the time taken for the machine to traverse through the hemisphere. The effects of interference are related to the path difference between direct and ground reflected sound. This, in turn, is dependent on the geometry existing between source and receiver. For the dynamic tests the source is moving and so the geometry, and hence the path difference, is continually changing during the evaluation of $L_{peq,T}$. Thus the effect of interference will be "averaged" and cancellations will become less pronounced resulting in smaller differences between the two sound power level determinations.

The reason for the differences at the higher frequencies is not so clear. It may be seen from the static data shown in Figure 4 that corresponding differences are close to zero. To examine these differences in more detail it is interesting to consider the change in one-third-octave-band sound power levels for each standard (ISO 3744 and ISO 4872) between static and dynamic tests. Differences for both standards are shown in Figure 7.

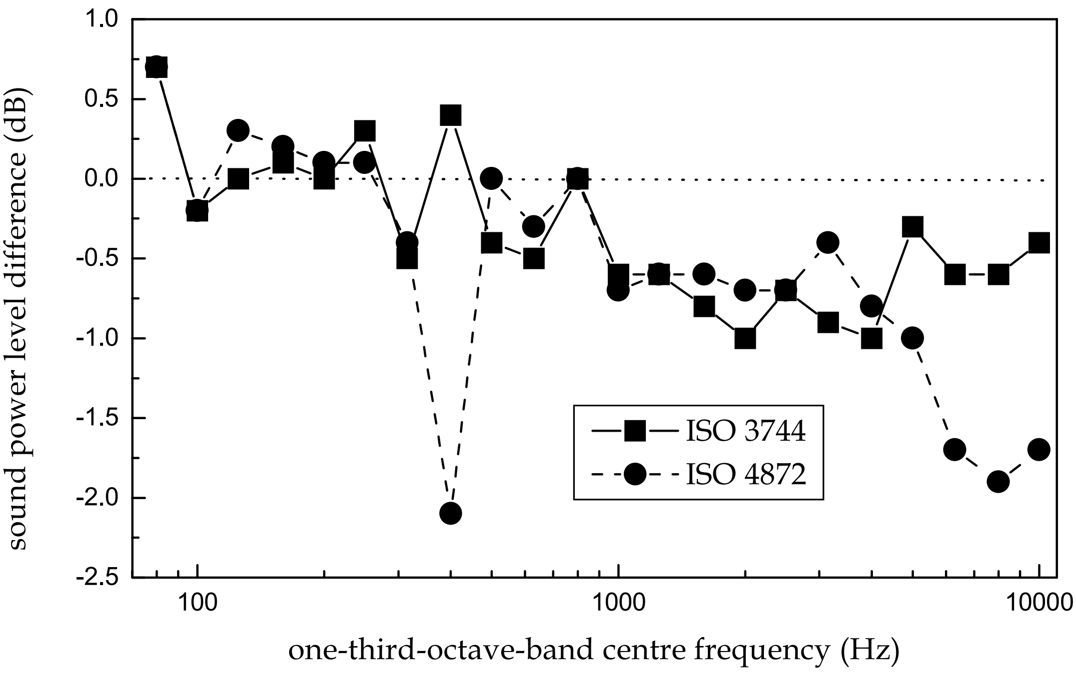

Figure 7 One-third-octave-band sound power level differences between static and dynamic tests

It can be seen from Figure 7 that at lower frequencies the two data sets are similar and close to zero, with the exception of the differences in the 400 Hz band (see discussion above). At frequencies from 1 kHz to 4 kHz there is a difference in level between static and dynamic tests of around 0.7 dB for both standards. This change in sound power level is reflected in the A-weighted data discussed in sub-section 6.1 where an average difference of 0.5 dB was observed. At frequencies above 4 kHz the differences associated with the ISO 3744 remain at about the same magnitude whereas those associated with ISO 4872 become much larger and for the top three frequency bands are around 1.7 dB. It may be concluded, therefore, that the differences at higher frequencies shown in Figure 6 are the result of changes in sound power levels determined according to ISO 4872. It is possible that this is a result of variation in the value of the Directivity Index at these higher frequencies. The microphone distribution specified in ISO 4872 uses only two microphone heights (ISO 3744 uses four different microphone heights) and so may not account fully for the apparent changes in Directivity Index as the machine travels through the hemisphere. Some evidence that this may be the case can be obtained from the 400 Hz data in Figure 7. The character of the sound in this band is tonal and so the machine will have a relatively large value of Directivity Index at 400 Hz. The large change in sound power level observed for the ISO 4872 data in Figure 7 (2.3 dB in comparison with the change of 0.4 dB corresponding to the ISO 3744 data) between static and dynamic tests is probably the result of the limited range of microphone heights employed for the ISO 4872 measurements.

However, because of the steeply falling spectral distribution at these higher frequencies, their contribution to A-weighted levels will be minimal. This may not be the case for noise sources with a pre-dominant high frequency content.

6.3 DYNAMIC RESULTS FROM REAL-TIME MEASUREMENTS

As outlined in the introduction to Section 6, sound power determinations were determined as a function of the machine position during the traverse. This required the use of the multi-channel data acquisition system developed at NPL as data were required from all microphones in real-time. The calculation of the equivalent sound pressure level $L_{peq,T}$, was performed using equation 1 with time T set to one second. The first one-second sample started as the machine passed a line joining microphone positions 2 and 8 and then continued at one-second intervals until the machine passed a line joining microphone positions 4 and 6. This resulted in nine one-second samples and subsequent sound power determinations.

6.3.1 A-weighted results from real-time measurements.

Nine A-weighted sound power level determinations were carried out as the machine travelled through the measurement hemisphere. The first determination was carried out during the one-second after the machine passed a line joining microphone positions 2 and 8; the fifth determination was carried out during the one-second after the machine passed the hemisphere centre and the ninth determination was carried out during the one-second after the machine passed a line joining microphone positions 4 and 6. The sound power levels at the centre of the hemisphere were 108.2 dB and 108.1 dB for ISO 3744 and ISO 4872 respectively. These levels compare well with the ISO 6395 data of 108.30 dB and 108.04 dB from Table 6. This is another indication that static and dynamic tests provide similar results (see discussion in sub-section 6.1).

The one-second-L_{Apeq} sound power levels determined as the machine travelled through the hemisphere varied by 0.9 dB and 0.7 dB for ISO 3744 and ISO 4872 respectively. These variations in sound power level correspond to the machine being located at positions 7 m either side of the centre of the hemisphere. This indicates that sound power determinations may not be very sensitive to small errors in machine location.

6.3.2 One-third-octave-band results from real-time measurements.

All nine one-third-octave-band sound power levels determined according to ISO 3744 and those determined according to the modified ISO 4872 are shown in Figures 8 and 9 respectively. The data from the 6-microphone array of ISO 6395 are very close to the ISO 4872 data so, for clarity they are not shown in Figures 8 and 9.

It can be seen from both Figures that there is a small data scatter but the spectra are essentially similar throughout the machine traverse. Because of the similarity, individual spectra are not specifically identified but the lower sound power levels are generally associated with measurements made as the machine entered the hemisphere (i.e. as it crossed the ground-plane line joining microphone positions 4 and 6). In this Report, a more detailed analysis is not carried out as, although it may be interesting, it would only serve to indicate, in a more quantitative manner, the variations of one-third-octave-band as the machine passed through the hemisphere and these data are not required by any of the ISO standards considered.

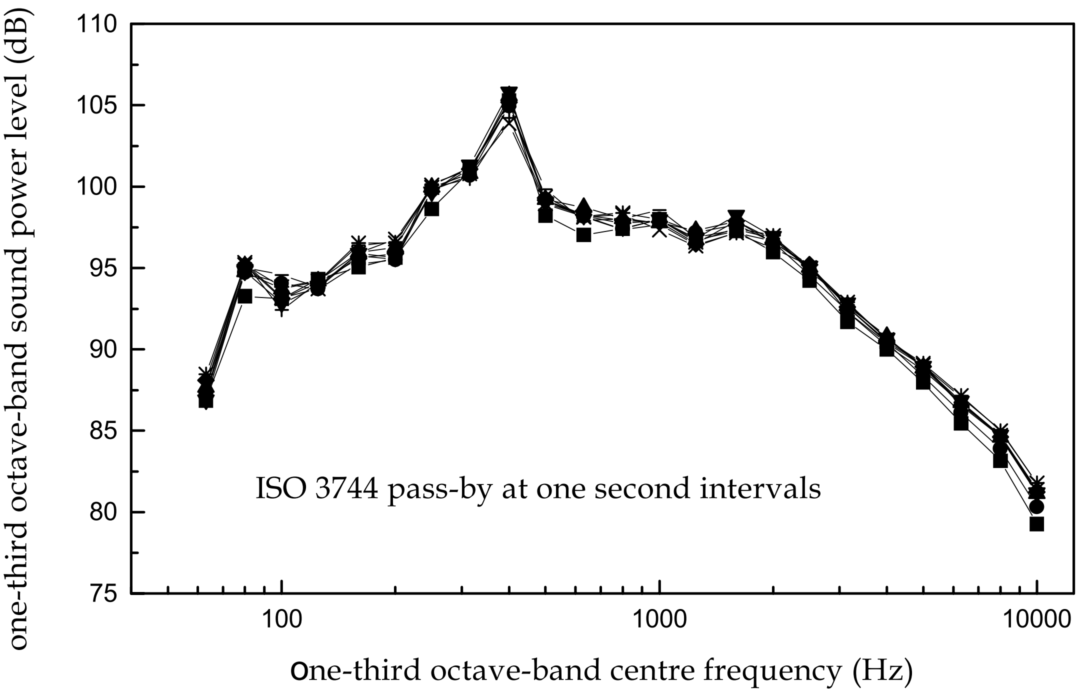

Figure 8 One-third-octave-band spectra measured during the machines travel through the ISO 3744 hemisphere

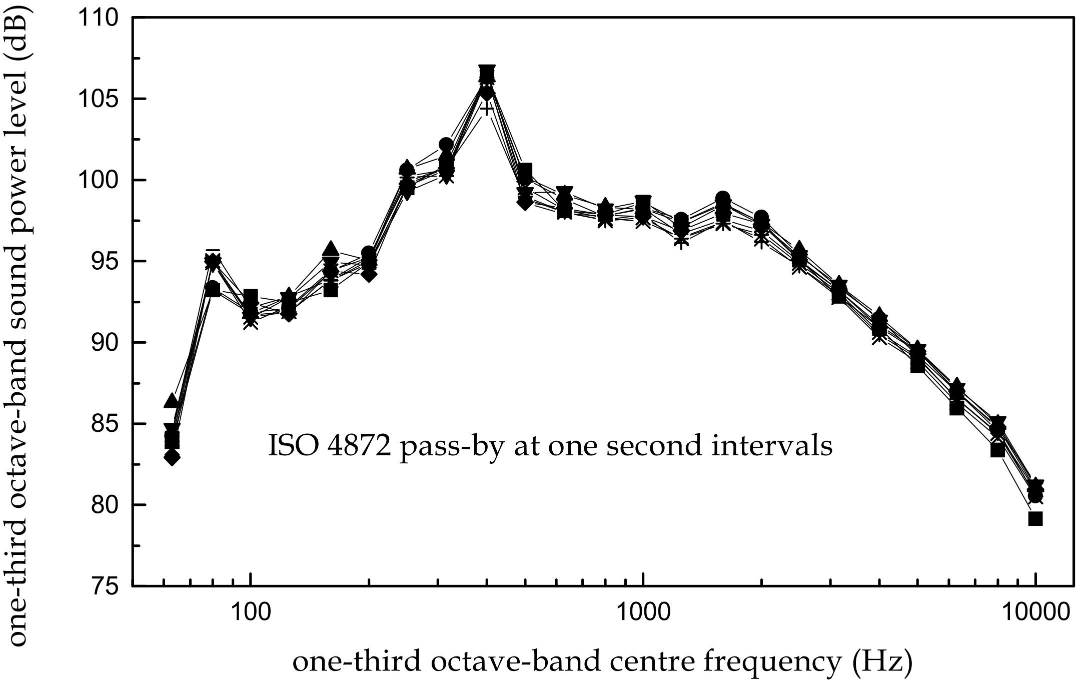

Figure 9 *One-third-octave-band spectra measured during the machine*s *travel through the ISO 4872 hemisphere*

7 CONCLUSIONS

Sound power levels determined according to ISO 4872 decrease as the radius decreases, being most apparent for the smaller values of radius. **It is clear that the requirement given in ISO 4872 for the radius to be at least twice the maximum dimension of the reference box is inadequate; a value approaching four times would seem to be necessary.**

Repeatability uncertainties associated with A-weighted sound power levels determined according to all four ISO standards considered in this report were very small resulting in standard deviations of repeatability of less than 0.1 dB.

A-weighted sound power levels determined according to ISO 3744 were slightly larger than those determined according to ISO 4872 but cannot be attributed to differences in the measurement methods. The difference between sound power levels determined according to ISO 4872 and those determined according to ISO 6393 and ISO 6395 were negligible. **It is concluded that differences between the sound power levels determined according to the four standards considered are not statistically significantly different.**

For static tests, ISO 4872 provides one-third-octave-band sound power levels that are approaching 2 dB higher than those provided by ISO 3744 at low frequencies, while at 400 Hz the value is over 3 dB lower and at higher frequencies both standards provide similar results. These differences are a result of the effects of ground reflections on measured noise levels. Although these differences in determined sound power levels at low frequencies have little effect on A-weighted levels, it is clear that **for research and development purposes care must be taken when interpreting lower frequency data.**

For dynamic tests, the differences at the lower frequencies and at 400 Hz are similar to those obtained for the static tests but at higher frequencies ISO 4872 provides levels up to 2 dB higher than those provided by ISO 3744. These higher frequency differences are probably the result of the limited range of microphone heights employed for the ISO 4872 measurements. However, because of the steeply falling spectral distribution, **the contribution of high frequency differences to A-weighted levels is minimal. This may not be the case for noise sources with a pre-dominant high frequency content.**

The average difference in A-weighted sound power levels between static and dynamic tests was approximately 0.5 dB. Although some regulatory requirements stipulate a dynamic test, this result indicates that **sound power level data from static tests may be sufficient during the machine development process.**

The small variations between sound power levels determined from values of one-second-L_{Apeq} evaluated as the machine travelled through the hemisphere are an indication that **sound power determinations are not very sensitive to small errors in machine location.**

8 ACKNOWLEDGEMENTS

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