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MEASURING THE SOUND POWER OF WOODWORKING MACHINES USING SOUND INTENSITY TECHNIQUES.

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1. INTRODUCTION

The introduction of the European Machinery Directive[1] has placed on manufacturers and suppliers of industrial machinery a duty to provide information concerning, among other things, the noise emission of their products. Already in the UK we have the Noise at Work Regulations, which ask manufacturers to provide some information on the noise levels produced by their machines, but the Machinery Directive is more specific. It states that:

(i) the sound pressure level (SPL) at an operators position must be stated, and that

(ii) if the SPL at an operator position exceeds 85 dB(A), then the manufacturer or supplier must declare the sound power level (SWL) of the machine.

This Directive does not come into force until 1995, but manufacturers of industrial machinery will need to have some mechanism in place on this date to enable them to declare the sound power emission of their products. They may also need to be able to measure SWL without having to resort to special facilities.

The three case studies described here were carried out to assess a relatively new technique for measuring SWL. The technique makes use of measurements of sound intensity over an imaginary surface completely enveloping the sound source. The measurements are not required to be carried out in a free-field (anechoic) environment, nor do strong levels of background noise invalidate the measurements. The objective of the studies was to assess the accuracy and ease of use of the technique. For this purpose, comparisons were made with a technique for measuring sound power level using measurements of sound pressure, based on ISO 3744[2].

2. METHODS FOR MEASURING SOUND POWER LEVEL

Standards have existed for many years on measuring the SWL of sound sources. The ISO 3740 series describes methods of varying degrees of precision based on measurements of sound pressure level at discrete points around a machine. The acoustic environment required by these standards is usually an anechoic chamber, or an outdoor area with no other machinery surrounding, and low background noise. In cases where anechoic facilities are not available, or the source cannot be moved or operated outdoors (perhaps because it normally operates as part of a chain of machines) then the application of these standard techniques becomes difficult. The two standard techniques that *are* intended for indoor application (ISO 3744 and ISO 3746 [3]) cannot easily cope with the presence of extraneous noise from nearby unrelated sources.

2.1 Sound intensity method

The development of sound intensity equipment, and the use of sound intensity for a variety of applications has led to the development of a standard method for measuring SWL using sound intensity. This standard is BS 7703[4] (equivalent to ISO 9614-1). BS 7703 specifies that an imaginary surface is defined which completely encloses the sound source being measured, and that simultaneous measurements of sound intensity and sound pressure are made at a number of discrete points normal to that surface. By calculating the average of the sound intensity measurements, and multiplying by the area of the surface, the total sound power being emitted through that surface is obtained. In addition, the measurement surface can be divided into a number of sub-surfaces which can be treated individually, if this makes the process easier.

A fundamental property of sound intensity is its ability to determine the magnitude and direction of net sound energy flow. This property leads directly to its use in measuring SWL in the presence of relatively high levels of background noise. Figure 1 illustrates this point.

Recommendations for the size and shape of the measurement surface are made in BS 7703, and for the number of measurement points used. In addition, a number of criteria are defined to check the adequacy of the instrumentation, and of the chosen measurement parameters (e.g. measurement surface, distance, measurement array). The criteria are based on four *field indicators* calculated from the measurements of sound intensity and sound pressure. The tests are an important part of the measurement process, since they can be used to determine the grade of accuracy of the measurement. Table 1 summarises the four field indicators and some related parameters. The field indicators can also provide guidance on possible actions to improve the accuracy of the measurements. These actions are summarised in Table 2.

2.2 Sound pressure level method

The sound pressure level method for measuring sound power, used for comparison in these studies, is defined in a draft standard ISO/DIS 230/5[5]. This is based on ISO 3744, but allows for a reduced number of measurement points. The standard defines a measurement surface comprising a rectangular parallelepiped enveloping the machine, one metre away from a reference surface that just encloses the machine. Nine measurement points are used, these being located in the centre of each face, and at each corner of the top face of the measurement surface. The sound power of the machine under test is calculated by taking the average of the nine measurements, and adding in correction factors for the size of the measurement surface and the properties of the room in which the tests take place.

3. THE WOODWORKING MACHINES

Measurements of the sound power emission of three types of woodworking machine were made. Woodworking machines were chosen for the following reasons:

(i) they are usually a 'manageable' sized type of machine for the purposes of trials,

(ii) they are most often operated as stand-alone machines, i.e. they do not normally operate as a component in a chain process,

(iii) they are often operated among other noisy machines in workshops, etc.,

(iv) current standards exist for measuring the SWL of woodworking machines using different techniques (therefore the information gathered could be compared with other data).

3.1 Planer moulder

The planer moulder had maximum dimensions of 1.25 x 2.5 x 1.36 meters (W x L x H). Lengths of wood are automatically fed through the planer at a definable feed rate, and meet four cutting blades arranged along the line of feed. The machine was situated in a large (6.4 x 27 x 34 metres), partially furnished room.

The measurement surface used for this machine was a rectangular box with dimensions of 3.25 x 4.5 x 2.36 metres. For the sound intensity measurements forty measurement points were used.

3.2 Band saw

The band saw had maximum dimensions of 1 x 2.2 x 2.65 meters (W x L x H). The wood to be cut is automatically fed onto a band saw being driven around the body of the machine. The machine table can be tilted at an angle to the main body. The band saw was situated in one end of a workshop, next to a large, open, roller shutter door.

The measurement surface used for this machine was a rectangular box with dimensions of 3 x 4.2 x 3.75 metres. For the sound intensity measurements fifty-four measurement points were used.

3.3 Router

The router had maximum dimensions of 2.2 x 2.75 x 2.4 meters (W x L x H). The router was a CNC machine and consisted of an assembly of two routerheads and two electric drills mounted over a large vacuum table. Both the table and the head assembly were able to move with respect to the main body of the router. The router was situated in a corner of a large workshop area.

The measurement surface used for this machine was a rectangular box with dimensions of 4.2 x 4.8 x 3.45 metres. For the sound intensity measurements fifty-four measurement points were used.

4. MEASUREMENTS OF SOUND POWER EMISSION

4.1 Equipment

The equipment used for the sound intensity measurements had to meet the following criteria:

- (i) capable of measuring sound intensity and sound pressure simultaneously,
- (ii) capable of storing a large number of measurements.

In addition, the following criteria were desirable:

- (iii) capable of measuring frequency content of the sound source, in addition to overall levels,
- (iv) a degree of portability in order to perform measurements in the field,
- (v) some capacity for performing calculations on the data, or ability to output data in standard formats so that calculations can be performed by an external device, e.g. computer.

The equipment used for these measurements consisted of a Brüel & Kjær Type 3545 Sound Intensity Probe, and a Brüel & Kjær Type 2133 Real-time analyser. The Type 2133 was programmed to measure both sound pressure level and sound intensity level simultaneously in third-octave frequency bands over the frequency range 50 Hz to 10 kHz, and to allow the four field indicators to be calculated. The same equipment was used for the measurements using the sound pressure level method.

4.2 Calibration

Before each set of measurements the system was calibrated for sound intensity, sound pressure and particle velocity. The calibration of sound pressure was checked following the measurements. In addition, the pressure-residual intensity index of the system was measured both at the beginning and end of the measurements (this is a quantity describing the amount of sound intensity erroneously reported by the system when the intensity is notionally zero - ideally this residual intensity is too small to affect the results).

To check the accuracy of the measurements, and the validity of the chosen measurement surface in each case, an absolute comparison test was used. This consists of a measurement of the sound power of a reference sound source (RSS). The sound power emission of the RSS with a known input signal had been measured under anechoic conditions. For each measurement case the sound power emission of the RSS was measured using the chosen measurement surface and measurement position array. The RSS was placed close to the main source of noise on each machine assessed, while the machine was not running. The result obtained from this measurement was compared with the free-field SWL of the RSS, to indicate the accuracy of subsequent measurements using the same surface and points.

4.3 Measurement procedure

4.3.1 Sound intensity method. The measurement procedure adopted for the sound intensity method was firstly to choose a suitable measurement surface and number of measurement points. Then a measurement of the SWL of the RSS was carried out with the chosen measurement arrangement, the machine itself being switched off, and the RSS placed close to the principle noise source of the machine. Following these initial measurements the SWL of the RSS was calculated, along with the field indicators for that measurement. If the SWL of the RSS was found to be close to that obtained previously under free-field conditions, and the field indicator tests indicate that the measurement configuration, environment and equipment are acceptable, then the measurements on the machine itself could proceed. If either the measured SWL of the RSS was not similar to its 'calibrated' value, or the field indicator tests suggested that there were some problems with the measurement parameters, then action could be taken at this stage to correct any problems.

4.3.2 Sound pressure method. The measurement procedure adopted for the sound pressure method was similar to that for the sound intensity method. The same measurement surface was used for each method. A measurement of the SWL of the RSS was carried out in order to calculate the environmental correction factor, K, to be used in subsequent measurements under the same conditions.

5. RESULTS

The results from the three measurements are summarised in Table 3. This shows the measured SWL of the RSS, the measured SWL of the three machines under specific operating conditions, and the results of the field indicator tests for each measurement. Also shown for comparison are the results from the sound pressure method of measuring SWL.

Figure 2 shows examples of results of the two measurement methods in terms of comparisons of sound power spectra.

The failures of field indicator tests indicated in Table 3 require some explanation. The failure of the F_4 test on the RSS while measuring the planer moulder would suggest that too few measurement points were used. This failure was not entirely unexpected, since only forty points were used for these measurements, where BS 7703 requires fifty points. However, the test was failed only in two of the twenty-four third-octave bands measured (at 400 and 500 Hz), which contribute less than 15% to the overall A-weighted sound power level of the RSS.

The failure of the two field indicator tests associated with the measurement of the router can be attributed to an enforced reconfiguration of the measurement system. The reconfiguration followed an equipment failure which occurred during the measurement.

All other failures of field indicator tests during the three sets of measurements were failed in only one or both of the lowest third-octave bands (50 and 63 Hz). Since in all cases very little sound energy was generated by the machines in these frequency bands, these failures detract little from the accuracy of the A-weighted measurements.

It should be noted that for all measurements, the '$F_2 < L_d$' test was passed, indicting that the instrumentation was performing within the tolerances required by the standard method.

6. DISCUSSION

It can be seen from Table 3 that in each of the three sets of measurements, the calculated sound power level of the RSS according to BS 7703 is within 1 dB of the calibrated SWL of 104.4 dB(A). Although not shown here, levels in individual third-octave bands were similarly close. It would therefore seem reasonable to attribute this degree of accuracy to all other measurements made with the same method and measurement array.

The graphs in Figure 2 indicate that the sound intensity method gives very similar results to the established sound pressure method. It is noticed that the sound intensity method tends to produce slightly lower A-weighted sound power levels.

The results of the field indicator tests have been discussed. They suggest that in each case, the instrumentation (sound intensity probe and microphone pair) performed well. Any failures are seen to arise either from a failure to apply the standard method rigorously (i.e. number of measurement points), or from a lack of 'information' in the sound energy distribution of the source.

The use of the RSS to provide a check of the measurement parameters illustrates the need to have some on-site facility for performing calculations on the data. If the calculations of SWL and the field indicators cannot be carried out at the time of the measurements, much time could be lost in having to repeat measurements, where a relatively simple check at the time could have identified any problem.

The major advantages of the sound intensity method over conventional methods for estimating sound power level are;

(i) the measurement can be carried out in a 'hostile' environment, i.e. indoors in the presence of background noise,

(ii) the method could also be considered to be more accurate, in that it uses a large number of measurement points distributed over the surface of the machine. This means that if a noise source produces a highly directional sound field, the sound intensity method is more likely to detect localised areas of high noise level. A measurement method using a small number of measurement points is more likely to miss these localised 'hot-spots', and could easily underestimate the sound power emission of the source.

A further advantage of the sound intensity method defined in BS 7703 is that it contains a number of tests to quantify the accuracy of the measurements, and provides a 'decision tree' to guide the user towards improving the accuracy if the test results indicate that this is necessary.

A disadvantage of the sound intensity method is that it can be time consuming, because of the large number of measurements required. Also, it needs specialised measurement equipment, and data manipulation facilities, preferably built-in to the instrumentation.

7. CONCLUSIONS

The sound intensity method of measuring sound power level defined in BS 7703 gives results in workplace situations which are comparable with free-field measurements. Field indicator tests show that, by taking a sufficient number of measurement points around a machine, high levels of accuracy can be obtained.

Comparisons with a sound pressure measurement method indicate that the two methods give similar results for machines with uniform sound fields. It is suggested that the sound intensity method, with its greater density of measurement points, would be more accurate in measuring on machines with non-uniform or highly directional sound fields.

The sound intensity method must be recommended over other methods such as the ISO 3740 series for situations where anechoic facilities are not available or practicable, and for its greater accuracy in non-uniform sound fields.

8. REFERENCES

[1] OFFICIAL JOURNAL OF THE EUROPEAN COMMUNITIES, "Council Directive on the approximation of the laws of the Member States relating to machinery" 89/392/EEC

[2] INTERNATIONAL STANDARDS ORGANISATION, "Acoustics - Determination of sound power levels of noise sources - Engineering method employing an enveloping measurement surface in an essentially free-field over a reflecting plane." ISO 3744-1981

[3] INTERNATIONAL STANDARDS ORGANISATION, "Acoustics - Determination of sound power levels of noise sources - Survey method employing an enveloping measurement surface over a reflecting plane." ISO 3746-1981

[4] BRITISH STANDARDS INSTITUTION, "Acoustics - Determination of sound power levels of noise sources using sound intensity. Part 1: Measurement at discrete points" BS 7703 : Part 1: 1993

[5] INTERNATIONAL STANDARDS ORGANISATION, "Acceptance code for machine tools - Part 5: Noise", Draft International Standard ISO/DIS 230/5

Table 1. Summary of field indicators

Parameter	Description
F_1	Qualifies the degree of steadiness with respect to time of the total field, in terms of the normalised standard deviation at a control position.
F_2	Measure of the phase mismatch in terms of the pressure-intensity index (using the magnitude of intensity)
F_3	Measure of the 'global' pressure-intensity index using signed intensity. (Large differences between F_2 and F_3 indicate substantial power flow into the source).
F_4	Relates to the normalised standard deviation of the averages, and the minimum number of points (N) to produce a 95% confidence in average intensity.
L_d	Dynamic capability index, relating to the pressure-residual intensity index and the precision of measurement (a characteristic of the instrumentation).
C	Constant relating to the degree of accuracy of the F_4 test.

Table 2. Actions to be taken on failure of field indicator tests

Test	Action
$F_1 > 0.67$	Take action to reduce the temporal variability of extraneous intensity or measure during periods of less variability or increase the measurement period at each position (if appropriate).
$F_2 > Ld$, or $F_3 - F_2 > 3dB$	Reduce average distance of measurement surface from source, or Shield measurement surface from extraneous noise sources or take action to reduce some reflections towards the source.
$N < CF_4$ and $1dB < F_3 - F_2 <= 3dB$	Increase the density of measurement positions uniformly in order to satisfy $N > CF_4$.
$N < CF_4$ and $F_3 - F_2 <= 1dB$	Increase average distance of measurement surface from the source using the same number of measurement positions or increase number of measurement positions on the same surface.

Table 3. Summary of the results from the three measurements

Machine	Measurement	Sound intensity method, and field indicator tests					Sound pressure method	
		SWL (dB(A))	$F_1 < 0.67$	$F_2 < L_d$	$F_3 - F_2$	$N > CF_4$	SWL (dB(A))	K (dB)
Planer moulder	RSS	104.9*	pass	pass	pass	*fail*	104.4†	3.7
	Idling	95.6	pass	pass	*fail*	*fail*	94.6	
	Cutting	104.9	pass	pass	*fail*	*fail*	104.0	
Band saw	RSS	105.4*	pass	pass	pass	pass	104.4†	5.1
	Idling	-	-	-	-	-	94.8	
	Cutting	103.0	pass	pass	pass	*fail*	103.3	
Router	RSS	104.1*	pass	pass	pass	pass	104.4†	3.8
	Idling	-	-	-	-	-	94.2	
	Cutting (with extraction)	99.9	pass	pass	*fail*	*fail*	99.7	
	Cutting (without extraction)	-	-	-	-	-	97.1	

*Calibrated SWL of the RSS is 104.4 dB(A)
†By definition, equal to the calibrated SWL of the RSS
NOTE: See text for a fuller explanations of the 'fail' markings

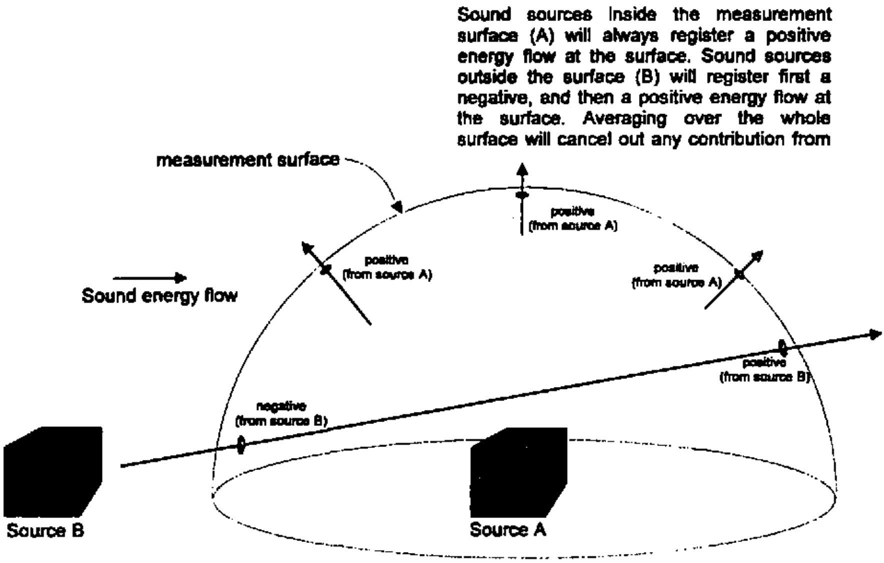

Figure 1. Illustration of the way in which the sound power level of a source can be measured in the presence of other sources.

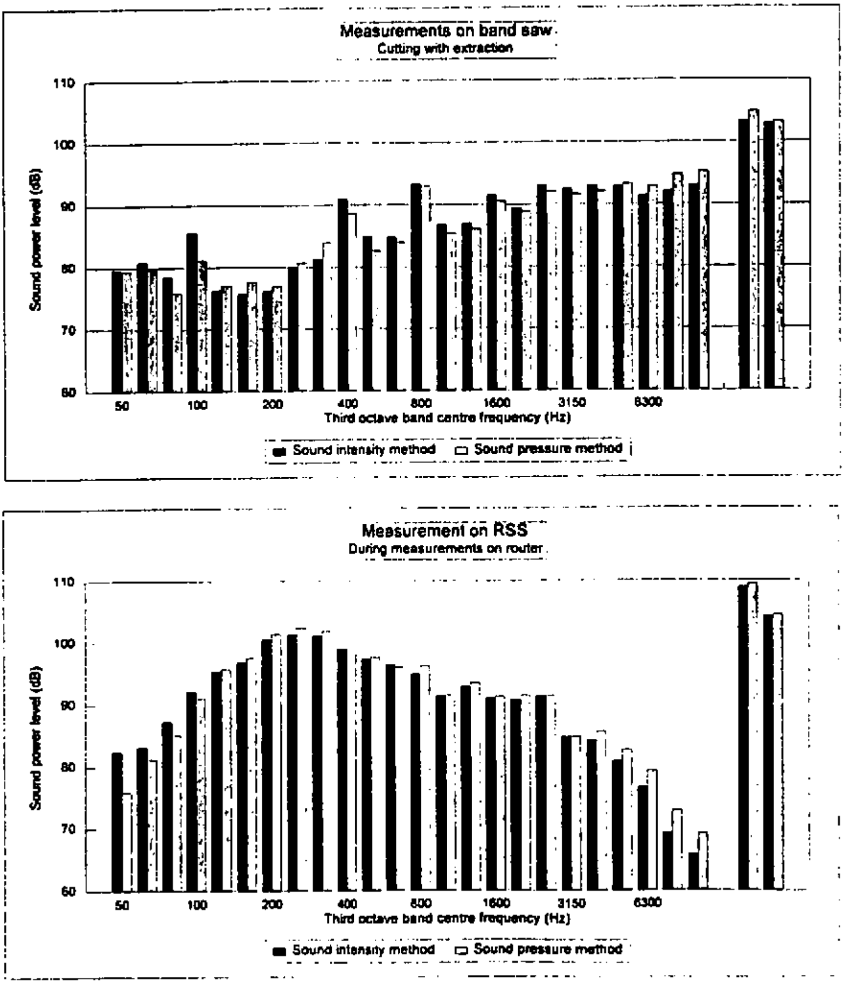

Figure 2. Comparison of methods of calculating sound power level