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SOUND POWER MEASUREMENT USING ACOUSTIC INTENSITY to ISO9614: Pt 1 - A CASE STUDY

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1. INTRODUCTION

Conventional standards for the measurement of Sound Power, [1]-[2], that rely solely on the measurement of Sound Pressure suffer from a number of drawbacks when measurements are attempted in workplace environments. The two main difficulties are that the acoustic environment is less than ideal and that measurements will be affected by other noise sources outside the measurement surface. This in many instances meant that machinery had either to be moved to special test environments or to commercial test houses in order that the sound power of the equipment could be obtained. In the late 1970s and early 80s Fahy, [3], and Chung, [4], showed that the Acoustic Intensity could be derived from the cross spectrum between two microphone signals. This, combined with the rapid developments that had taken place in analysis and measurement instrumentation, formed the basis for a practical Instrument that could actually measure Intensity rather than solely Sound Pressure. The benefits that intensity has is that it is the true measure of energy flow at a point and is a vector quantity. Consequently, if measurements are carried out around a surface enveloping a source the intensity due to extraneous noise (assuming of course this is stable with time) cancel and a true measure of the test source is obtained. The other consequence is that the technique is tolerant of the acoustic environment and is limited only by the quality and accuracy of the measurement instrumentation. This opens up the possibility of carrying out Sound Power measurements in areas that would not have been possible with Sound Pressure based standards and means that in many cases equipment does not have to be moved to special test areas. It was some time before an International Standard was produced, [5], although it had been available in draft format since 1989. Since the issue of the draft standard, NEL has carried out Intensity measurements on approximately 20 or so pieces of equipment in accordance with the Draft and latterly the full issue of ISO9614:pt 1 in a wide variety of acoustic environments. This paper presents an overview of the standard and a case study of one of these measurements.

2. ISO 9614: Part 1

Before looking at the case study it is worth spending some time looking at the main points of the standard. The first major point is that the current standard is based on measurements at fixed or "discrete" points around the machine. A "scanning" method, [6], is due for publication and will form Part 2 of the standard and provide the user with an alternative way of performing the measurements. The second major point is that the standard covers all three grades of accuracy; Precision, Engineering and Survey. The actual grade of accuracy achieved in a measurement is determined retrospectively.

In essence, the standard fragments the entire measurement surface into a number of segments, fig. 1, and a measurement of Sound Pressure *and* Sound Intensity is carried out in the middle of each segment. The power through any one segment is obtained simply by multiplying intensity by the segment area. The total Sound Power is obtained by adding up the Sound Power from all segments.

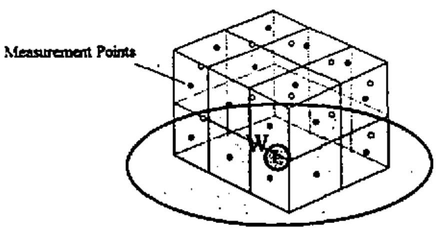


Figure 1.

The standard is only valid between the 50Hz to 6300Hz 1/3 Octave bands (63Hz to 4000Hz Octave bands) but some measurements should be carried out in the 31Hz, 40Hz, 8kHz and 10kHz bands to check the validity of the A-weighted total. A typical measurement sequence would consist of the followed stages;

a) Prior to actual measurements, checks are carried out to calibrate the instrumentation by measuring its "dynamic capability", L_d, and to confirm the stability of the sound field with time by measuring a "Temporal Variability" field indicator, F_1. The value of L_d is obtained by subtracting a "bias error factor" (either 7dB for Survey accuracy or 10dB for Precision and Engineering accuracy) from the instrumentation's "pressure residual intensity index", δ_{pIo}. This can either be re-measured prior to each measurement campaign (the preferred method used by NEL) or recalled from a previous occasion. F_1 is used to determine the common averaging time to be employed for each measurement point.

b) Define the measurement surface. This should be no closer than 0.5m (on average) from the source surface. At least 10 positions should be used with a minimum of 1 position/m² although 50 positions can be used if the total surface area is greater than 50 m².

c) Carry out background noise checks. Measure A-weighted L_p at 5 positions and compare against L_p with machine running. This need not be done if the source drives other sources of significant extraneous noise outside the measurement surface.

d) Perform the actual measurements using a wind shield if outdoors or if the wind speed is greater than 2 m/s.

e) After measurement a number of further field indicator checks are carried out on the captured data to determine the validity and accuracy of the measurement. Refer to the standard, [5], for the formula for each indicator. In addition to F_1, three other indicators are used. These are:

F_2 - The "Surface Pressure Intensity" indicator. This checks the variation of the sound field and the difference between the Sound Pressure and the Intensity from the captured data. It performs a calculation based purely on the magnitudes of the differences between Sound Pressure and Intensity.

F_3 - The "Negative Partial Power" indicator is very similar in concept to F_2 but the calculation is based on the differences between Sound Pressure and Intensity taking into account the sign of the intensity (i.e. either + or -) of the captured data.

F_4 - The "Field Non-Uniformity" Indicator - is used to check whether sufficient measurement points have been used to achieve the desired grade of accuracy.

The two main checks are: **Criterion 1** given by $F_2 < L_d$ and **Criterion 2** given by $N < C.F_4^2$ (N being the number of measurements and C being a factor given in the standard). Criterion 1 checks the measured sound field against the probe accuracy to determine the validity of the captured data. Criterion 2 is used to determine the accuracy grade that has been achieved on a band-by-band basis. A third check is carried out to see if F_3-F_2 is less than 3dB or less than 1dB; this indicates the importance of extraneous noise, reflecting surfaces and source directivity.

3. CASE STUDY

3.1 The Unit Under Test - Pump Skid.

Figure 2 shows the actual unit being tested. This consisted of a skid with a number of sources such as pumps, motors and mixing agitators. Figure 3 shows the test shop layout where measurements were performed. The pump skid was approximately 3m x 5m x 3.7m in size and sat close to an equally large mixing tank skid. Measurements were carried out on both units but results for the mixing tank are not included here.

3.2 The Measurement Grid.

To perform the measurements the measurement surface was defined 0.7m out from the major machine outline and as shown in figure 4. This split the surface into a total of 51 segments grouped into 7 separate zones having the same segment area. To physically perform the measurements the grid baseline only is marked on the test shop floor and the location of vertical rows of points marked on this. Due to the height of the machine, measurements were made in columns at each baseline position using a pole marked out to pre-set heights as a guide. The operator was able to walk over the skid's superstructure to reach the measurement locations on the top surface. As can be seen from the grid layout, the adjacent mixing tank was treated as a reflecting plane since it was too close to the pump skid to allow measurements to be carried out along that face. This is quite standard practice to treat large areas such as a tank wall as a reflecting plane if it would interfere with the measurements. This can obviously only be done if the plane itself is rigid and does not radiate noise. In the above case the mixing unit was not running so did not in itself contribute to the noise.

3.2 Recording of Measured Data.

All of the data was captured using a Brüel & Kjær 2133 Analyser fitted with a Type 3545 Intensity Probe using ½ inch microphones with a 12 mm spacer. Prior to measurement, the systems was calibrated using a Type 3541 Intensity calibrator to measure δ_{pIo}. The measurement sequence was controlled by B&K software and all data stored on floppy disc. The software performs the "field indicator" calculations so that the Criterion 1 and Criterion 2 checks can be evaluated. Measurements are normally collected in 1/3 Octave bands.

3.3 Documentation of Test Results & Data.

Over the time that NEL have been carrying out Intensity measurements, we have developed a system of recording relevant information which is based around the use of what we have called "Measurement Record Data Sheets". Figure 5 shows an example of the data sheet 2 of the above case study. Sheet 1 is not shown but this normally includes details of the unit under test, the environment, instrumentation etc... These sheets provide a condensed form of all information required to evaluate the Sound Power from the captured data including the results of the various field indicator checks mentioned in section 2. Most of the information on Sheet 1 is gathered prior to measurement whilst Sheet 2, fig 5, can only be completed after the measurements have been completed.

3.4 Derivation of Accuracy.

The data contained in Sheet 2 forms the basis of that required to determine the accuracy of the measurement. The standard does not give good guidance on the derivation of Overall accuracy so NEL have developed an approach which is based on an assessment of individual 1/3 Octave bands. Since a measurement can contain some bands with a "negative" intensity (which are outside the scope of ISO9614) any such bands must not be included in the A-Weighted or Linear totals so a manual addition of bands has to be performed to assess the Overall levels. Similarly, the standard is only valid in the 50Hz to 6300Hz 1/3 Octave bands and only data in this range should be added together. The approach we have adopted is to use the accuracy for the 1/3 Octave bands that can be obtained by direct application of the standard. To obtain Octave band accuracies, the three 1/3 Octave bands are added in order of grade of accuracy (i.e. all in Precision first, then all in Precision+Engineering, then all in Precision+Engineering+Survey etc...) and a check carried out on each stage of the addition to see whether the band total has changed by more than the standard deviation for that accuracy class. If the total changes by more than the allowed amount the accuracy of the band is moved one class lower (e.g. from Engineering to Survey). A similar procedure is followed to add *all* 1/3 Octave bands together to obtain overall Linear and A-Weighted totals.

3.5 Case Study Result.

Table 1 shows the Sound Power results derived from the measurements. Generally in the machines we have tested we have found that an Engineering Grade can be achieved for the A-Weighted total.

	Frequency Band (Hz)									
	63	125	250	500	1000	2000	4000	6300	Lin Total	A-Wt Total
dB(re 1pW)	90	91.6	99.6	104.2	110.9	110.5	99.8	84.2	114.5	114.6
Accuracy Grade	O	O	2	2	3	2	2	1	3	2

Table 1. Octave Band Sound Power Levels and Accuracy Achieved

The results of the field indicator checks, fig 6, showed that the reduced accuracy in all bands below 200Hz is due to low accuracy of the probe. This is known to be due to the fact that the microphone configuration was reversed to ease measurements on the upper surface. The 400Hz band is due to the proximity of reflecting surfaces (since F_3-F_2 >3dB) but possibly also affected due to the fact that F5 failed. The 800Hz and 1000Hz bands both have reduced accuracy due to source directivity (since F_3-F_2<1dB). All factors considered, the overall accuracy was to class 2.

4. GENERAL OBSERVATIONS

4.1 Accuracy of the Measurements.

It should be noted that one of the main factors that determines the validity of the measured data is the **Criterion 1** test; i.e. $F_2 < L_d$. This is directly related to the accuracy of the instrumentation system and can mean the difference between obtaining a result that is within the scope of ISO 9614 or one that fails. We would advise users to check the performance of their Intensity probes (i.e. measure the system's δ_{pIo}) on a regular basis or preferably immediately prior to a measurement campaign. Care should be taken when carrying out such checks in the field since we have found that any vibration of the calibrator base can adversely affect the apparent δ_{pIo} measured.

4.2 Choice of Averaging Time & Time Taken to Complete Tests.

The F_1 indicator is used to determine the common averaging time per point. A compromise has sometimes to be struck if the test for F_1 fails and a long averaging time needs to be used since this may make measurements impracticable due to the lengthy time required to complete all measurements. We have found it useful to refer to the L_p spectrum to determine if the failure is in a band that will not contribute significantly to the total. One of the potential drawbacks of ISO9614: Pt 1 is the number of measurement points that have to be used. For large machines, or where ladders have to be used to reach the upper measurement points, we have found that the complete measurement of the surface at one running condition will take roughly 3 times the number of measurement points, N, times the averaging time, t, per location; i.e. 3.N.t. Therefore, in the case described above, the measurements took approximately 1½-2 hours to complete (excluding the time for setup and calibration). For small machines, or where there is easy access to all measurement points, the total measurement time will be much less; perhaps only 1½.N.t. The measurement time could however pose problems and adequate precautions should be taken to ensure sufficient cooling is available and that the machine load remains constant throughout the duration of the tests. If the load drifts or the machine has to be stopped to allow it to cool then this will almost certainly result in a lower grade of accuracy being achieved for the measurements.

4.3 Acceptability of Accuracy Grade Achieved.

The standard provide comprehensive guidance on the interpretation of the results of the various field indicator checks and the steps that can be taken to improve accuracy of the results. The approach we have adopted in all our measurements has, to-date, been to accept the grade of accuracy achieved but qualify this with an explanation of why this has been achieved. If the accuracy is to be improved then some, or all, of the previous measurements may have to be repeated. Unless a complete failure of the measurements occurs, we would not advocate repeating any measurements due to the time this takes. As mentioned, we have normally been able to achieve Engineering grade on A-Weighted total using this approach.

4.4 Microphone Spacing and Microphone Size.
The spacer between the microphones can be changed to alter the frequency range covered by the measurements. The standard spacer for ½ Microphones is 12mm which gives coverage up to 7.3kHz with a 2dB error (5.3kHz with a 1dB error). The low frequency limit is dictated by the accuracy of the probe and instrumentation system. Changing to a 50mm spacer may improve accuracy at low frequency (below 100Hz) but the upper 2dB limit drops to 1.8kHz so this cannot be used to cover the full 50-6300 Hz frequency range of the standard. Again, due to the practical constraints frequently imposed by the time available for measurements, a double pass of the measurement surface is seldom desirable. In choosing which spacer to use we would recommend the Sound Pressure Level spectrum at a representative position is examined to determine which portion of the spectrum is important. If the A-Weighted total is the main concern, then lower frequencies are less important so this should also be taken into consideration. One final point that is worthy of note is that ½ inch microphones are the most commonly used size and intensity calibrators (e.g. the B&K Type 3541) are designed for this size. An alternative microphone is the ¼ inch size and these can be used to measure intensity up to 10 kHz if fitted with a 6mm spacer. We would advise caution in the use of this size since to-date there is no calibrator available that allows the measurement of δ_{pI_0} for ¼ inch microphones hence the Criterion 1 test cannot be carried out.

5. OTHER USES FOR SOUND INTENSITY

Although this paper has concentrated on the use of intensity to obtain sound power, it has two main other uses which are worthy of note. Since the earliest days of intensity measurement the technique was used more for source location than for actual sound power measurements. Today, the technique is still a powerful tool that can be used to "map" the sound field over a surface and obtain contours of intensity which can be related to the locations of noise sources. Measurement are carried out at a large number of fixed points on the surface and these points form the basic information that is used to plot the 2-D contours. The other use, which is a more recent one, is to do "sound field holography" which effectively is a 3-D map of Intensity on a surface. This form of map is developed by again carrying out fixed point measurements but for each measurement location the intensity is measured in each of three mutually perpendicular axis. This allows the flow of noise to be plotted and is useful not only for source location but also to track the energy flow in the sound field.

6. CONCLUSIONS

The main conclusion that we at NEL have reached is that Acoustic Intensity is a viable method of obtaining Sound Power Levels in-situ in cases where other standards would be unworkable. Caution and a high degree of operator skill are however required to perform and interpret the results of the field indicator checks.

7. REFERENCES

[1] ISO 3744 - 1994. Acoustics - Determination of sound power levels of noise sources - Engineering methods for free-field conditions over a reflecting plane. (BS has not been updated yet)

[2] ISO 3746 - 1979. Acoustics - Determination of sound power levels of noise sources - Survey method. (Equivalent to BS 4196 : Part 6 : 1981)

[3] Fahy, F.J. - Measurement of acoustic intensity using the cross-spectral density of two microphone signals. J. Acoust. Soc. Amer., 62(L) (1977), 1057-9.

[4] Chung, J.Y. - Cross-spectral method of measuring acoustic intensity without error caused by instrumentation phase mismatch. J. Acoust. Soc. Amer., 64 (1978), 1613-16.

[5] ISO 9614 - 1: 1993. Acoustics - Determination of sound power levels of noise sources using sound intensity - Part 1: Measurements at discrete points. (No BS equivalent yet).

[6] ISO/DIS 9614 - 2 (Committee draft). Acoustics - Determination of sound power levels of noise sources using sound intensity - Part 2: Measurements by scanning.

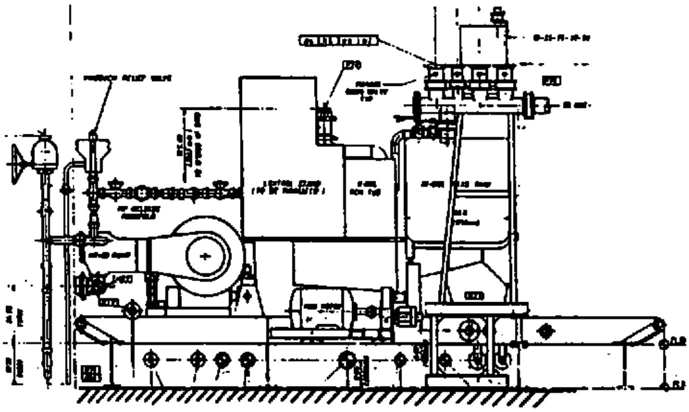


Figure 2. Pump Skid

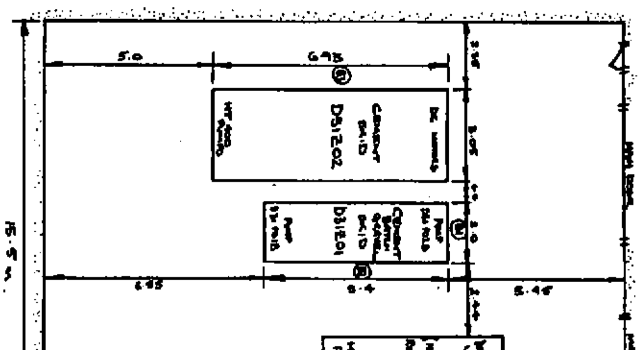
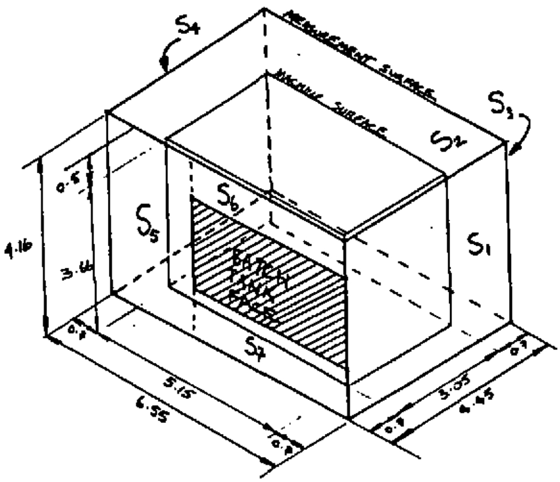
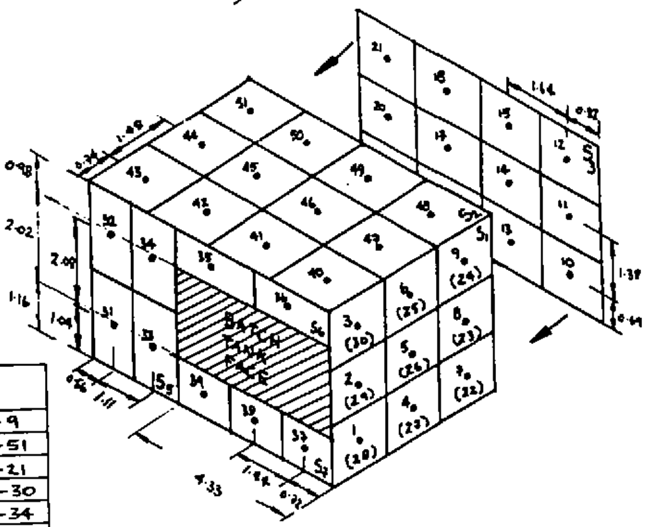


Figure 3. Floor plan of test area

ACOUSTIC INTENSITY CASE STUDY





Surface	Area	No. Points	Ref
S1	18.512	9	1–9
S2	29.15	12	40–51
S3	27.25	12	10–21
S4	18.512	9	22–30
S5	9.23	4	31–34
S6	4.24	2	35–36
S7	5.02	3	37–38
S8	–	–	–
S9	–	–	–
S10	–	–	–
S11	–	–	–
S12	–	–	–
TOTAL	111.91	51	

Figure 4. Intensity measurement grid

Acoustic Intensity (ISO/DIS 9614-1) Measurement Record

Reference Number	551/90	Unit	PUMP SKID	Page 2 of 2
Analysis		1/1 Octave	✓ 1/3 Octave	1/12 Octave
Average Sound Pressure	dB(A)			
Failure Bands				

Band Centre	F5 52 Secs	F2<Ld	F3-F2<3dB	N>C.F4^2 Class 3	Class 2	Class 1	F3-F2<1dB	Power dB re 1pW +	Power dB re 1pW −	A Weight dB	Power dB(A) +
50		×					×	/	98.5	-30.2	/
63		×	×	×	×	×	×	86.0	/	-26.2	59.8
80	×	×				×	×	87.8	/	-22.5	65.3
100		×					×	85.0	/	-19.1	65.9
125		×					×	88.0	/	-16.1	71.9
160		×						87.0	/	-13.4	73.6
200		×						89.8	/	-10.9	78.9
250						×	×	95.0	/	-8.6	86.4
315	×					×	×	97.0	/	-6.6	90.4
400	×		×	×	×	×	×	99.0	/	-4.8	94.2
500								95.5	/	-3.2	90.3
630						×	×	102.0	/	-1.9	100.1
800					×	×		107.1	/	-0.8	106.3
1000					×	×		107.2	/	+0.0	107.2
1250						×		102.5	/	+0.6	103.1
1600						×		106.8	/	+1.0	107.8
2000						×		109.0	/	+1.2	108.2
2500						×		101.5	/	+1.3	102.8
3150						×		98.5	/	+1.2	99.7
4000						×		92.5	/	+1.0	93.5
5000						×		87.8	/	+0.5	88.3
6300								84.2	/	-0.1	84.1
							TOTAL	114.5			114.6

A-Weight Check

Band Centre	Lw dB re 1pW +	Lw dB re 1pW −
25		/
31.5		/
40		/
8000	81	/
10000	79	/

Additional Comments

1. Lw poor due to probe reversal to ease measurements on top measurement surface (S1)
2.

National Engineering Laboratory — Intens v3.0

Figure 5. Measurement record sheet