Investigation on standardised sound intensity methods for the determination of the sound power level of hydraulic pumps

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The new test code (ISO 16902 - 2003) for the determination of sound power levels of hydraulic fluid power pumps using sound intensity techniques intends to greatly simplify the measurement of the noise generated by these components. In fact, the methods based on sound pressure measurements require a very specialized and costly test environment due to the fact that the fluid-borne and structure-borne vibrations of the pump can be transmitted to the whole hydraulic circuit. Moreover, this propagation gives rise to background noise levels which could greatly affect the measurement of the airborne noise emitted by the pump.

This paper reports the results of an experimental investigation intended to identify which of the three standardised methods for determining the sound power using sound intensity (series ISO 9614 part 1 to part 3) is the most suitable when it is applied to determine the airborne noise generated by an hydraulic fluid power pump. The comparison among these three test codes should confirm or reject the expectation reported in the Introduction to ISO 16902, saying that for these sources just an "engineering" or "survey" grade of accuracy can be achieved.

Measurements were carried out on a gear pump mounted on a specific hydraulic circuit under controlled conditions of installation and operation. The measurement surface had a parallelepiped shape and three different arrays of measurement positions and three different scanning paths were selected for discrete points (9614-1) and scanning procedures (9614-2 and 3), respectively.

1 Introduction

In recent years, manufacturers of machine components have been requested by their customers to pay attention to the noisiness of their products, even if no legislation applies to these products directly.

For hydraulic components a new test code intended to simplify the noise data acquisition was published in 2003. It defines the installation and the mounting conditions for the components but refers to ISO 9614 for the determination of the sound power level. Whichever part (1, 2 or 3) of the latter standard is selected, sound intensity measurements can be carried out even in presence of extraneous noise, as long as it is stationary over time and coming from sources placed outside the measurement surface. Anyway, the accuracy of the measurement is sensitive to local differences and each part of the Standard has field indicators and procedures that have to be evaluated in order to achieve the desired grade of accuracy according to Table 1.

Table 1: Achievable grades of accuracy with ISO 9614

Measurement	Part	Precision (grade 1)	Engineering (grade 2)	Survey (grade 3)
Discrete points	1	x	x	x
Scanning	2		x	x
	3	x		

This paper reports the results of the tests based on part 1, 2 and 3 of ISO 9614. The authors already reported extensively on part 1 and 2 in other works [1,2].

2 Experimental tests

The experimental setup and the measurement surface do not depend on the method chosen for sampling the intensity field normal to the measurement surface (by discrete points or by scanning). The tests differ among them in terms of measuring procedure and measuring time, as explained in sections 2.2.1 and 2.2.2.

2.1 Experimental set-up

A group 1 (size B) pump with 12-tooth gears and a displacement volume of 3.2 cm^3 was mounted on a hydraulic test rig. The operating conditions of the whole system were constantly checked with suitable gauges and the working pressure and temperature were hold at values of 150 bar and 60 °C, respectively.

According to one of the mounting conditions suggested by ISO 16902, a concrete wall with pipes passing through it was built at pump mounting face and the prime mover had a non-rigid support. The size of the reflecting wall depends on the lowest characteristic emission frequency of the pump (296 Hz).

All the measurements were carried out in a large shed, in presence of stationary background noise. A constant speed electric motor was driving the shaft at 1480 rpm.

2.2 Data acquisition

Measurements were made by means of a monoaxial sound intensity probe equipped with ½" microphones and a 12 mm spacer and connected to a B&K Pulse multi-channel analyser.

The measurement surface was the same for all the sampling methods and had a parallelepiped shape with dimensions 0.59x0.39x0.23 m^3. The pump inlet and outlet pipes were both included within the surface. The measurement surface was divided in 5 rectangular partial surfaces equivalent to the parallelepiped sides.

Three different measurement arrays (5x2x3, 6x3x4, 9x4x6) were defined on the surface and were used for all the three sampling methods.

The component of the sound intensity vector normal to the measurement surface and the mean pressure between the transducers were acquired in one-third octave bands within the range 200÷6300 Hz.

For each array and for each sampling method the acquisition was repeated three times in order to check the repeatability of the results.

2.2.1 Measurement at discrete points

For measurements accordant with ISO 9614-1, the three measurement arrays were different because of the number of measurement points uniformly distributed over the entire surface.

The first array (5x2x3) had 47 measurement points: 15 on the frontal side, 6 on each lateral side and 10 points both on the top and the bottom sides. The second array (6x3x4) had 84 measurement points: 24 on the frontal side, 12 on each lateral side and 18 points both on the top and the bottom sides. The third array (9x4x6) had 174 measurement points: 54 on the frontal side, 24 on each lateral side and 36 points both on the top and the bottom sides.

The measuring time for each point was 32 s. The movement of the sound intensity probe was computer-controlled by an automatic positioning system with three degrees of freedom that was developed in order to reduce as much as possible the acquisition time.

2.2.2 Measurement by scanning

For measurements performed by scanning (ISO 9614-2 and ISO 9614-3), the three measurement arrays were different because of the scan-line density on each partial surface.

The first array (5x2x3) had: 3 horizontal e 5 vertical lines on the frontal side, 3 horizontal e 2 vertical lines on each lateral side and 2 horizontal e 5 vertical lines both on the top and the bottom sides. The second array (6x3x4) had: 4 horizontal e 6 vertical lines on the frontal side, 4 horizontal e 3 vertical lines on each lateral side and 3 horizontal e 6 vertical lines both on the top and the bottom sides. The third array (9x4x6) had: 6 horizontal e 9 vertical lines on the frontal side, 6 horizontal e 4 vertical lines on each lateral side and 4 horizontal e 9 vertical lines both on the top and the bottom sides.

The scan was carried out manually with a scanning speed as constant as possible.

For measurements accordant with ISO 9614-2, on each partial surface, two orthogonal scanning paths were selected. Therefore, the average scan-line density was 8,3 m^{-1} for the first array (5x2x3), 11,2 m^{-1} for the second array (6x3x4) and 16,1 m^{-1} for the third array (9x4x6). On partial surfaces with too short scanning paths, the scan was repeated several times on the same path to fulfil the requirement of a scanning time greater than 20 s but with a speed ranging from 0,1 to 0,5 m/s.

For measurements accordant with ISO 9614-3, on each partial surface the scan was performed twice on a chosen scanning path (horizontal). Therefore, the average scan-line density is slightly different from that reported previously. Moreover, in this set of tests, the number of segments into which each partial surface was divided were equal to the number of measurement points selected for ISO 9614 part 1. The first array (5x2x3) had an average scan-line density of 8,1 m^{-1} with 47 segments. The second array (6x3x4) had an average scan-line density of 11,2 m^{-1} with 84 segments. The third array (9x4x6) had an average scan-line density of 16,2 m^{-1} with 174 segments. The scanning time for each scan was determined by the averaging time that satisfied the test of temporal variability multiplied by the number of segments, on condition that the scanning speed do not exceed 0,5 m/s.

3 Results

For each sampling method, the grade of accuracy was evaluated according to the field indicators and to the procedures provided for by the Standards.

3.1 Measurement at discrete points

For measurements accordant with ISO 9614-1, Table 2 reports the results obtained for each run (I, II and III) on each measurement array (5x2x3, 6x3x4 and 9x4x6). These results are expressed in terms of: overall linear and A-weighted sound power levels over the range 200 ÷ 6300 Hz; time necessary to complete each run; checking for the adequacy of the measurement equipment; checking for the presence of strongly directional extraneous sources; checking for the adequacy of the array of measurement positions.

The frequencies that failed these verifications are explicitly indicated.

Table 2: Overall levels and checking of the criteria indicated in ISO 9614-1

Array	Run	L_W dB	L_{WA} dB(A)	Criterion 1 ($F_2 < L_d$)			F_3-$F_2 \leq 3$ dB	Criterion 2 ($N > C \cdot F_4^2$)		
				grade 1	grade 2	grade 3		grade 1	grade 2	grade 3
5x2x3 N=47 Time=1h30'	I	60.0	60.5	OK	OK	OK	Not at 630 Hz	Not at 630, 1k, 3.15k, 4k Hz	Not at 630, 4k Hz	OK
	II	60.7	61.2	OK	OK	OK	Not at 630 Hz	Not at 400, 630, 1k, 2.5k, 3.15k, 4k Hz	Not at 630 Hz	OK
	III	61.1	61.6	OK	OK	OK	OK	Not at 630, 1k, 2k, 2.5k, 3.15k, 4k Hz	Not at 630 Hz	OK
6x3x4 N=84 Time=2h	I	61.7	62.2	OK	OK	OK	OK	Not at 630, 2k, 3.15k, 4k Hz	OK	OK
	II	61.4	61.8	OK	OK	OK	Not at 630 Hz	Not at 630, 3.15k, 4k Hz	Not at 630 Hz	OK
	III	62.1	62.6	OK	OK	OK	OK	Not at 1k, 3.15k, 4k Hz	OK	OK
9x4x6 N=174 Time=3h	I	59.8	60.3	OK	OK	OK	Not at 630 Hz	Not at 630 Hz	Not at 630 Hz	OK
	II	61.4	61.9	OK	OK	OK	OK	OK	OK	OK
	III	61.2	61.6	OK	OK	OK	OK	OK	OK	OK

Data reported in Table 2 show that the attainable grade of accuracy differs among the arrays: the precision grade is achievable with the 9x4x6 array of points, while the 6x3x4 and 5x2x3 configurations lead to the engineering grade and survey grade, respectively. For measurements aimed at obtaining only the A-weighted sound power level, also the 5x2x3 configuration could lead to a sound power level with an engineering grade of accuracy, on condition that the component (630 Hz) not satisfying both F_3-$F_2 \leq 3$ dB and criterion 2 is excluded. This omission is allowed by the Standard as this noise component has a level almost 15 dB lower than the highest A-weighted band level.

3.2 Measurement by scanning

For measurements performed by scanning (ISO 9614-2 and ISO 9614-3), Table 3 and Table 4 report the results obtained on each run (I, II and III) by two operators (A and B) for each measurement array (5x2x3, 6x3x4 and 9x4x6). These results are expressed in terms of overall linear and A-weighted sound power levels over the range 200 ÷ 6300 Hz. The time necessary to complete each run is also indicated.

3.2.1 ISO 9614-2

Since this part of the Standard attains at most the engineering grade of accuracy, the procedures for achieving it seemed to be less restrictive then those required by ISO 9614-1.

Nevertheless, the fulfilment of criterion 3 (partial power repeatability check) turned out to be extremely difficult and no run satisfied that requirement in every frequency band. On the contrary, criteria concerning both the evaluation of instrument capability (criterion 1: $F_{pI} < L_d$) and of negative partial power (criterion 2: $F_{+/-} \leq 3$ dB) achieved engineering grade of accuracy except for two runs: 6x3x4 array - operator B - III run (630 Hz) and 9x4x6 array - operator A - II run (500 and 800 Hz).

If criterion 3 is not fulfilled, section 8.3.1 of the Standard provides for an additional test in order to check whether the sum of the partial sound powers passing through partial surfaces on which criterion 3 is not satisfied is more than 10 dB below the source sound power determined from the remaining partial powers passing through partial surfaces on which criterion 3 is satisfied. This additional test failed again in any case. Anyway, in four runs the failure occurred at frequencies with band levels that were negligible in the determination of the overall sound power level. Therefore, if only an A-weighted sound power level had been required, engineering grade of accuracy could have been achieved for: 6x3x4 array - operator A - I run; 6x3x4 array - operator A - II run; 6x3x4 array - operator B - I run and 9x4x6 array - operator A - II run.

Table 3: Overall levels for measurements according to ISO 9614-2

	5x2x3 array Time=15'						6x3x4 array Time=20'						9x4x6 array Time=25'					
Operator	A			B			A			B			A			B		
Run	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
L_W *dB*	60,5	60,7	60,7	60,8	60,8	61,1	60,1	60,2	58,6	60,8	59,8	60,2	60,9	61,1	60,9	61,0	61,1	60,9
L_{WA} *dB(A)*	61,3	61,4	61,3	61,5	61,5	61,7	60,7	60,8	59,1	61,4	60,5	60,9	61,5	61,8	61,6	61,6	61,7	61,6

Table 4: Overall levels for measurements according to ISO 9614-3

	5x2x3 array Time=7'						6x3x4 array Time=9'						9x4x6 array Time=15'					
Operator	A			B			A			B			A			B		
Run	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
L_W *dB*	59,8	59,9	60,0	60,0	60,0	60,5	59,9	59,9	60,1	60,1	60,3	60,5	60,3	60,4	61,0	60,9	61,0	61,2
L_{WA} *dB(A)*	60,5	60,7	60,7	60,8	60,8	61,2	60,4	60,4	60,6	60,8	60,9	61,1	60,8	61,0	61,5	61,5	61,6	61,8

3.2.2 ISO 9614-3

As to the procedures for achieving the desired grade of accuracy, the check for the repeatability of the scan on a partial surface (criterion 1) was not satisfied in any run, similarly to what happened in the application of ISO 9614-2. On the contrary, the check for the adequacy of the measurement equipment (criterion 2: $F_{pI} \leq L_d$), the check for the presence of extraneous noise (criterion 3: $F_{pIn} - F_{p|In|} \leq 3$ dB) and the check for field non-uniformity (criterion 4: $F_s \leq 2$ dB) achieved the precision grade of accuracy except for few runs and at frequencies with band levels that were negligible in the determination of the overall sound power level.

Unfortunately, since this part of the Standard is aimed at achieving the highest grade of accuracy only, no additional procedure is provided for ignoring the fulfilment of criterion 1 on partial surfaces with a low partial sound power.

4 Discussion

4.1 ISO 9614-1

The application of this part of the Standard had shown that the greater the number of points, the higher the grade of accuracy attained. Moreover, since the time necessary to complete each run strictly depends on the chosen measurement array, the greater the number of points, the longer the measuring time.

The “coarse” measurement array (5x2x3) with 47 points attained a survey grade of accuracy on the whole spectrum and an engineering grade (except for the I run) on the A-weighted levels because of the exclusion of the 630 Hz frequency band. Unfortunately, this configuration did not draw advantages from such a highly sophisticated measurement technique: in fact, high uncertainty values were associated to the sound power levels. In addition, even with an automatic probe positioning system, this measurement array needed a measuring time of 1 hour and a half, anyhow.

It is surely worthwhile using this technique on finer measurement arrays in order to achieve a higher grade of accuracy. Better results, in fact, were obtained with the 6x3x4 array (84 points) that achieved always an engineering grade of accuracy on the whole spectrum with a measuring time only half an hour longer.

However, it has to be noticed that increasing to a greater extent the measuring time (from 2 to 3 hours) with the 9x4x6 measurement array (174 points), a precision grade of accuracy was even achieved on the whole frequency distribution in two runs.

4.2 ISO 9614-2

Thanks to the additional procedure allowing to ignore the results of the partial power repeatability check (criterion 3) on certain partial surfaces, the application of ISO 9614 part 2 permitted to attain even an engineering grade of accuracy in few cases. This result, however, was achieved only on A-weighted sound power levels because it required the exclusion of some frequency bands.

Therefore, the application of this part of the Standard highlighted that the time necessary to complete each run is surely lower than that required for part 1 (approximately one sixth shorter) but the grade of accuracy hardly attained the engineering level. Sometimes, due to the constraints related to criterion 3, it was also referred to a restricted range of frequencies and to the A-weighted sound power level, only.

4.3 ISO 9614-3

Part 3 of the Standard has been recently developed in order to achieve the highest grade of accuracy even with measurements performed by scanning. For this aspect, part 3 complements part 2 of ISO 9614 but limits adverse situations by giving more severe criteria.

As expected, the application of this part of the Standard had a critical stop in the check for the repeatability of the scan (criterion 1), because the scan performed manually is meant to have an intrinsic low repeatability.

Hence, the time necessary to complete each run according to part 3 was even lower than that required for part 2 but unfortunately no test run satisfied all the procedures to achieve the desired grade of accuracy.

4.4 Overall sound power levels

The main purpose of ISO 9614 is to provide a procedure for the determination of the sound power level of a source with a defined level of uncertainty. Therefore, it is interesting to look whether the test conditions that negatively affected the requirements have whatever influence on the overall levels too.

In this respect, all the A-weighted overall sound power levels obtained for each sampling method, on each array and for each run are plotted in Figure 1.

The x-axis scale is centred to 61.7 dB(A) which is the average value of the two sets of data that attained the precision grade of accuracy on the whole spectrum (9614 part 1 - 9x4x6 array - II and III runs).

The y-axis is divided into 3 categories (measurement arrays) in order to gather up the results obtained by each part of the Standard on the same measurement array. Each category has three sets of data distributed on three lines: the first (•) for data obtained by ISO 9614-1, the second (◆) and the third (×) for data obtained by the application of ISO 9614-2 and ISO 9614-3, respectively.

Moreover, a distinction has been made among the tests that attain different grades of accuracy, even with the exclusion of certain frequencies. Precision grade of accuracy is displayed with a circle around the indicator while engineering grade is displayed with a square.

In order to show the dispersion of data around the estimate of the true value, two areas have been identified. They include the data within a standard deviation s for precision grade of accuracy (s = 1 dB) and for engineering grade of accuracy (s = 1.5 dB).

Even if the checking for the adequacy of the array of measurement positions and the partial power repeatability check were not satisfied, a high percentage of cases are included in these areas: 75.6% within the uncertainty interval ±1 dB and 97.8% within the interval ±1.5 dB.

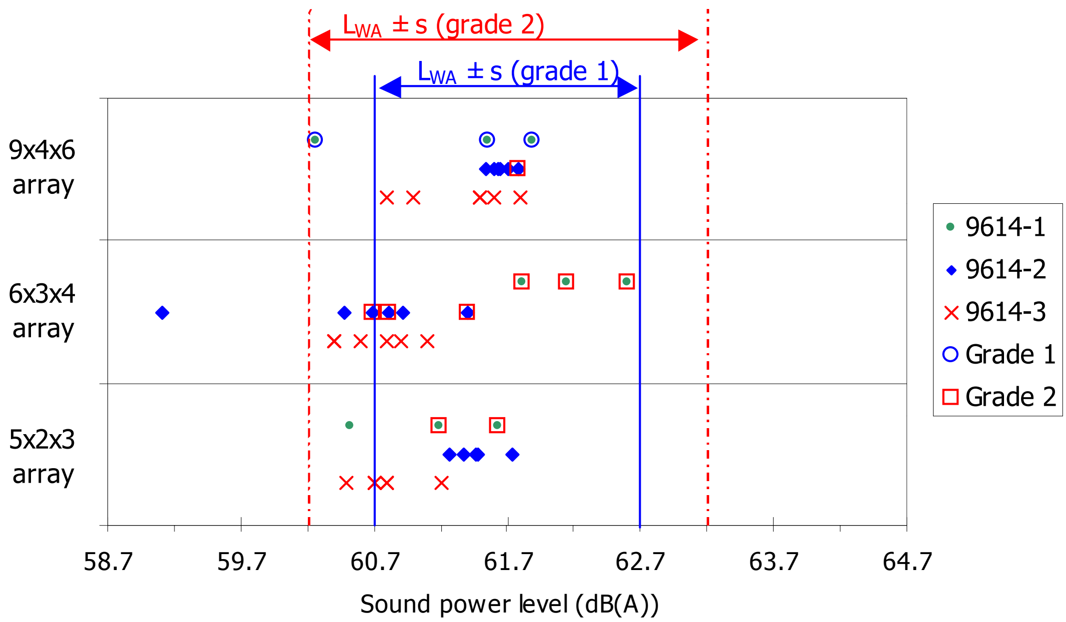

Figure 1: A-weighted sound power levels for different sampling methods and measurement arrays

As to the frequency distribution, the best estimate of the pump noise emission among all the experimental data has been obtained by averaging the sound power spectra of the two sets of data that attained the precision grade of accuracy on the whole spectrum. This averaged sound power level spectrum is qualified as the best estimate of the true frequency distribution and is reported in Figure 2.

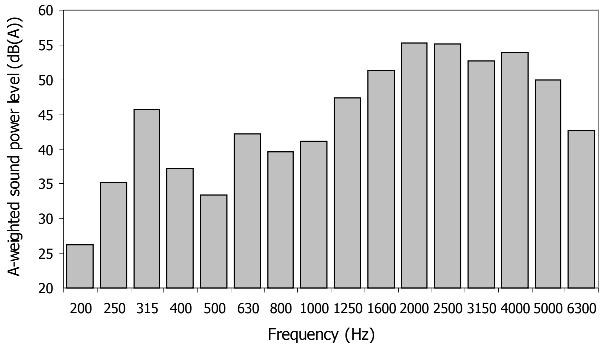

Figure 2: Averaged A-weighted sound power level

Figure 3 shows how the A-weighted sound power levels are spread around the true value for each frequency band. Data obtained with the application of those parts of the Standard allowing the higher grade of accuracy are here reported and are displayed with different indicators: (◆) for part 1 and (×) for part 3.

In order to qualify the spread of the data around the averaged value in terms of standard deviation, two areas have been identified with a grey background colour: the narrower indicating a 68% confidence interval and the wider for a 95% confidence interval.

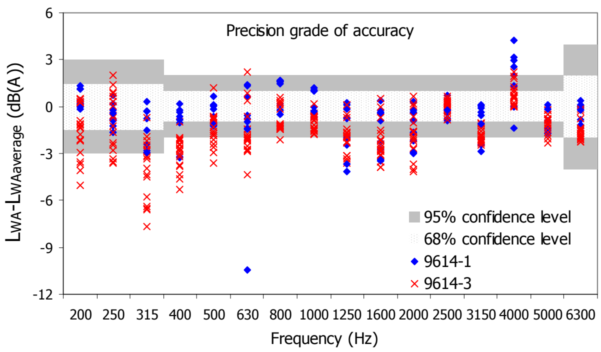

Figure 3: Spread of the A-weighted sound power levels around the averaged value

In the low frequency range up to 630 Hz, the band levels obtained with the application of part 3 of the Standard are highly spread around the averaged value. These levels are outside the ± 2s interval but these frequencies are almost always negligible in the determination of the overall sound power level.

On the contrary, the high spread that occurs in the medium-high frequency range is more critical because these frequencies are components predominant in the spectrum.

Anyway, the frequencies with the highest difficulties in fulfilling the criteria provided for by the Standard are always highly spread around the averaged value, whatever part of the Standard had been applied.

5 Conclusions

The application of ISO 9614 for the determination of the sound power emitted by a hydraulic fluid power pump has rejected the expectation mentioned in ISO 16902 saying that for these sources just an engineering or survey grade of accuracy can be achieved. The precision grade of accuracy, in fact, was attained applying ISO 9614-1 on the finest grid of measurement points under consideration.

ISO 9614-1 is surely hard to be applied and, even with an automatic positioning system of the sound intensity probe, the time necessary to complete each run for tests that achieved a precision grade of accuracy is not lower than 3 hours. On the contrary, ISO 9614-2 and ISO 9614-3 are more suitable in terms of time consumption (25 minutes at most) but they can not be used when also the sound power spectrum is required.

In addition, when applied to such kind of sources, ISO 9614-2 allowed to guarantee the expected grade of accuracy for the overall A-weighted sound power levels while ISO 9614-3 never led to the desired grade of accuracy.

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