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A CRITICAL REVISION OF *ISO STANDARD 9614-1: DETERMINATION OF SOUND POWER LEVELS OF NOISE SOURCES USING SOUND INTENSITY*

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ABSTRACT - Experimental testing was performed to investigate the validity of ISO Standard 9614-1 for determining sound power levels of noise sources using sound intensity at discrete points. Among the conditions varied during testing were test environment, source position, extraneous noise, and measurement surface. On the basis of this investigation and extensive industrial testing, a critical revision of the standard has been written with the intent to eliminate the ambiguity and repetitiveness encountered in the original version.

1 INTRODUCTION

Sound power determination, of paramount importance in qualifying an acoustic source critical, is mandated by the EU Machine Directive CEE 392/89. Sound power is the only parameter that enables comparing several sources and characterizing sources in any environment. In addition, it can be used as an input for acoustic prediction software.

To uniform standards for noise measurement and abatement, the EU Standard Committee selected the ISO standards for application in EU directives on the basis of their completeness and widespread diffusion. The ISO standards are issued according to the two main categories of methods for measuring sound power from a source:
methods based on measuring sound pressure (ISO Standards 3740 to 3747)
methods based on measuring sound intensity (ISO Standard 9614, Parts 1 and 2).

ISO Standard 9614 was selected for our investigation for two reasons: 1) because the methods it describes can be carried out under less restrictive environmental conditions and 2) because the uncertainty of the results can be evaluated during measurement processing. This work is divided into two parts. In the first, the previsions of ISO 9614-1 (measuring sound intensity at discrete points) are analyzed and revisions are proposed. The revisions are illustrated with references to the original text: Only those parts that underwent major revision are described; minor modifications have been omitted for brevity. In the second, the reference source for use in laboratory testing is described. The results of experimental testing conducted in the laboratory and in the field on actual machines are presented.

2 PROPOSED REVISIONS TO ISO STANDARD 9614-1

2.1 Introduction (References: Foreword and Paragraphs 0.1, 0.2, 0.3, 1.1)

ISO Standard 9614 is divided into two parts:
Part 1: Measurement at discrete points
Part 2: Measurement by scanning.

The standard is based on the principle that "the sound power radiated by a source is equal in value to the integral of the scalar product of the sound intensity vector and the associated elemental area vector over any surface totally enclosing the source". Earlier standards such as ISO 3740 to 3747 are based on sound pressure measurements. Since, however, the relationship between sound intensity and pressure at single measurement positions is dependent on the source and environment characteristics, as well as measurement position, ISO 3740 to 3747 specified the characteristics that ensure the measured sound power value would be meaningful. ISO 9614 differs from its predecessor in the following respects:

It can be applied with high levels of extraneous noise.
It can be applied more frequently in situ.
It requires both sound intensity and pressure measurements.
The uncertainty of the sound power determined is classified with test and calculations during processing of the measurements.
A weighted sound power level is evaluated on the basis of constant percentage bandwidth levels.

2.2 Reference Standards (Reference: Paragraph 2)

2.3 Noise Source (References: Paragraphs 0.3, 1.1, 3.13, 4.1, 4.2, 5.2.1, 7.1, 7.2)

2.4 Test Environment (References: Paragraphs 1.2, 3.9, 4.2, 5.1, 5.2.1, 5.2.2, 5.3, 5.4)

2.5 Instrumentation (References: Paragraphs 3.10, 6.1, 6.2, 6.2.1, 6.2.2)

Use instruments, including the sound intensity probe meeting the requisites of IEC 1043. Use Class 1 instrumentation to comply with Grades 1 and 2 accuracy levels. In accordance with IEC 1043, calibrate the instrumentation in compliance to national standards at least once a year and record the results in the test report.

Before each group of measurements, calibrate and measure the p-I index, taking into account the ambient temperature and pressure. If no manufacturer's calibration instructions have been furnished, proceed as follows:

Check the sound pressure level of each of the intensity probe's microphones using a Class 0, 1, or 1L calibrator according to IEC 942.

Set the probe on the measurement surface, with its axis perpendicular to the surface at a position characterized by an intensity level higher than the surface average intensity. After measuring the sound intensity, rotate the probe 180 deg, with the axis perpendicular to the measurement surface and without changing the position of the probe center. Measure the sound intensity again. The result is satisfactory if the two intensity values are of different sign and do not differ more than 1.5 dB at the maximum band level measured in octave or one-third-octave bands.

2.6 Frequency Analysis (References: Paragraphs 1.1, 4.3, 8.1)

Frequency analysis measurements, which can be carried out in octave or one-third-octave, are used to evaluate the total sound power level and *A*-weighted total sound power level. Therefore, *A*-weighted total sound power level is not measurement directly by means of an *A*-weighted filter.

Current limitations of the instrumentation mandate the following frequency limits:

octave: 63 - 4000 Hz
one-third-octave: 50 - 6300 Hz.

The *A*-weighted total sound power level is to be considered correct if there are no significantly high levels at frequencies beyond the measuring range. Hence, levels not more than 6 dB below the *A*-weighted total sound power level after *A*-weighting are considered significant. If the sound power is evaluated in a more limited frequency range, the frequency range must be indicated in the test report.

Instruments that process signals in constant percentage bandwidths require an averaging time that respects the relation $BT \geq 400$, where B is the bandwidth at the lowest frequency used and T is the averaging time. For instruments which synthesize octave or one-third-octave bands from narrow-bad-analysis, the equivalent averaging time must be established according to IEC 1043. Special care must be in the case of cyclic signals.

2.7 Measurement Positions (References: Paragraphs 0.3, 3.7, 3.8, 8.2)

The measurement positions must be distributed as uniformly as possible over the measurement surface. There must be at least one measurement position per square meter and at least 10 positions. If the measurement surface exceeds fifty square meters, the following statements apply:

With significant extraneous noise, a minimum of 50 measurement positions are required and there must be at least one measurement position per two square meter.

With insignificant extraneous noise, no more than 50 positions are required and their distribution over the measurement surface should be as uniform as possible.

Extraneous noise can be considered insignificant if, with the source off, the *A*-weighted sound pressure levels fall by at least 10 dB at five measurement positions distributed uniformly over the measurement surface.

2.8 Definitions (Reference: Paragraph 3)

2.9 Range Indicators (Reference: Annex A)

2.10 Testing and Degree of Accuracy (References: Paragraphs 0.3, 1.3, 4.3, 8.2, 8.3.1, 8.3.2, 8.4, 10.5, and Annex B)

ISO Standard 9614-1 sets three classes to evaluate the sound power and the degree of accuracy:

Grade 1: precision
Grade 2: engineering
Grade 3: survey.

The uncertainty level associated with each grade is related to the random errors in the measuring procedure and the maximum bias error (limited by the selection of a suitable bias factor K used in Test 2 for degree of accuracy), but does not account for the instrument tolerances and the effects of the variations in source installation and operating conditions.

The degree of accuracy depends upon the kind of noise generated by the source, the kind of extraneous noise, the source absorption, and the measuring and sampling procedures. The tests required by the standard are designed in relation to these factors.

The sound power levels in several frequency bands can be ignored (and thus the uncertainty of their determination can be considered irrelevant) provided the following conditions are met:

If only the A-weighted determination is required, any single A-weighted band level of 10 dB or more below the highest A-weighted band level shall be neglected. If two or more levels meet this condition, they can be ignored if the level of the sum of the A-weighted sound powers in these bands is 10 dB or more below the highest A-weighted band level.

If only the total sound power level is required, all levels 10 dB lower than total can be ignored.

Test 1: $F_1 \leq 0.6$

Test 1 is conducted at a measurement position typical of the measurement surface before and after all measurements have been made. The purpose of the test is to establish the temporal variability of the sound field during measurement. If the test condition is not met in all the bandwidths under examination (which therefore cannot be ignored according to the above criteria), the temporal variability of the sound field must be reduced.

Test 2: $F_2 < L_d$

Test 2 establishes the instrumentation's dynamic capability to perform specific measurements. The test is more restrictive if F_3 is used in place of F_2. If the test is not successful for all the bandwidths under examination, the procedures indicated in Table B.3 of the original standard should be followed or else:

If only the A-weighted total sound power level is required, eliminate the bandwidths not meeting test conditions from the calculation and indicate the effects of uncertainty in the test report.

If only the total sound power level is required, indicate the uncertainty effects in the test report.

Test 3 : $F_3 - F_2 \leq 3$ dB

Test 3 verifies the absence of highly directional and excessively reflective emissions on the surrounding environment of the external sources. If the test fails to give satisfactory results for all the bandwidths under examination, follow the procedures indicated in Table B.3 of the original standard.

Test 4 : $N > CF_4^2$

Test 4 determines whether the number of measurement positions and their locations are suitable for representing the spatial variability of the sound field over the measurement surface. If the test results are not satisfactory for all bandwidths, either modify the number and/or distribution of the measurement positions or:

Indicate in the test report the estimate of the confidence interval at 95% for the octave or one-third-octave bands that failed according to the formula

$$10\log(1 \pm \frac{2F_4}{\sqrt{N}})\ \text{dB}$$

If only the A-weighted total sound power level is required, eliminate the bandwidths that failed from the calculation and indicate the uncertainty effects in the test report.

2.11 Test Report (Reference: Paragraph 10)

Annex C

Annex D

3 THE REFERENCE SOURCE

A reference source was developed for laboratory testing with emissions of the following characteristics:

- radially uniform
- stable in time
- possibility of concentrated emissions in selectable directions.

Our first step was to select the geometry of the icoshedral figure (polyhedral with 20 triangular surfaces) as the best compromise between the conflicting needs to approximate the spherical shape and to apply flat-based loudspeakers. To enhance manageability, we used a portion of the polyhedral figure composed of 15 tetrahedral components. Each loudspeaker had its own tetrahedral speaker made of a 14-mm-thick, medium density fiberboard. The shape of the speakers was especially suitable because the possibility that stationary waves could form was minimized by the absence of parallel walls.

The source, guided by a random signal, was controlled from a console containing the microphone switches. The loudspeakers were pretested according to manufacturer's instructions. To ensure stability, we developed a device that allowed a control microphone to be accurately assembled at a given position with respect to the loudspeaker. This is critical since, in the near field, the sound pressure can vary markedly, even when the position of the microphone varies only slightly. To minimize the interference resulting from the others loudspeakers, the stability measurements were made with a single pair of operating diffusers, one facing the other. The measurements of the emissions before and after each test confirmed that the loudspeakers were capable of providing long-term stable emissions.

4 RESULTS OF EXPERIMENTAL TESTING

All tests were conducted in octave in frequencies ranging from 50-6300 Hz to Grade 2 (engineering) degree of accuracy. To cover the entire frequency range, it was necessary to use double spacing (or microphone separation) of the sound intensity probe to carry out the measurements:
low frequencies (50-1000 Hz): spacing: 50 mm; averaging time: 35 s
high frequencies (1250-6300 Hz): spacing: 8.5 mm; averaging time: 10 s.

Testing was conducted in three locations, two indoors and one outdoors. A parallelepiped measurement surface was used. Conditions such as environmental characteristics, source position, background noise, and measurement surface were varied.

The standard was revised on the basis of the test results. For brevity, only the main revisions are illustrated below.

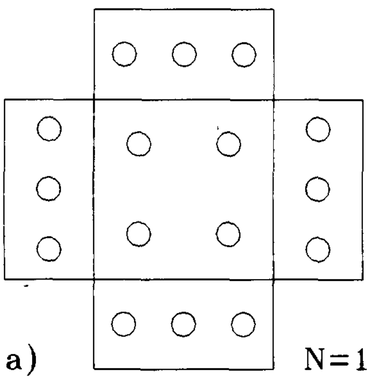
4.1 Test 4 - $N > CF_4^2$

The standard gives the minimum number of measurement positions distributed uniformly on the measurement surface after Grade 2 testing and determines whether these selections fit the sound field's spatial variability on the measurement surface. If this condition is not fulfilled, the standard recommends either modifying the measurement surface—which necessitates remeasuring all the positions!—or else uniformly increasing the number of measurement positions.

We recommend the alternative solution of gradually increasing the number of positions, starting from the measurement segments where F_4 is highest. The test procedure should then be repeated until the proscribed conditions are met. This procedure is optimum for minimizing the number of positions to be added to meet proscribed conditions and is also in agreement with Test 4 objectives.

An example is given in Figure 1: (a) shows the minimum distribution required by the standard (16 points) and the result of the application of Test 4. If the standard's recommendation is followed, we need 64 points (b), whereas our proposed method requires only 37 points (c).

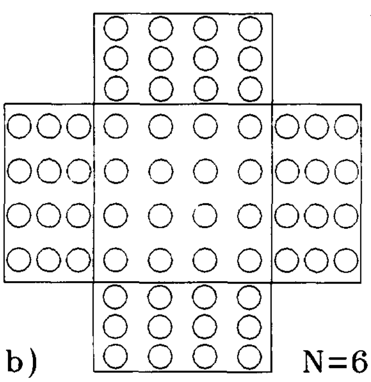
a)



N=16

[Hz]	CF_4^2	[Hz]	CF_4^2	[Hz]	CF_4^2
50	2	315	10	2000	27
63	6	400	7	2500	18
80	5	500	10	3150	18
100	3	630	34	4000	21
125	8	800	25	5000	24
160	7	1000	50	6300	3
200	21	1250	98		
250	15	1600	43		

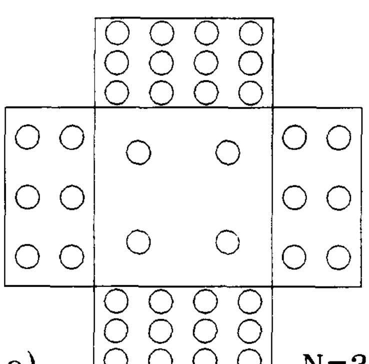
b)



N=64

[Hz]	CF_4^2	[Hz]	CF_4^2	[Hz]	CF_4^2
50	6	315	7	2000	15
63	8	400	8	2500	12
80	6	500	7	3150	17
100	7	630	12	4000	15
125	14	800	32	5000	19
160	5	1000	43	6300	18
200	22	1250	11		
250	21	1600	18		

c)



N=37

[Hz]	CF_4^2	[Hz]	CF_4^2	[Hz]	CF_4^2
50	6	315	7	2000	15
63	8	400	7	2500	12
80	6	500	8	3150	17
100	8	630	14	4000	15
125	12	800	31	5000	19
160	7	1000	34	6300	18
200	31	1250	11		
250	18	1600	18		

Figure 1. Example of the effectiveness of the alternative point-adding procedure.

4.2 Validity of F_4

We investigated the validity of F_4—which in actuality is a normalized standard deviation—by examining the face of the parallelepiped surface with the highest value of F_4 (nonuniformity of the sound field). We mapped the face by carrying out 96 acquisitions over the uniformly distributed positions. The mapping surface, measuring 1.8 x 1.30 m, was divided into 12 rows and 8 columns. The measurement positions were 15 cm apart. Having acquired the intensities, we used a Matlab program to analyze the values of F_4. We selected an increasing number of measurements (3x2, 4x3, 6x4, 12x8), each time calculating the value of F_4 per one-third-octave and determining its value in relation to the variations in the number of measurement positions considered. We thus verified that, except at very low frequencies, F_4 can be considered a representative parameter.

4.3 Constant C

After having calculated the sound power levels in configurations with different numbers of measurement positions, we observed that the values never differed more than 2 dB. This led us to suspect that thė Test 4 constant C was overestimated. The suspicion was confirmed by comparing an equivalent standard, S31-100 issued by the French AFNOR, which exhibits lower values (Table.1).

Table 1. Constant C values in ISO 9614-1 and AFNOR S 31-100.

Octave bands [Hz]	1/3 octave bands [Hz]	ISO 9614-1 Grade 2	S 31-100 Grade 2
63-125	50-160	11	8
250-500	200-630	19	15
1000-4000	800-5000	29	28
	6300	14	10

4.4 Hot Point Procedures

We investigated the additional hot point procedures recommended by ISO Standard 9614-1 with only some of the loudspeakers operating. The following observations are in order:
According to ISO 9614-1, the measurement positions should be arranged in decreasing order of magnitude on the basis of the positive partial sound powers passing through each measurement segment and then the upper subset N_α through which more than half of the total sound power (area S_α) should be determined: If N_α is less than half the total number of segments, the procedure can be applied. Conversely, we feel that it would be more correct to refer to a part of the surface (for example, one face of the parallelepiped) as recommended in Paragraph 4.1 rather than to a single segment.
ISO 9614-1 recommends calculating the number of positions to add in area S_α (which,, however, might not be located on the same measurement face). According to our experimental testing, the number of positions added by this method is tremendously overestimated. As an example, we started with 16 measurement positions uniformly distributed with a highly directional source. As this number did not meet Test 4 requirements, we applied the hot point condition. The number of additional positions recommended by ISO 9614-1 at the most critical

bandwidth is 220, whereas, if we apply the criterion described in Paragraph 4.1, only 28 are required. The same result was obtained in testing with different configurations.

4.5 Uncertainty in Determining Sound Power Levels

The analysis of the sound power levels obtained in testing with various bandwidths following completion of the ISO 9614 checks exhibits much less variability than in Table 2 of ISO Standard 9614-1 (uncertainty in determining sound power levels). Although further testing must be conducted to statistically validate this result, the ISO values appear to be considerably overestimated.

5 CONCLUSIONS

A revision of ISO 9614-1 was undertaken to eliminate the problems of poor organization, repetitiveness, and ambiguity that emerged during application of the standard. The proposed revision is based on practical tests that account for the notable variability of the source characteristics and test environments in relation to the huge number of existing industrial case histories. An analogous investigation of Part 2 (ISO 9614-2) is forthcoming.

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REFERENCES

Standard ISO 9414-1 Acoustics - Determination of Sound Power Levels of Noise Sources Using Sound Intensity" - Part 1: Measurement at Discrete Points, 1993.