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SOUND POWER DETERMINATION USING ACOUSTIC INTENSIMETRY, APPLYING DISCRETE POINTS AND SCANNING METHODS

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Abstract. *Acoustic noise control designs are most well succeeded when one has a better knowledge of the acoustic sound power, generated by the sources. In this framework, acoustic parameters measurements, as sound power levels (SWL) and sound pressure levels (SPL), are imperative for an efficient acoustic attenuation system.*

Traditional methods used to determine sources sound power, request special environments as reverberation and anechoic chambers, which includes high initial investment. As an alternative to this high investment, the two microphones (or intensity) technique can be a reasonable tool to determine sources SWL.

This work aims the analysis and implementation of the intensity technique at Institute of Aeronautics and Space (IAE). For this purpose, sound intensity measurements of an acoustic source, with a known sound power, were performed. This SWL, which was determined by the Sound Pressure Method in Reverberation Chamber, according to the ISO 3743-2 standard, was used as the reference data to verify the accuracy of the proposed method.

Discrete points and scanning methods were applied according to ISO 9614-1 and ISO 9614-2 standards, respectively, to determine the source's SWL. For a more detailed analysis and to confirm the efficiency of the intensity technique, measurements were done for different distances of the source as well as for high background noise levels. The field indicators according to ISO 9614-1 and ISO 9614-2 standards were also analyzed to have an indication of the referred field and the dynamic capacity of the used instrumentation. The number of measurement points, temporary variation of the source and the uncertainty of the applied method were also considered on such analysis.

Measured and reference (obtained by the Sound Pressure Method in Reverberation Chamber) SWL comparisons were done, showing good agreement.

Keywords: *sound power, sound intensity, acoustic source*

1. INTRODUCTION

Acoustic designs for noise control purposes present better performances when the sound power of the investigated source is well characterized. Sound power represents the total acoustic energy, emitted by a source in a time interval (Souza, 2003). It is an intrinsic characteristic of the noise source, independently of the environment as well as the measurement distance (González et al, 2000). The sound power of a noise source can be determined by the method of the sound pressure and by the two microphones or intensity technique. The acoustic intensity technique is based on the principle of the two microphones, separated by a known distance (Figure 1) and presents a series of advantages, when one compares this technique to the sound pressure method (ISO 3743-2 standard). As previously mentioned, acoustic intensity technique is a reasonable alternative to the traditional power determination methods, since it is not required expensive acoustic facilities and, therefore, high initial investments for civil constructions of the reverberant or anechoic chambers are not required. Applying such an intensity technique, with only a simple data acquisition system and respecting standard (ISO 9614-1 and ISO 9614-2) required parameters, one can obtain accurate source SWL determinations. Besides, these measurements can be done in the presence of background noise.

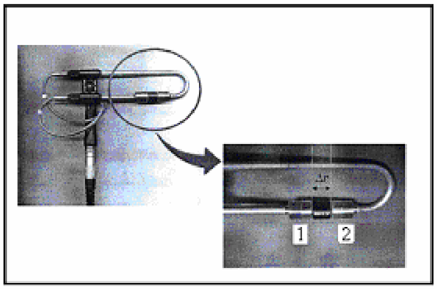

Figure 1. Sound intensity probe

In view of establishing accurate intensity measurement technique at IAE, this work presents procedures for implementation of the referred technique, applying standards requirements and using the available intensity measurement equipments in the Laboratory of Acoustic Measurements.

The sound intensity can be estimated by the relation of pressures captured by microphones 1 and 2, separated by a known distance, as described in equation (1):

$$\hat{I}_r \cong -\frac{1}{2\rho\Delta r}\overline{[p_1(t)+p_2(t)]\int[p_2(t)-p_1(t)]dt} \qquad (1)$$

where:
I_r: is the sound intensity estimate in the direction (r) [W/m^2];
p_1(t): is the sound pressure in the time domain captured by microphone 1 [Pa];
p_2(t): is the sound pressure in the time domain captured by microphone 2 [Pa];
Δ_r : is the separation distance between microphones 1 and 2 [mm];
ρ : is the volumetric density of the environment [kg/m^3];

Applying the sound intensity technique, the sound power determination of an acoustic source is obtained by generating measurement surfaces, which limit the distance between the source and the position of the measurement intensity probe. Since the relation between intensity and power is proportional to the area (equation (2)), these surfaces are used in the sound power calculations. Standards ISO 9614-1 and ISO 9614-2 determine that this minimum distance is limited to 500 mm and 200 mm, respectively, in relation to the source. Figure 2 illustrates the sound radiation of a noise source inside the measurement surface, in the presence of background noise, which is generally the real case for SWL measurements, using intensity technique (Pierotti et al, 1999).

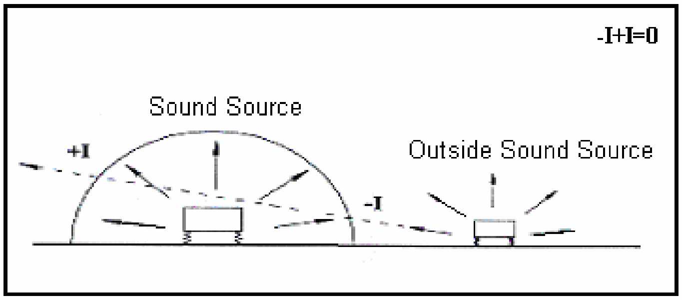

Figure 2. Sound intensity measurement, in the presence of background noise

The sound power generated by a noise source inside a surface is given by equation (2):

$$W_s = \int_s I_n dS \qquad (2)$$

where:
W_s : is the average sound power generated by the source inside of surface S;
I_n : is the sound intensity in the normal direction of the surface S;
dS: is the area element.

Equation (2) allows that the sound power generated by a source is determined, even in the presence of other sources or background noise, since the energy that crosses the measurement surface towards the interior of the surface S (or against the normal direction), is not considered (Souza, 2003).

2. INTENSITY MEASUREMENT METHODS

2.1 Discrete points method

This method, used to perform the sampling of the sound intensity field, consists of locating the intensity probe in the central points of pre-defined areas, for a sufficient time, avoiding statistical or sampling errors, according to standard ISO 9614-1. This time is given by the relation $B \cdot T \geq 400$, where:
B: is the width of the lower band of interest;
T: is the average time necessary to perform the measurement.

This relation assures a maximum error of 5% in the sound intensity measurement with a 95% confidence level for a Gaussian distribution (Bertoli and Santos, 2004).

Figure 3. Test with surfaces of 110x110 cm

The Figure 4 shows the orientation and sequence of the measurement points data acquisition, using assemblage with surfaces of 110x110 cm, as shown in the Figure 3.

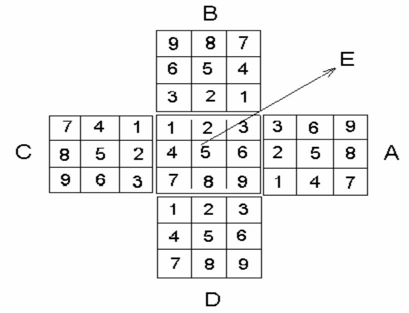

Figure 4. Orientation and sequence of the measurement points (surfaces of 110x110 cm)

Standard ISO 9614-1 establishes criteria so that the uncertainties of the acquired results during the measurements are in acceptable limits, considering frequency bands and grade of accuracy. In the presence of strong reverberant field, high background noise, near field effects and localized sound radiation of the source, improvement actions may be taken, in view of having lower uncertainties, allowing validating results in a wider frequency band. The uncertainties by frequency bands and grade of accuracy are described in Table 1 (Souza, 2006). As described by Jornada et All., these uncertainties type A may still be combined to an uncertainty type B to be expressed as the final uncertainty of the measurement (see section 3.4).

Table 1: Limits of uncertainties in accordance with Standard ISO 9614-1

Octave band centre frequencies [Hz]	One-third-octave band centre frequencies [Hz]	Standard deviations (s)		
		Precision (Grade 1) [dB]	Engineering (Grade 2) [dB]	Survey (Grade 3) [dB]
63 - 125	50 - 160	2	3	-
250 - 500	200 - 630	1,5	2	-
1000 - 4000	800 - 5000	1	1,5	-
	6300	2	2,5	-
A-weighted	-	-	-	4

In view of verifying the requirements of the standard ISO 9614-1, the index of residual pressure-intensity (δ_{PI0}) was determined to obtain the dynamic capacity (L_d) of the employed measurement system (Souza, 2006). After that, sound intensity measurements, using surfaces of 110x110 cm were performed to evaluate the behavior of the following field indicators: temporal variability (F_1), surface pressure-intensity (F_2), negative partial power (F_3) and non-uniformity (F_4), as required by standard ISO 9614-1.

Second the standard ISO 9614-1, a way of having better measurement accuracy is applying improvement actions. As such, with the objective of improving the field indicators, the following improvement actions were taken:

- Reduction of the measurement surface from 110x110 cm to 80x80 cm;
- Increase the number of measurement points by surface from 9 to 12 points.

The Figure 5 illustrates the new set-up, applying the improvement actions, as described above.

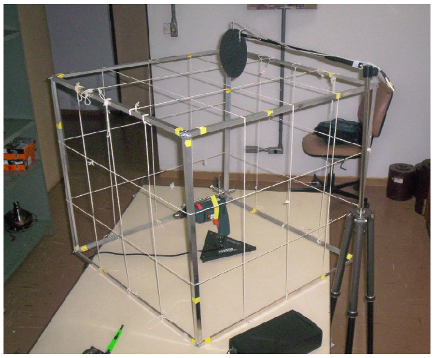

Figure 5. Test with surfaces of 80x80 cm

Figure 6 illustrates as the adopted measurement points for the surface of 80x80 cm, as well as the sequence of measurements.

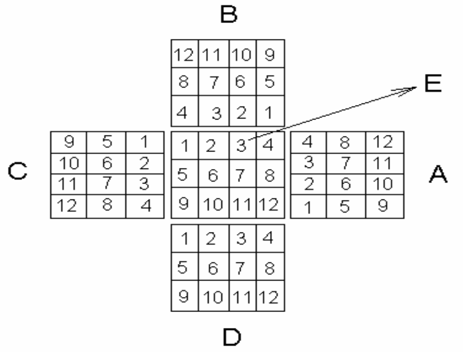

Figure 6. Orientation and sequence of the measurement points (surfaces of 80x80 cm)

2.2 Scanning method

Standards ISO 9614-2 and ISO 9614-3 present methodologies for the sound power determination, by means of sound intensity measurements, applying scanning method. This method consists on sampling the normal intensity to the measurement surface by sweeping the sound intensity probe in continuous movement in one or more directions, in view of having a time and space average data, instead of only the space averaged data, obtained by the discrete points method, described on item 2.1. Figure 7 illustrates the measurement procedure, adopted for the scanning method (Souza, 2006).

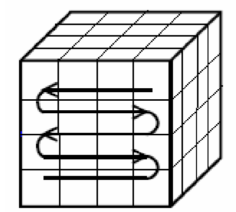

Figure 7. Measurement by scanning method

Differently of the discrete points method, only the size of the surface was decreased as adopted improvement action for this scanning method. The Figure 8 illustrates as the orientation of the sound intensity probe was adopted, for the both measurement surface sizes (110x110 cm and 80x80 cm).

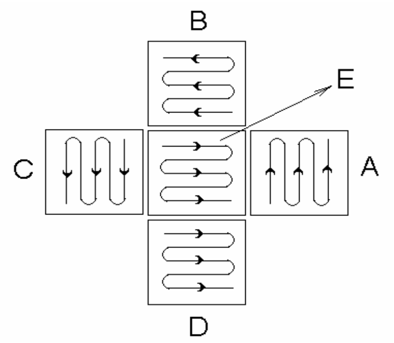

Figure 8. Orientation of the sound intensity probe in the surfaces of 110x110 cm and 80x80 cm

The sweeping speed of the sound intensity probe is obtained considering the total distance, which is covered by the probe in each partial surface for the adopted measurement time, as specified by Standard ISO 9614-2. This Standard also establishes the uncertainties for frequency bands and degrees of exactness. In view of having the measurement results according to the uncertainties described in Table 2, the improvement action described above must be taken.

Table 2: Limits of uncertainties in accordance with standard ISO 9614-2

Octave band centre frequencies [Hz]	One-third-0ctave band centre frequencies [Hz]	Standard deviations (s)	
		Engineering (Grade 2) [dB]	Survey (Grade 3) [dB]
63 - 125	50 - 160	3	-
250 - 500	200 - 630	2	-
1000 - 4000	800 - 5000	1,5	-
	6300	2,5	-
A-weighted	-	1,5	4

3. RESULTS

The next figures illustrate the results of the obtained field indicators for the sound power measurements, using intensity technique and the applying available equipments at Institute of Aeronautics and Space/Laboratory of Acoustic Measurements.

As such an electric drill was used as the sound source. (Bertoli and Santos, 2004) used this same electric drill to determine its SWL, using the Sound Pressure in Reverberant Chamber Method – ISO 3743-2 standard. These obtained results are used in this work as reference SWL values to be compared to the values, obtained by the proposed methods.

Standards ISO 9614-1 and ISO 9614-2 require that some indicators are verified, before determining SWL by the intensity technique. Analyses of such indicators are presented below.

3.1 Field indicators by discrete points method (ISO 9614-1, 1993)

For the both measurement surfaces (110 x 110 cm and 80 x 80 cm), the sound field time variation indicator presented values F_1 = 0,3 dB. The ISO 9614-1 standard requires that this value must be $F_1 \leq 0{,}6dB$. As such, this parameter satisfies the standard requirement, for both measurement surfaces.

The Figure 9 illustrates the results for the dynamic capacity (L_d), compared to superficial pressure-intensity indicator (F_2). One observes that a small variation in F_2 is obtained, when the measurement surface size is decreased to 80 x 80 cm. As such a better definition of the useful measurement frequency range is done, which can be adopted from 250Hz to 8 kHz. The $L_d > F_2$ criterion, as described by ISO 9614-1 standard, was not satisfied for frequency bands below 250 Hz. This is due to the fact that the generated acoustic field by the electric drill imposes inaccuracies for the low-frequency bands. Furthermore, the dynamic capacity (L_d), which is an intrinsic parameter of the adopted instrumentation, does not achieve this standard requirement, below 250 Hz, and considering the environment where the tests were performed, as shown in Figures 3 and 4.

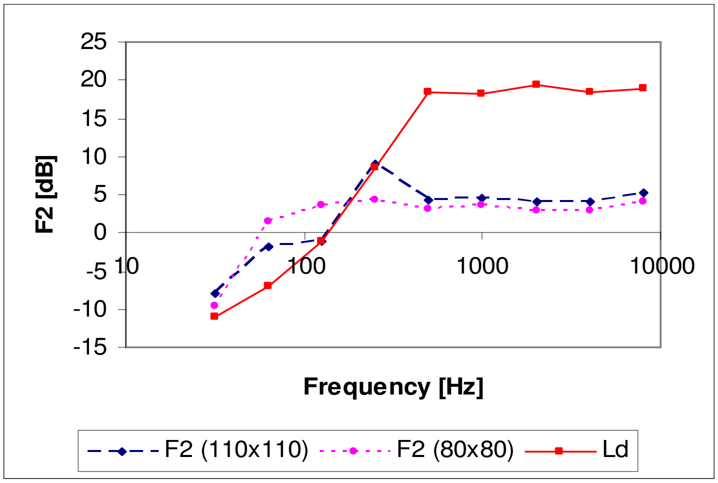

Figure 9: Verification of the $Ld > F_2$ criterion

ISO 9614-1 standard establishes the $(F_3 - F_2)$ criterion, which is required to be smaller or equal to 3 dB. Figure 10 presents comparisons for these indicators, considering the obtained results for both measurement surfaces and the 3 dB limit for the whole measurement frequency range.

Analysis of the figure 10 shows that the adopted improvement actions yielded better results, since the standard requirement is satisfied for the complete frequency range. As one can see, the $(F_3 - F_2) \leq 3$ dB requirement is satisfied for the 80 x 80 cm measurement surface. Note in this same figure, that this indicator does not satisfy this requirement for the 110 x 110 cm measurement surface, at 250 Hz central frequency.

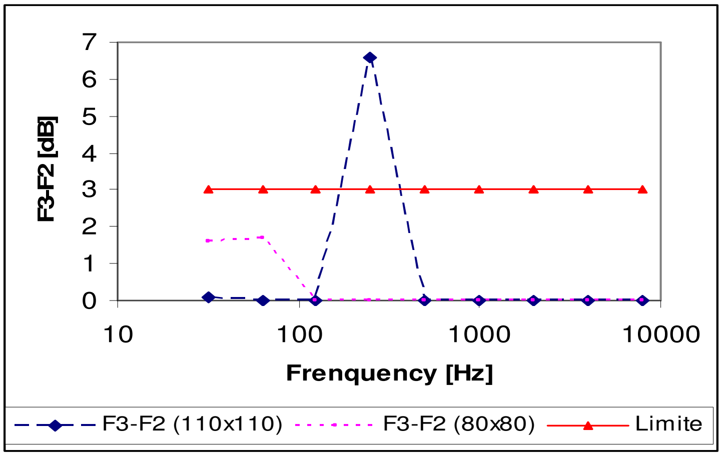

Figure 10: Verification of the F_3-$F_2 \leq 3$ dB criterion

The ISO 9614-1 standard also requires that $N > CxF_4^2$, where "N" is the number of measurement points and "C" is a constant that is function of the frequency band.

This non-uniformity field indicator is also compared to N=45 and N=60, respectively, for both measurement surfaces, in the figure 11. Note in the figure 11 that this requirement is not satisfied only at 250 Hz central band for the 110 x 110 cm measurement surface. After the improvement actions, a wider measurement frequency range can be obtained, starting from 63 Hz central frequency.

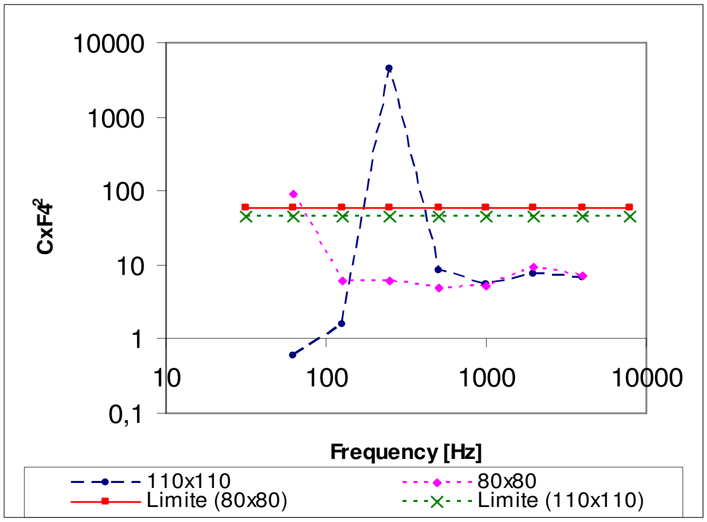

Figure 11: Verification of the $CxF_4^2 < N$ criterion

3.2 Field indicators by scanning method (ISO 9614-2, 2000)

In the figure 12 the dynamic capacity (L_d) X superficial pressure-intensity indicator (F_{PI}) comparison is shown. One verifies that the useful measurement frequency range is the same as that established by the discrete points method, as shown in Figure 9. Compare the obtained results for the F_{PI}, from Figures 12 and 9, and see that the scanning method presented a better result at the 250 Hz central frequency, when the 110 x 110 cm measurement surface was used. However, the dynamic capacity (L_d) also does not satisfy the standard requirement, below 250 Hz.

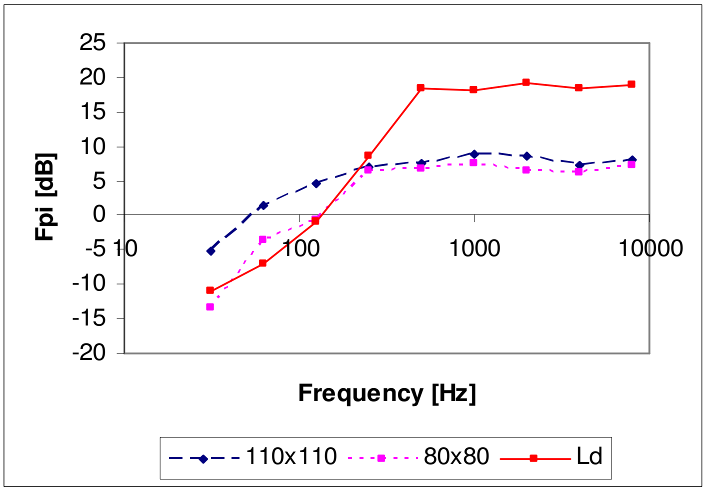

Figure 12: Verification of the L_d x F_{pi} criterion

For these tests applying the scanning method, the negative partial power indicator ($F_{+/-}$) is also verified. Figure 13 shows the comparisons for the two measurement surfaces described in this work. One can see in the referred figure that $(F_{+/-} \leq 3dB)$ criterion, is satisfied for the complete frequency range, when 80 x 80 cm surfaces is used. On the other side, the 110 x 110 cm surface does not satisfy this criterion only at the 63 Hz central frequency.

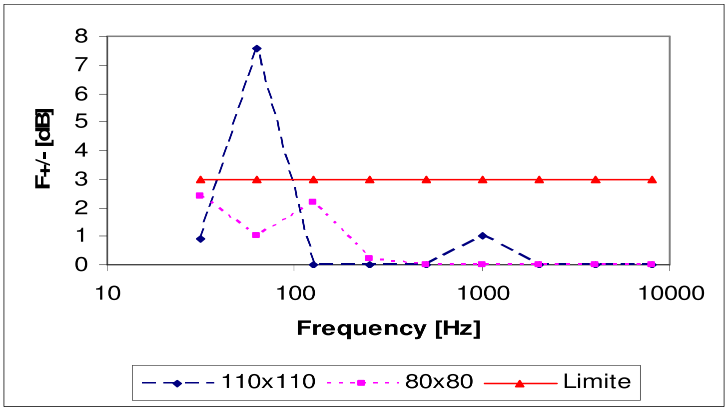

Figure 13: Verification of the $F_{+/-} \leq 3$ dB criterion

Considering all these indicators verifications, one could establish an operational measurement frequency band, taking into account the requirements of the ISO 9614-1 and 9614-2 standards, for discrete points and scanning methods, respectively. This bandwidth was defined, for the both intensity measurement methods, from 250 to 8000 Hz. The 80 x 80 cm measurement surface has shown to yield more accurate results.

3.3 Sound Power Levels Comparison

As mentioned before, (Bertoli and Santos, 2004), have determined the SWL of the same electric drill used in this work as acoustic source, using the Sound Pressure Method in Reverberant Chamber – ISO 3743-2 standard. The values obtained in the referred work are adopted as the reference values for the comparison with the obtained values presented by discrete points and scanning methods.

Figure 13 illustrates the SWL comparisons, in 1/1 octave frequency bandwidth, obtained by applying ISO 9614-1 and 9614-2 standards and using 80x80 cm measurement surfaces.

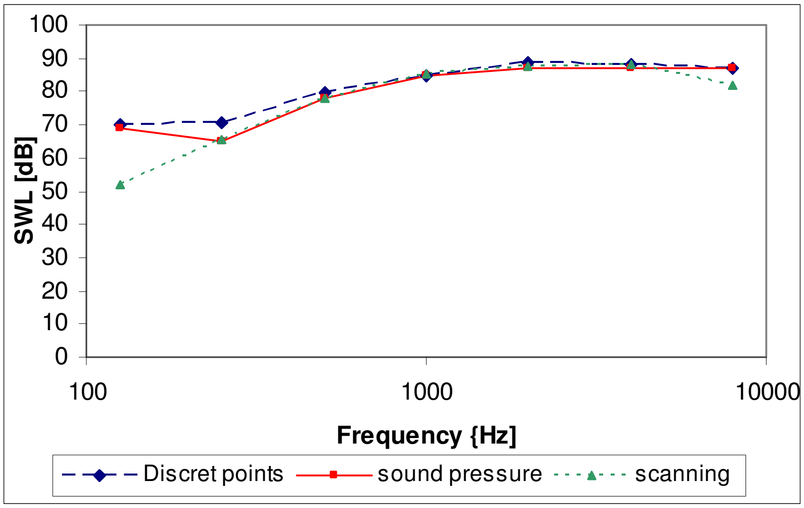

Figure 13: Results of the sound power

Note in the Figure 13 that, for the defined useful measurement bandwidth, from 250 to 8000 Hz, the SWL obtained by the intensity methods (applied in this work) and sound pressure in reverberant chamber method are similar. At 250 Hz central frequency, the scanning method presented better agreement with the reference values than the discrete points method. Furthermore, considering operational handling and test duration, scanning method is preferable, when compared to the discrete points method, since it is an easy handling and fast test. Below 250 Hz, measurements applying the intensity methods do not present good accuracy. As described before, the available equipments of the Laboratory of Acoustic Measurements only allow having accurate intensity measurements, in bandwidths above 250 Hz. However, if one considers the overall sound power levels (OSWL), these three different methods yielded 93.7 dB, 92.6 dB, and 93.5 dB, for discrete points, scanning and sound pressure in reverberant chamber methods, respectively. It is important to consider the uncertainties described on Tables 1 and 2, to establish the OSWL of the source.

3.4 Uncertainties involved with the sound power measurements using the IAE instrumentation

The final result of the SWL is associated to an uncertainty type A, as described by Tables 1 and 2, by frequency band, plus an uncertainty type B due to the equipments of the measurement chain. As such one can describe the final uncertainty associated to the SWL measurements as the combined uncertainty by frequency range.

The combined uncertainty is given by the mean square of the uncertainties type A and type B, as described by equation (3).

$$u_c = \sqrt{u_A^2 + u_B^2} \tag{3}$$

where:

u_c: is the combined uncertainty (type A and type B)

u_A: is the uncertainty type A, given by Tables 1 and 2, by frequency band, depending on the adopted measurement method.

u_B: is the uncertainty type B, as specified on the calibration chart of the equipments of the measurement chain.

As such, one has:

$$u_c = \sqrt{u_A^2 + u_B^2} = \sqrt{1.5^2 + 0.8^2} = 1.7$$

Considering an interval with 95% of confidence, one adopts limits for the whole frequency range using a coverage factor k = 2. However, the expanded uncertainty can be expressed using equation (4).

$$U = k.u_c = 3.4 \tag{4}$$

As an example, one could express the SWL obtained in 1,000 Hz, in 80x80 cm surface, by the point discrete method as being: $(84.9 \pm 3.4)\,dB$.

4. CONCLUSIONS AND ROAD MAP FOR THE FUTURE

Laboratory of Acoustic Measurement has established accurate procedures to apply intensity measurements for determining SWL generated by acoustic sources, considering ISO 9614-1 and 9614-2 standards requirements.

A good agreement between measurement intensity methods (discrete points and scanning) as proposed in this work and sound pressure in reverberant chamber method was achieved.

The improvement actions, as proposed by ISO 9614-1 and 9614-2 standards, have presented better result. As such, the 80 x 80 cm measurement surfaces presented more satisfactory results.

A measurement frequency band, for the available instrumentation at Laboratory of Acoustic Measurement, was defined from 250 Hz to 8,000 Hz.

For the studied sound source, one can neglect the SWL measurements at the central frequencies 31,5 Hz, 63 Hz e 125 Hz, since at these frequency bands the generated levels are small, when one compares with the SWL generated at the superior frequency bands. This can be done due to the fact that the low SWL in dB can be neglected when the addition between SWL in different octave bands are computed on the OSWL.

Even though the dB(A) weighting function is applied only for Sound Pressure Levels (SPL) metrics, this weighting function can be applied for the SWL, since a ± 1,5 dB(A) uncertainty of the type A value is associated to the SWL.

Road map for the future

Studies of the acoustic impedance of sound absorption materials to be applied as acoustic blankets in space industry may be carried. Car industry and aeronautics can also apply the referred technique.

Sound source localization using intensity measurement techniques may also be studied, since quiet environments are required, mostly in the car and aeronautics industries.

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