SOUND POWER MEASUREMENT

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Abstract –. *This paper presents a typical sound power measurement of a hammer drill machine, following the standard ISO 3741:2011. All measurements took place in a residence which qualifies as a reverberant chamber located in Buenos Aires, Argentina . The sound power value is presented with a type A weighting in third-octave bands frequencies. A comparison is made between the sound power values measured and those provided by the manufacturer.*

INTRODUCTION

Sound power is the rate at which sound energy is emitted per unit time. It represents the power of a force radiated on a surface towards the medium of propagation. Sound power is not dependent of the room nor the distance, it is the total power emitted by the source in all directions.

Its value is commonly obtained by measuring sound pressure at a point in space despite being room and distance dependent.

Sound power is the descriptor of noisiness of a sound source and its measurement plays an important role determining specifications for noisy machines, for instance.

The objective of this paper is to measure the sound power level of a hammer drill machine according to ISO 3741:2011[] and to make a comparison between the results and those provided by the manufacturer.

FRAMEWORK

Sound power level is defined as ten times the logarithmic ratio between sound power and a reference of 1 pW, shown in equation 1.

$$Lw = 10\ log\left(\frac{W}{W0}\right) \quad (1)$$

Sound pressure level is defined as ten times the logarithmic ratio of the time T integrated sound pressure p squared and the reference of 20 μPa squared, as shown in equation 2.

$$Lp = 10\ log\left(\frac{1}{TP_0^2}\int_{t1}^{t2} p(t)\ dt\right) \quad (2)$$

Reverberation time T_{60} is defined as the time taken by the acoustic energy to decay 60 dB in a room. For practical uses it is often measured the T_{10} which corresponds to a decay of 10 dB.

The acoustic absorption coefficient α is the fraction of acoustic power that has not been reflected by a surface. By multiplying this coefficient to each surface the equivalent absorption area A can be obtained.

It is possible to obtain the sound power level by measuring sound pressure level corrected by airborne noise terms and considering the room´s volume, total surface and reverberation time as well as meteorological parameters such as temperature and static pressure.

SOUND SOURCE SELECTION

For this measurement, the machine used as a sound source is a hammer drill. The product name is Einhell TH-ID720E and it is shown in Figure 1.

Figure 1: Sound source, Einhell TH-ID720E, Hammer Drill Machine.

This product is made by Einhell in Germany, assembled in China. The hammer drill is powered by main´s electricity at 220V, 50Hz. Its total electrical power is 720 W, working at up to 2700 RPM in the drill mode and up to 43200 RPM in hammer mode. The machine has a rotary knob that modifies the power output..

Table 1 shows sound specifications of the machine provided by the manufacturer, which include sound power level as well as sound pressure level, A-weighted, including measurement uncertainty. However, it does not provide third-octave band levels.

Table 1: Manufacturer sound specifications

L_{pA} Sound Pressure Level	95.6 dB(A)
K_{pA} Uncertainty	3 dB
L_{wA} Sound Power Level	106.6 dB(A)
K_{wA} Uncertainty	3 dB

Measurements were done in accordance with EN 60745 standard. The manufacturer recommends the use of earmuffs in order to avoid hearing damage. Specifications for the vibration emission value (a_h) are also provided in various applications from hammer drilling in concrete to drilling in metal.

The hammer drill weighs 2.1 kg and is 325 mm long, 242 mm tall and 80 mm wide. Its volume is calculated to be around 2 L. Dimensions of the hammer drill are shown in Figure 2.

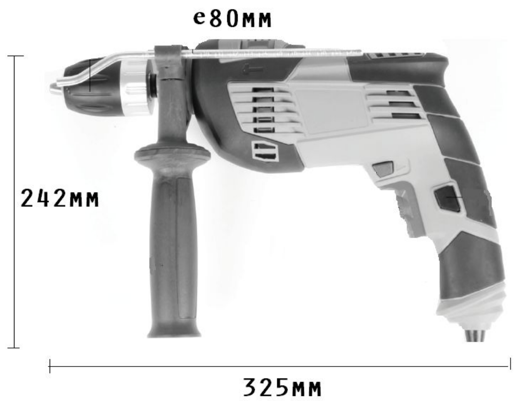

Figure 2: Sound source dimensions

Subjectively-evaluated, the machine makes a loud mid to high frequency noise. It could be said that some discrete frequencies can be heard. This presumption was later supported by frequency response measurements.

STANDARD SELECTION

The standard used by the manufacturer for noise and vibration measurements is EN 60745, which is based on the ISO 3740 series. However, it does not specify the standard version. One of them, 60754-1 “for general requirements”, suggests the use of the ISO 3744 which uses a semi-anechoic chamber with a reflection surface as measurement environment. Such environment requires a room with little to no reflections at all. The reflective surface must have an absorption coefficient lower than 0.06.

Due to the machine dimensions it is suggested a semi-spheric arrangement. For this arrangement, the standard details the positions of every microphone very precisely. In this case the sound source is a portable machine, which needs to be measured in a normal use scenario, which implies being hold by an operator while it is measured. This procedure may influence considerably the stability of the center position of the sound source by inevitable human motion, invalidating the measurement. This effect could be even worse when dealing with direccional and discrete frequency sound sources, such as this hammer drill analysed.

For this reasons it is prefered a more controlled type of measurement. The ISO 3744 is a class II engineering method, which gives less accurate results than a class I precision method, such as the ISO 3741. This standard would allow the use of a reverberant chamber and a measurement configuration that does not depend on a geometric pattern as it benefits from the diffused field, obtaining more accurate results. Moreover, reverberant chamber´s requirements are easier to meet than those of a semi-anechoic chamber and reflective surface.

Therefore, the standard chosen for this measurement was the ISO 3741:2011.

Broadly speaking it was chosen considering sound source dimensions, class I precision accuracy, A-weighted third-octave-band resolution; benefits associated to a reverberant chamber method for the measurement of hand held machines and finally, the availability of such chamber that satisfies the standard required conditions.

STANDARD´S METHOD

Standard Description

The ISO 3741:2011 belongs to the series of ISO 3740 to ISO 3747 which specifies several methods for determining acoustic power and energy levels depending on the sound source, room type and precision degree. The ISO 3741 is a precision method grade 1 which requires a reverberation room as test environment. By using this method it is possible to determine sound power level in third-octave bands with A-weighted and unweighted levels.

Equipment such as microphones, cables and instrumentation must be class 1 according to standard IEC 61260.

Chamber requirements

The standard allow any source volume less than 2% of the reverberant chamber´s total volume, V, which has to be at least 70 m^3 for center band frequencies of interest greater than 200 Hz. Otherwise, the standard specifies the volume needed for each case, shown in Table 2.

Table 2: ISO minimum chamber volume

Lower third octave frequency of interest	Minimum chamber volume required
200 Hz	70 m^3
160 Hz	100 m^3
125 Hz	150 m^3
100 Hz	200 m^3

Microphone and source positions

The standard requires at least 6 microphone positions (N_M) for wide band sound source emission, but this number may increase for narrow band and discrete frequency sources depending on the standard deviation, taken considering each microphone measurement. If it is lower than 1.5 dB, a total of 6 microphone positions will be enough for each third octave band. However, if it is greater than 1.5 dB, the number rises to 15 microphone positions counting for each third octave band. Moreover, if the standard deviation is greater than 3 dB, a total of 30 microphone positions are needed. The number of sound source positions, Ns, is also dependant of the standard deviation as shown in equation 3, where Ks is a tabulated factor based on the standard deviation.

$$Ns \geq Ks \left[\frac{T_{60}}{V} \left(\frac{1000}{f} \right)^2 + \frac{1}{N_M} \right] \quad (3)$$

Every microphone must be more than 1 m apart from any wall and d_{MIN} from the source, calculated using equation 4.

$$d_{MIN} = 0.16 \sqrt{\frac{V}{T_{60}}} \quad (4)$$

The source must be more than 1.5 m from any wall. Distances between microphone and sources positions must be at least $\frac{c}{2.2 f\, min}$ meters apart. Every measurement must be longer than 10 seconds for bands of interest higher than 200 Hz but longer than 30 seconds for bands lower than 160 Hz.

Background Noise corrections

Once all measurements are gathered, SPL is averaged for each microphone position considering the number of sound source positions. For differences of source to noise level lower than 15 dB, the standard applies a noise correction factor, K1, which depends on the difference level and the band frequency. For both cases when the difference is greater than 10 dB in frequencies between 250 Hz and 5 kHz, and differences greater than 6 dB in frequencies lower than 200 Hz and higher than 6300 Hz, the K1 is obtained using equation 5.

$$K1 = -10 \log \left(1 - 10^{-0.1Lp} \right) \quad (5)$$

For differences lower than 6 dB, K1 is set to 1.26 dB or 0.46 dB depending on the third octave band. The noise-corrected sound pressure levels are obtained by subtracting the corresponding K1 factor to each non-corrected SPL third octave band value.

Afterwards, all microphone positions are averaged for each third octave band according to equation 6.

$$L_P = 10 \log \left[\frac{1}{N_M} \sum_{1}^{N_M} 10^{0.1Lpi} \right] \quad (6)$$

Sound Power Level

Finally, the sound power level is obtained by adding to the Lp value in each third octave band a term which contains parameters that describes chamber and meteorological characteristics. This term is composed by smaller terms explained as follows: the tenth logarithmic ratio of the absorption equivalent area; added to the tenth logarithmic ratio between the surface area times sound´ speed and eight times the volume times the third octave band central frequency; added to 4.34 times the ratio of the equivalent area to the total surface; added to the reference and radiation correction factors C1 and C2, ending with the subtraction of 6 dB. Corrections factors C1 and C2 are dependent of the static pressure and temperature measured in the reverberant chamber at the moment of the measurement. General formula for obtaining the sound power level is shown in Annex.

MEASUREMENT SETUP

The reverberant chamber chosen for this measurement is a living room of a private property located in a residential area of Buenos Aires province in Argentina. The dimensions are shown in Table 3 and Figure 3.

Table 3: Reverberant chamber dimensions

Parameter	Value
Length	8.75 m
Width	3.45 m
Height	2.72 m
Total Surface Area	138 m^2
Total Volume	78.22 m^3

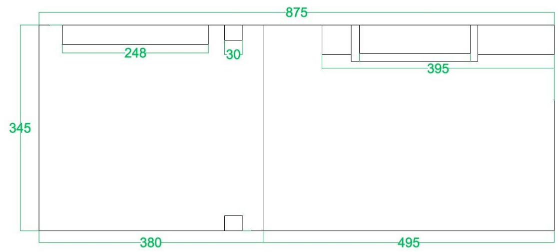

Figure 3: Reverberant chamber dimensions [cm]

The room satisfies the minimum chamber volume required by the standard for measurements with a 200 Hz center frequency band of interest and above. It has a 12 cm step which divides the floor surface, it has 2 columns by the walls and some furniture surfaces attached to the walls.
From the dimensions it can be calculated the volume to surface ratio, which needs to be lower than the reverberation time for each third octave band measured in the room following the standard requirements.

Static pressure and temperature were recorded before and after the measurements took place.
Positions for each microphone measurement were printed on the floor using masking tape considering minimum microphone, source and walls separations.

Equipment used
The equipment used in this measurement are listed below:

- Behringer ECM8000 Microphone
- XLR, USB cables
- Mic Stands
- Focusrite Scarlett 18i6 Audio interface
- Svantek SV-30-A Calibrator
- Balloons
- Macbook pro

Microphones were calibrated before and after each series of measurements as specified by IEC 60942 standard. Signals to be processed were recording using Audacity software.

METHOD

In order to measure the machine in real case scenario, it is a good idea to test the hammer drill in more than one mode. In this case, the machine is measured working by itself and over a wooden surface.
In this section is described the methodology applied in order to obtain the sound power level.
Before starting the measurements, it is recommended to perform a preliminary frequency response measurement as it helps determine its tonal characteristics and frequency range. From this range, a minimum and maximum center band frequency of interest must be chosen. In the case of this machine, 250 Hz was chosen as the lowest frequency of interest considering chamber volume and the lack of noise content in the 200 Hz band, whereas 10 kHz was chosen as the highest frequency of interest, being the upper limit considered by the standard.

Calibration
In order to obtain real SPL values, microphones must be calibrated with a reference level produced by a Svantek calibrator. The calibration procedure consists of attaching the calibrator to each microphone connected by a particular xlr cable to the preamplifier that will be used during the measurement. The preamp level must be set avoiding clipping levels, and not changed after the whole measurement is finished. In this case, each microphone and preamp pair was calibrated to 94 dB at 1 kHz sinusoidal signal.

Reverberation Time
Reverberation time was obtained following ISO 354 standard. A total of 10 balloons were used in different room positions avoiding symmetrical configurations. The room was equipped with an air conditioner with dehumidifier capabilities. The dehumidifier was turn on for an hour and stopped

immediately before starting the measurements. Microphone position was changed after every measurement. For this instance it was used a Behringer ECM8000 microphone through a Focusrite 18i6 preamp and AD converter. Samples were recorded at 44.1kHz, 16 bit in Audacity freeware environment. The resulting signals were processed afterwards by a custom RT-calculator program developed in Matlab and also with the use of “Aurora-Acoustical Parameters-Module” in Audacity recording software. By this procedure, it was obtained the T30 parameter for each third octave band.

Background Noise

In order to obtain the sound power level, Leq must be measured first which has to be noise corrected depending on level differences between sound source and background noise. While the machine is powered off, several measurements are performed in different places of the reverberant chamber in order to obtain the background noise level. 15 Microphone positions were used with 10 second length recordings across the room.

Sound Pressure Level

The sound power level measurements of the background noise and machine noise were obtained with the ISO 3741 direct method previously described. For this measurements, the machine was set to operate in the maximum power drilling mode, as recommended by the standard. The machine was held by a standing person who triggered it while it was being recorded by two microphones simultaneously, which positions were changed afterwards, sequentially until the first 6 preliminary measurements were done, 30 seconds long each. This recordings were processed on site by an Excel spreadsheet previously programed to calculate the maximum standard deviation and minimum microphone and source positions. In this case, the standard deviation was 2.9 dB which implied a minimum of 15 microphone positions for each of the 2 sound source positions needed. Minimum recording length was calculated to be 10 seconds. Measurements were carried out until reaching the minimum microphone positions number required by the standard. This procedure was done for the case in which the machine was held in the air and then repeated for when the machine was being used over a wooden surface. This surface consists of a 11 x 8.5 cm rectangular box, 60 cm high. Finally, a total of 30 background noise levels were recorded in different positions. The total amount of recordings done for this measurements was 90 files using a Macbook pro computer.

Figure 3: Measurement Set up

Figure 3 shows the measurement set up used, two microphone positions were displaced within the contour boundaries marked with masking tape on the floor. The inner rectangle allows for sound source positions whereas the outer rectangle delimits microphone allowed positions. For every sound source position, 15 measurements were done maintaining minimum distance between microphones. Microphones were placed every

Sound Meter

The audio recorded by each microphone associated to its preamp can be processed by a computer code in order to extract the SPL values developed in Matlab.

Once the audio and calibration files are imported, the user runs the calibration process, which converts the recorded signal to Pascal units. Then the user can choose between the standard integration times: fast, slow or impulse, meaning 1 s, 135 ms and 35 ms respectively. Afterwards, the third octave filter is applied meeting the requirements in ANSI S1.11-1986 standard as shown in Figure 4.

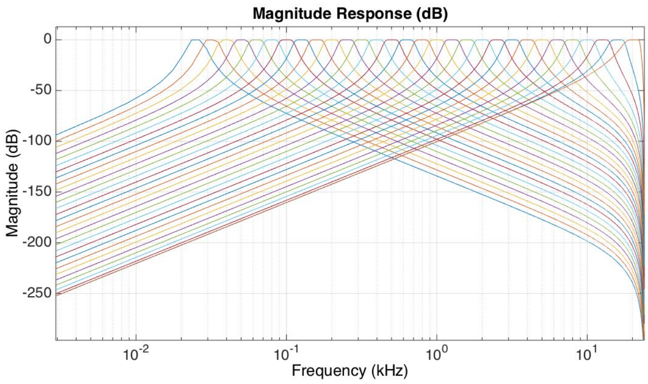

Figure 4: Filter design meeting ANSI S1.11-1986.

The ponderation is applied by user's choice (A, B, C or Z, no ponderation) and the figures are displayed. The data shown indicates the global SPL value throughout time and another plot for any frequency chosen (centered in third octave bands). A spectrogram of the original signal is shown as well as the global Leq value obtained. The data can be exported into a normalized Excel spreadsheet and into a .csv file as a backup.

Excel Sound Power Calculator

After the developed sound meter obtains every sound pressure level in third octave bands from every measurement, it is time to apply the standard 3741 method´s averages and corrections in order to calculate the sound power level. In order to accomplish this, an excel spreadsheet was developed. It requires user´s input data such as minimum and maximum frequencies of interest, chamber dimensions, third octave reverberation time, microphone and source positions used; and meteorological parameters. Once the SPL arrays from each microphone position is loaded into the sheet, algorithms compute the corrections and calculate the sound power level for every third octave band in A, B, C and Z weightenins. The program also compiles the results into a printable technical data formal presentation format.

Uncertainty calculation

ISO 3741 considers the total standard deviation as the uncertainty level u(Lw). It uses the mathematical model described in ISO 98-3, which can be substituted with interlab measurement results.

The standard deviation σ_{TOT} is the combination of deviations associated with the method reproducibility and measurement working conditions as described in equation 6.

$$\sigma_{TOT} = \sqrt{\sigma_{RO}^2 + \sigma_{OMC}^2} \qquad (6)$$

The expanded uncertainty can be calculated as shown in equation 7.

$$U = k\ \sigma_{TOT} \qquad (7)$$

Considering a normal distribution, for a confidence value of 95% it is required a k value of 2.

Depending of the machine characteristics, for little time variations, σ_{OMC} can be set to 0.5 dB; on the other hand, for unstable machines, values should be closer to 2 dB up to 4 dB. It can be obtained by calculating the standard deviation of consecutive measurements with a fixed microphone position, usually where sound pressure levels are the highest in the room. In this case, 3 consecutive measurements in 6 different microphone positions were recorded, each with a total length of 10 seconds. Each standard partial standard deviation was calculated independently and then combined by taking the square root of the sum of the partial deviations squared.

The deviation for working conditions can be obtained by considering independent deviations associated with environmental parameters such as static pressure, relative humidity, temperature, method, chamber volume, and reverberation time calculations. For a flat frequency response machine σ_{RO} can be set to 0.5 dB. However, because the machine used in this case does not qualifies as having a flat frequency response, the deviation is set to the maximum admissible values by the standard, shown in Table 4.

Table 4: Maximum σ_{RO}

Frequency band	σ_{RO}
100 - 160	3.0
200 - 315	2.0
400 - 5000	1.5
6300 - 10000	3.0

By maximizing the expected procedure deviation, resulting values are almost certain to fall in the uncertainty range. However, by doing this, the resulting range might become too large.

RESULTS & DISCUSSION

Meteorological Parameters

At the time of the measurement, meteorological parameters such as temperature, static pressure and humidity were recorded, as shown in Table 5. The standard allows greater meteorological parameter deviations for humidity levels greater than 50%, and is more tolerant to temperature variations for temperatures over 20°C. This variations consist of 10% and 5°C respectively.
Humidity levels have an effect over reverberation time for high frequency bands, lowering its values slightly.

Table 5: Meteorological parameters

Parameter	Value
Temperature	24°C
Humidity	95 %
Static Pressure	100.7 kPa

Reverberation Time

Reverberation time processed by Aurora´s T30 calculator module is shown in Figure 5.
It is shown that reverberation time is lowered by humidity conditions for high frequencies. The largest T60 values are associated to mid third octave bands. It may be possible that the actual reverberation time curve tend to be flatter with normal humidity conditions.
The T30 curve can be considered flat. Reverberation time average values are displayed in Table 6.

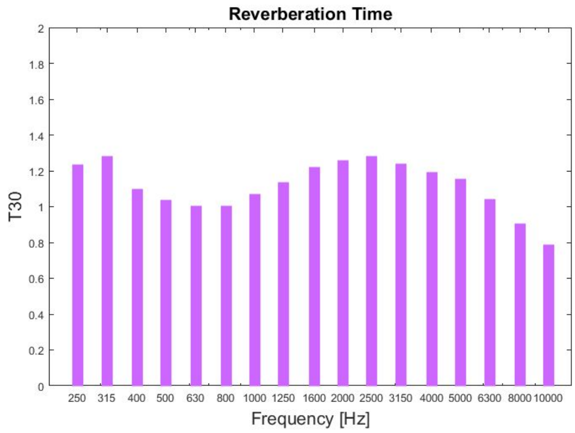

Figure 5: Reverberation Time

Reverberation time values are used to know the minimum distance allowed between microphone positions and sound source.
After applying equation 4, d min was calculated to be 1.59 m.

Table 6: Reverberation Time

Frequency [Hz]	T30 [s]
250	1.24
315	1.28
400	1.10
500	1.04
630	1.00
800	1.00
1000	1.07
1250	1.14
1600	1.22
2000	1.26
2500	1.29
3150	1.24
4000	1.20
5000	1.16
6300	1.04
8000	0.91
10000	0.79

From the T60 values it can be obtained the equivalent absorption coefficient, using Sabine's equation displayed in Annex for A.
It is observed that the equivalent absorption area calculated is significantly homogeneous across every third octave center frequency band. The equivalent absorption area is the biggest for high frequencies, particularly for 10 kHz. Because this A values come from RT values, the graph should have the same trend, but opposite at the same time.
Equivalent absorption area results are shown in Table 7.

Table 7: Equivalent Absorption Area

Frequency [Hz]	A [m2]
250	10.08
315	9.75
400	11.37
500	12.01
630	12.41
800	12.41
1000	11.67
1250	10.97
1600	10.21
2000	9.94
2500	9.72
3150	10.08
4000	10.46
5000	10.79
6300	12.00
8000	13.74
10000	15.84

Background Noise Levels

Noise levels were mainly caused by traffic noise. This can be seen by the increased low frequency levels shown in Figure 6. Every third octave band sound pressure level is lower than 35 dB (Z).
This means that for any third octave sound source level greater than 50 dB (Z), it will not be required any noise correction.
Values for background noise pressure levels are shown in Table 8.

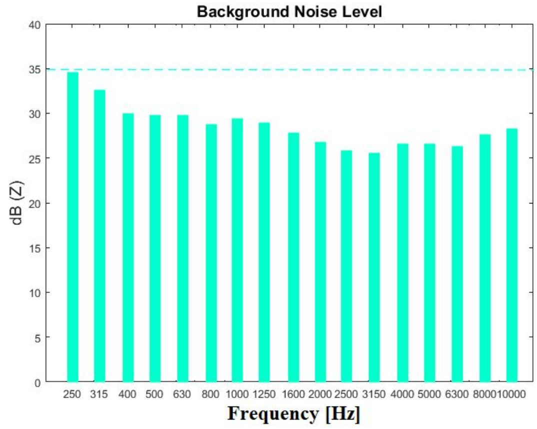

Figure 6: Background Noise Level

Table 8: Background Noise Levels

Frequency [Hz]	dB (Z)
250	34.69
315	32.66
400	30.06
500	29.81
630	29.90
800	28.79
1000	29.44
1250	29.03
1600	27.87
2000	26.83
2500	25.94
3150	25.64
4000	26.67
5000	26.70
6300	26.30
8000	27.71
10000	28.37

Every third octave band background noise value is greater than the maximum sound pressure level required by the standard in order to qualify for the absolute noise criteria. However, for this cases the standard allows the use of the relative noise criteria described in the methodology section which compares its difference with the machine noise levels. Results can be seen in Figure 8.

Tonal Characteristics

Once the initial parameters are calculated and after the preliminary tests are processed, it is time to determine the machine tonal characteristics that will define the minimum microphone and source positions.

By performing a frequency response analysis in Audacity and exporting its results to matlab environment for plotting, it is obtained the frequency response of the machine, shown in Figure 7.

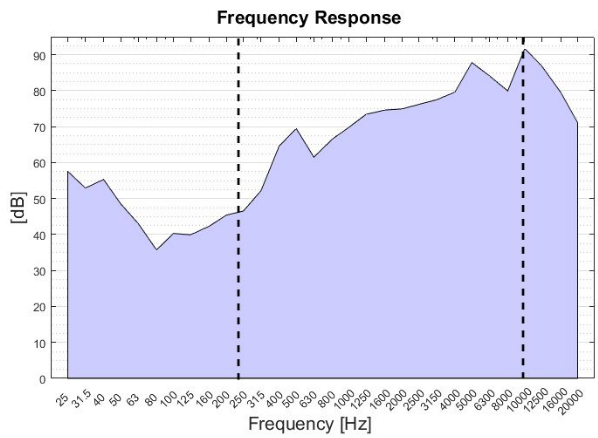

Figure 7: Machine frequency response

By analyzing its shape and comparing to background noise levels, the minimum frequency of interest was set to 250 Hz. The highest frequency of interest is 10 kHz which is also the maximum frequency allowed by the standard. Frequency response fells almost sharply for bands from 12500 to 20000 Hz, in spite of maintaining a considerable level overall. Levels per third octave band for a particular measurement are shown in figure 6.

In a deeper analysis of the machine´ spectrum, distinctive discrete frequencies can be found. This frequencies are 446, 890, 5442, 11092, 16512 and 21815 Hz. Each one is a multiple integer of the fundamental, meaning they are harmonics.

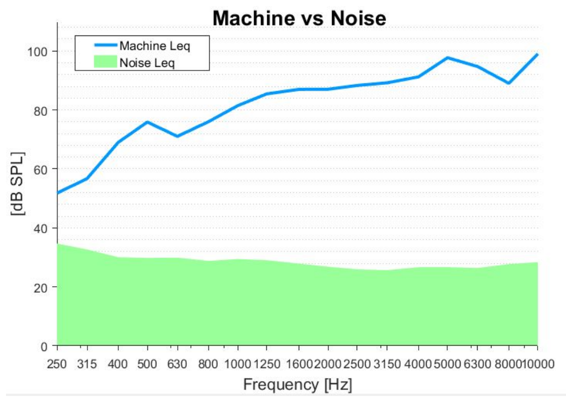

Figure 8: Machine Leq vs Background Noise

Standard deviations obtained in the preliminary measurements are shown in Figure 9. It can be observed that standard deviation for a total of six, 30 second long, different positions measurements varies a lot depending on the frequency. It is the lowest for mid range frequencies and increases both for low and high frequencies. Most bands have deviations lower than 1.5 dB. However, maximum deviation occurs at 250 Hz, with a value of 2.9 dB, which is lower than 3 dB but greater than 1.5 dB.

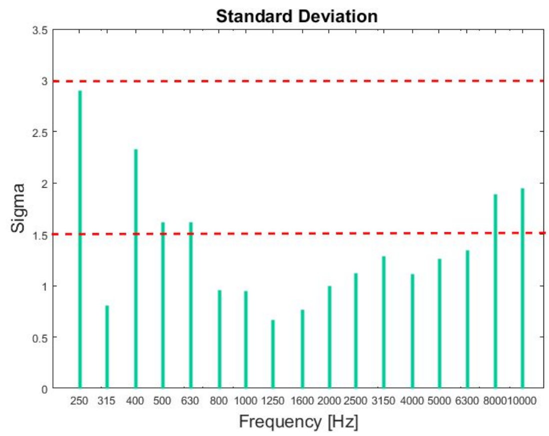

Figure 9: Preliminary Standard Deviation

Based on this result, and according to the standard requirements, the machine is considered to have discrete frequency noise levels. Therefore, 15 microphone positions are required for each sound source position, which is calculated to be 2, according to equation 3 detailed in previous sections.

Sound Pressure Level

Once knowing the number of different microphone and sound source positions, as well as their minimum distances, machine noise pressure levels can be measured following ISO 3741 methodology,

Every resulting third octave band level in every microphone position for every source position is loaded into an Excel spreadsheet calculator which applies the standard algorithms and noise corrections. This procedure is done for both working modes of the machines, by itself and drilling over a wooden surface.

Sound pressure levels obtained for each mode are shown in Table 9.

Table 9: Sound Pressure Level [Lp]

Frequency [Hz]	**AIR** [dB(Z)]	**WOOD** [dB(Z)]
250	60.36	63.68
315	63.30	65.61
400	73.79	77.01
500	79.07	77.44
630	72.92	73.35
800	76.82	77.58
1000	81.43	81.00
1250	84.84	84.46
1600	85.96	85.15
2000	84.80	85.24
2500	86.99	86.21
3150	87.99	87.03
4000	90.20	89.23
5000	97.19	96.11
6300	94.80	92.44
8000	90.12	88.72
10000	101.50	99.81

Looking at the averaged sound pressure levels for both modes in Table 9, it is observed that no value is lower than 50 dB, which represents a 15 dB difference to the highest background level. This is also true for each individual microphone position measurement, which shows that no noise correction coefficient is needed for the selected third octave frequency range of interest.

Sound Power Level

Following ISO 3741 standard, the sound power level is calculated by taking the sound pressure level for every third octave band and add some terms which are associated to the reverberant chamber characteristics and meteorological conditions at the time of the measurement. This terms are shown in detail in the Annex section, A1.

Calculation demonstration

For the third octave band with central frequency of 1 kHz, the non corrected averaged acoustic sound pressure level of the machine at full power by itself is equal to 81 dB(Z). Considering background noise level for 1 kHz is lower than 29.5 dB(Z), the difference is more than 50 dB. For differences greater than 15 dB, noise correction coefficient is not applied. Therefore, the corrected sound pressure level is equal to 81 dB (Z). The equivalent absorption area for 1 kHz is calculated with equation 8.

$$A = \frac{55.26}{c}\left(\frac{V}{T60}\right) \qquad (8)$$

Where the volume V is equal to 78.22 m^3, the reverberation time for 1 kHz is 1.07 s and the sound speed c is calculated to be 345.54 m/s considering a temperature of 24°C at the time of the measurement. The equivalent absorption area for 1 kHz is equal to 11.67 m^2.

For the next calculations it is needed the total surface of the chamber, which in this case is equal to 138 m^2.

The last coefficients needed in order to obtain the sound power level are C1 and C2, shown in equation 9 and 10.

$$C1 = \left[-10\ log\left(\frac{p}{P0}\right) + 5\ log\left(\frac{273+\theta}{\theta 0}\right)\right] \qquad (9)$$

$$C2 = \left[-10\ log\left(\frac{p}{P0}\right) + 15\ log\left(\frac{273+\theta}{\theta 0}\right)\right] \qquad (10)$$

Where $\theta_0 = 314\,K$ and $\theta_1 = 296\,K$. C1 and C2 coefficients are calculated to be -0.0929 dB and -0.3324 dB respectively considering temperatures of 24°C and static pressure levels of 100.7 kPa.

Adding all this values will return the Lw value for 1 kHz as described in the standard´s methodology previously explained and shown in annex A1. This value is 86.34 dB (Z). In order to obtain the Lw A-weighted, it is necessary to add the corresponding weighting correction, which in the case of 1 kHz corresponds to 0 dB. Therefore, the final Lw value for 1 kHz calculated is 86.34 dB (A).

If this calculations are repeated for every third octave band, it can be obtained the sound power level for each center band frequency of interest. Sound Power levels calculated for every third octave band for both “air” and “wood” modes are shown in Table 10.

It can be observed that sound power levels, for the case in which the machine was drilling over a wooden surface, are slightly lower than those obtained by measuring the machine by itself, on the air. This power loss may be due to friction generated by the wood resistance to the drilling bit movement, which results in a slower bit speed, and subsequently, lower sound pressure value measured.

Table 10: Machine Sound Power Level [Lw]

Frequency [Hz]	**AIR** [dB(Z)]	**WOOD** [dB(Z)]
250	65.45	63.68
315	68.02	65.31
400	79.04	77.01
500	84.44	77.44
630	78.32	73.35
800	82.12	77.58
1000	86.36	81.00
1250	89.42	84.46
1600	90.15	85.15
2000	89.82	85.24
2500	90.88	86.21
3150	92.02	87.03
4000	94.39	89.23
5000	101.50	96.11
6300	99.59	92.44
8000	95.55	88.72
10000	107.61	99.81

Differences between "air" and "wood" modes are minimal in broad terms, however, for some third octave bands differences are more significant, specially for the bands of 500, 6300, 8000 and 10000 Hz. This bands are linked to the machine´s discrete frequencies found in previous spectrum analysis. It is possible that the wooden surface restricts the bit´s speed and therefore, resonant frequencies associated to the drills revolutions are lowered consequently.

A-weighted third octave values for sound power level are shown in Table 11. Differences in levels between modes in this chart are considerably smaller.

Table 11: Machine Sound Power Level [Lw]

Frequency [Hz]	**AIR** [dB(A)]	**WOOD** [dB(A)]
250	56.85	60.17
315	61.42	63.42
400	74.24	77.46
500	81.24	79.60
630	76.42	76.85
800	81.32	82.07
1000	86.36	85.93
1250	90.02	89.64
1600	91.15	90.33
2000	91.02	90.46
2500	92.18	91.40
3150	93.22	92.26
4000	95.39	94.41
5000	102.00	100.92
6300	99.49	97.14
8000	94.45	93.05
10000	105.11	103.42

Third octave band values between modes are also visually compared in Figure 10.

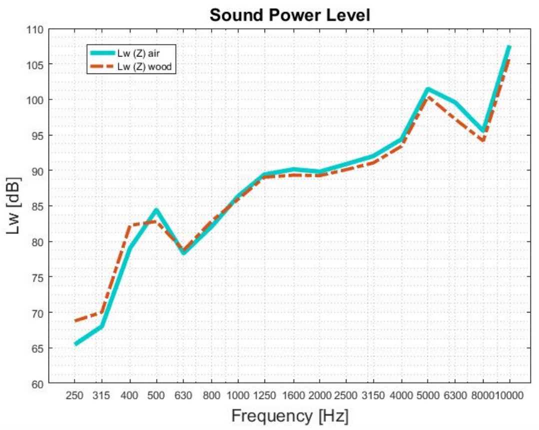

Figure 10: Machine´s sound power level over air and wood

Uncertainty

Uncertainty values are determined with a k=2 factor, which offers a 95% confidence value for the $Lw \pm U$ range. The standard deviation for each third octave band was calculated following ISO 3741 recommendations previously described in the methodology section. Because the machine was shown to have discrete frequencies, σ_{RO} value could not be assumed to be 0.5 dB. Instead, the standard´s maximum deviations were used. σ_{OMC} values were calculated considering repeated measurements with the same microphone positions. The combined σ_{TOT} was obtained applying equation 6. Uncertainty values for each third octave band were used for both sound pressure level and sound power level results, shown in Table 12 for both modes.

Table 12: Uncertainty [U]

Frequency [Hz]	**AIR** [dB]	**WOOD** [dB]
250	5.07	5.23
315	4.61	4.77
400	4.64	4.83
500	4.59	4.73
630	3.25	3.52
800	3.24	3.70
1000	3.29	3.52
1250	3.38	3.62
1600	3.21	3.50
2000	3.17	3.36
2500	3.11	3.37
3150	3.17	3.39
4000	3.19	3.52
5000	4.00	4.36
6300	6.78	7.01
8000	6.17	6.32
10000	6.59	6.81

Uncertainty levels shown in the chart are two times the deviation value. Which means, it can be assured with a 68% of confidence that the real Lw value is within the range of half the uncertainty values shown. Deviation is lowest for mid range third octave bands, however, it grows for both lower and higher frequencies , reaching a maximum at 10 kHz (due to operator´s acoustic shadow), with 6.59 dB and 6.81 dB for air and wood modes respectively. This values are used later for each global uncertainty.

Final Results

Final global values are reported in Table 13.

Table 12: Uncertainty [U]

Parameter	Air	Wood
Lp	103.42 dB (A)	102.03 dB (A)
Lw	108.54 dB (A)	107.09 dB (A)
U[95%]	6.59 dB	6.81 dB
U[68%]	3.29 dB	3.41 dB

Global sound power level given by the manufacturer's data sheet is 106.6 dB (A) with an uncertainty of 3 dB. The Lw measured in this work is within the range for both the “air” and “wood” measurements. However, the manufacturer does not clarify the confidence level of their uncertainty value, which is assumed to be 95%. Sound pressure level given by the manufacturer is 95.6 dB with 3 dB of uncertainty. This level is considerably smaller than the ones obtained in this work for both modes, however, this may be due to difference in measurement procedure, as the manufacturer may have used an anechoic chamber for its measurements, resulting in a much lower sound pressure level than the one obtained in a reverberant chamber. After all, Lp is a property which depends on the environment while Lw is a property associated to a sound source, independently of the chamber used.. Lw third octave sound power levels described in Table 11 are also shown in Figure 11.

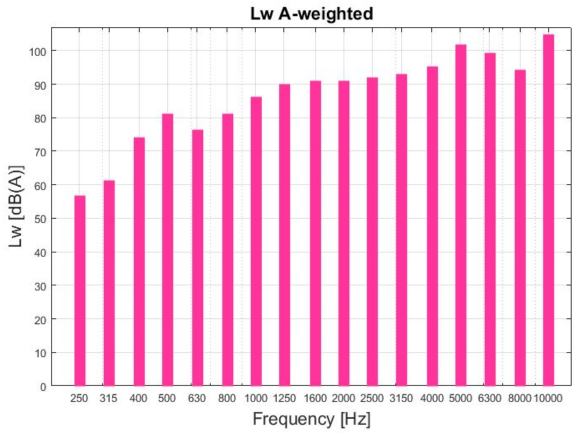

Figure 11: Machine´s sound power level

It is necessary to stress that deviation values in this measurement were set according to the maximum values allowed by the standard, considering a machine with tonal characteristics. In practice, this values could be considerably smaller, resulting in a much lower uncertainty overall.

CONCLUSIONS

Being able to measure the sound power of this machine in such non-ideal environment as described with results close to the specified by the manufacturer is considered a success.

A fully-functional sound meter software was developed in Matlab, resulting in an useful tool for any sound engineer or related professional, as well as was useful in this measurement to *translate* the digital data into SPL information for the sound power calculations.

For this measurement, it was chosen a higher precision method to evaluate the sound power level of the machine than the one used by the manufacturer. However, maximization of standard deviation levels due to the tonal characteristics of the machine led to larger uncertainty levels than expected.

We were surprised about the close values in both conditions: the drill by itself and with a wooden piece, as we expected intuitively much more difference in an early stage. It can be explained as described in the calculation demonstration as a result of the friction generated by the wood resistance to the applied force and the result of the interaction between the drill and the wooden shape.

Although a dodecahedron was not used for the RT measurement as recommended by the standard, the results using balloons is a certain approximation to the real value, mostly in the analysed spectrum portion.

Despite having a bunch of different uncertainty results (from 3 to 7 dB), it should be considered depending on each third-octave center frequency. Most of the measured bands present an uncertainty value around 3 dB, same value as given by the manufacturer and acceptable for this kind of experiments.

REFERENCES

-ISO 3740:2001, Acoustics. Determination of sound power levels of noise sources. Guidelines for us of basic standards.

-ISO 3741:2011, Acoustics. Determination of sound power levels and sound energy levels of noise sources using sound pressure. Precision methods for reverberation test rooms.

-ISO 3744:2011, Acoustics. Determination of sound power levels and sound energy levels of noise sources using sound pressure. Engineering methods for an essentially free field over a reflecting plane.

-ISO 60745-1:2007, Acoustics. Handheld motor operated electric tools. Safety. Part 1. General requirements.

-ISO 6926:2002 Acoustics. Requirements for the performance and calibration of reference sound sources used for the determination of sound power levels.

-ISO 3382:1997 Acoustics. Measurement of the reverberation time of rooms with reference to other acoustical parameters.

ANNEX

A1: Sound Power Level Calculation

$$L_W = \overline{L_{p(\mathrm{ST})}} + \left\{ 10\ \lg \frac{A}{A_0} \mathrm{dB} + 4{,}34 \frac{A}{S} \mathrm{dB} + 10\ \lg \left(1 + \frac{S\,c}{8\,V\,f} \right) \mathrm{dB} + C_1 + C_2 - 6\ \mathrm{dB} \right\}$$

$\overline{L_{p(\mathrm{ST})}}$	corrected acoustic sound pressure level
$A = \frac{55{,}26}{c} \left(\frac{V}{T_{60}} \right)$	equivalent absorption area
$A_0 \quad = 1\ \mathrm{m}^2$	reference area
$p_{\mathrm{s},0} \quad = 101{,}325\ \mathrm{kPa},$	reference static pressure
$\theta_0 \quad = 314\ \mathrm{K},$	reference temperature 0
$\theta_1 \quad = 296\ \mathrm{K}.$	reference temperature 1
$C_1 = -10\ \lg \frac{p_\mathrm{s}}{p_{\mathrm{s},0}} \mathrm{dB} + 5\ \lg \left(\frac{273{,}15 + \theta}{\theta_0} \right) \mathrm{dB}$	correction coefficient 1
$C_2 = -10\ \lg \frac{p_\mathrm{s}}{p_{\mathrm{s},0}} \mathrm{dB} + 15\ \lg \left(\frac{273{,}15 + \theta}{\theta_1} \right) \mathrm{dB}$	corection coefficient 2

PREGUNTAS:

1. *¿Cuándo una fuente de ruido es considerada tonal? Referencie en relación a una norma.*

Una fuente de ruido es considerada tonal al generar alta energía acústica en frecuencias discretas, distinguibles por encima del resto del espectro. Según la norma ISO 3741, si la desviación típica de los niveles de presión acústica, S_M, obtenidos a partir de la ecuación (10) excede de 1,5 dB para una o más bandas de tercio de octava, la fuente sometida a ensayo emite sonido que contiene componentes de frecuencia discretas significativas. Esto implica que si entre diversas mediciones hay una desviación superior a 1.5 dB, se considera fuente tonal y se deben llevar a cabo mayor cantidad de puntos de medición para poder mapear correctamente el mensurando. Esto también puede ser interpretado como una indicación de patrón directivo de la fuente en cuestión, ya que si fuera totalmente omnidireccional, estando inmersa en un campo homogéneo, no debería darse esta diferencia. Por eso es que a continuación de la cita, la norma aclara que de no satisfacer esos valores, deben considerarse modificaciones en las posiciones de micrófono o en el recinto de medición. Difícilmente una máquina de estas características pueda generar un ruido no tonal, ya que al tener motores rotativos, se genera preferencia en la emisión por bandas relacionadas con la frecuencia de revolución de la herramienta. Como fue analizado en este caso, se genera una frecuencia fundamental y sus armónicos asociados, visibles en todo el espectro en cuestión.

2. *¿Qué conclusiones puede extraer al comparar la información brindada por el fabricante y los resultados obtenidos?*

A pesar de no haber podido lograr dar con un elemento con especificaciones de nivel de potencia sonora en resolución de tercio de octava, encontramos el presente taladro con indicaciones de nivel de presión y potencia sonora, junto con su incertidumbre de cálculo y la norma implementada, características que no suelen abundar en este tipo de elementos.
En líneas generales los resultados obtenidos y las especificaciones técnicas provistas por el fabricante son muy similares. Aun así, las diferencias entre ellos pueden devenir tanto de las diferencias en el método de medición como de las condiciones (presión estática, temperatura y/o humedad) en las que se mide. A su vez, el recinto también tiene su influencia sobre los resultados y su volumen, forma, superficies, materiales constructivos y su tiempo de reverberación son determinantes. Además al ser una máquina de mano, el error humano no deja de ser despreciable. La incertidumbre del método aplicado para este trabajo se solapa con la incertidumbre del método del fabricante por lo que se puede decir que los resultados son coherentes.

3. *¿El fabricante tiene laboratorios propios o envía las unidades a medir fuera de sus instalaciones?*

No se logró conseguir información sobre si la firma Einhell Germany tiene laboratorio propio o si terceriza las mediciones acústicas pertinentes para el análisis de sus maquinarias. Se hizo el intento de contactar a la industria en variadas oportunidades por diversas vías pero no se obtuvo respuesta alguna. Por otro lado, los manuales, tanto en formato digital como en formato papel, no especifican dónde o qué institución realiza los exámenes acústicos.

4.

¿Cuál es la incertidumbre de los resultados medidos?

La incertidumbre de los resultados obtenida es dos veces el desvío total que contempla las mediciones en cada modo de operación independientemente. El desvío total es una combinación entre el desvío de reproductibilidad del método, asociado a la norma y factores meteorológicos; y la incertidumbre debido a la inestabilidad de la máquina, que considera variabilidad en la obtención de resultados. El desvío total obtenido por banda fue muy variable, con máximos de 3.29 y 3.41 dB respectivamente para los modos de máquina al aire y sobre una superficie de madera. Para un nivel de confianza del 95% se utilizó un k de valor 2; por lo que la incertidumbre resultante en los valores globales es de 6.58 y 6.82 dB respectivamente. A primera impresión, son suficientemente altos para una norma de precisión de clase 1. Sin embargo esto se atribuye a que el desvió de reproductibilidad del método utilizado fue considerado en sus valores máximos admitidos por la norma, ya que es lo que ésta recomendaba en caso de no disponer una fuente de ruido con espectro plano.

5.
¿Cuáles son los factores de error más importantes en la medición realizada y cómo puede asociarlos a la incertidumbre obtenida?

Hay múltiples fuentes de errores posibles en esta medición. Con la intención de caracterizar la herramienta en uso normal, se presenta la fuente de error humana: el operario. Por el método implementado y los recursos técnicos disponibles, la medición tuvo que ser repetida gran cantidad de veces, con movimiento de micrófonos y de fuente, lo que provoca fatiga sobre quien opera el taladro durante las mediciones. Puede tender a no apretar del todo el gatillo, generando distintas velocidades del equipo y puede moverse la mecha sobre la madera durante su perforación y generar variedad de efectos de resonancia y acústicos sobre el ambiente. Asimismo, se produce cierta sombra acústica del operario sobre los micrófonos que se encuentran a su espalda, por lo que la medición en alta frecuencia probablemente se vea afectada. Por otro lado, la velocidad del motor está sujeta a condiciones eléctricas de la instalación de red del recinto de medición, con lo cual, cualquier variación de la tensión de red puede haber repercutido sobre la alimentación del taladro, lo que influye sobre su velocidad y por lo tanto el ruido emitido.

Los micrófonos utilizados suponen ser de respuesta en frecuencia regular y “plana”, pero es conocido en electroacústica que esa es una condición muy difícil de lograr para todo sistema electrónico y electroacústico, por lo que toda la medición es afectada por la respuesta en frecuencia resultante de toda la cadena de medición, sus distorsiones y ruidos y sus errores de cálculo y transducción.

Por otra parte, al ser una norma de complejidad por su diversidad de escenarios planteados según lo que se mida, cómo y dónde, puede estar sujeto a errores de interpretación, consideraciones no válidas para este tipo de ensayos, errores de cálculo manual y computacional, errores de lectura del instrumento, entre otros.

Al fin y al cabo, la intención es minimizar los errores sistemáticos implementando métodos estandarizados realizables con atención a los detalles según requiera por condiciones del mensurando.