Using a monopole sound power source to determine machinery sound power

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Summary

The sound power emission of machinery is used for specification of enclosures, barriers and isolation in buildings. And for verification of the actual sound power emission after installation. Determination of the sound power emission in an acoustic chamber, or in free-field are often impossible for large machines, or even for smaller machinery which depends on infrastructure for normal operation. On-site measurements in non-ideal acoustic environments are required.
The reference power source method is attractive because of limited complexity and time efficiency and it can be applied even when the acoustic environment is difficult. This paper relates to the reference sound power source method as described in ISO 3741 and later work.

To improve accuracy and efficiency of this type of measurements, a small and omni-directional reference power source is used. The source is based on a high acoustic impedance loudspeaker, such that it can be placed close to reflecting surfaces. And the internal sensors provide a sound power proportional signal. This allows adaption to the acoustic environment and to potential background noise by using an adapted level and signal type.

A vacuum cleaner was used as a time-stable test-object. Its sound power from three different sites was compared to investigate the reliability of the method and of the prototype sound power reference source.

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1. Introduction

The paper relates to the reference sound power source method as described in ISO 3741 and later work [9,10]. The intention of the study and development is to allow higher efficiency and accuracy of sound power identification using reference source measurements.
According to a study made by Kurtz and published recently [8], there are significant differences between the results obtained when following the different standards and none of them is known as a reference method. In fact, a European Metrology Research Program was started in order to obtain a reference method for determination of the unit watt in airborne sound, and was partially published by Brezes and Wittstock [11].
The reported work in this paper does not target the absolute accuracy of the unit watt, but it targets broader and more efficient application of the reference sound source methods. For this purpose, a new reference sound source (RSS) was developed. It differs substantially from most existing reference sound sources which are based on regulated fans and target a time invariable power level [1,2,3]. The new source solution is based on small loudspeakers with a high acoustic impedance an internal reference signal to provide a time invariable and sound power proportional signal. Others have also used a dodecahedron source calibrated for reference sound power measurements [4]. The sound source used in this investigation, as visible in Figure 1, has the following properties:

1. The potential output sound power level is high over a broad frequency range. Any type of generated signal can be used (band-limited period random, sine sweeps, chirps, etc.), because it is captured by the reference signal. This allows some adaption to the acoustic environment and to potential background noise.
2. The dimensions of the source are kept small (10cm diameter) and the design is chosen to have a good approximation of omni-directionality. This is to allow bringing the source much closer to the test object, at multiple locations, and under any inclination.
3. The small size and high acoustic impedance drivers make the sound power output more predictable.

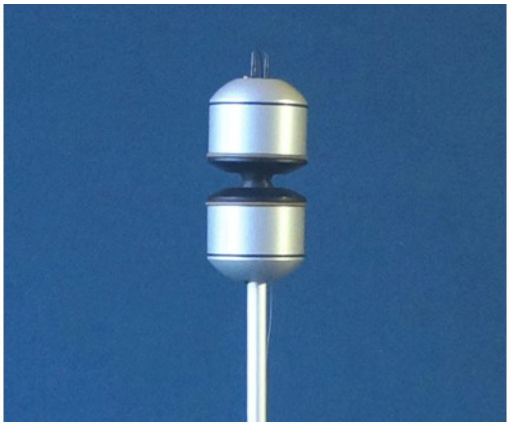

Figure 1. Small omni-directional source, used as power reference in this paper.

We will first repeat some theoretical background and ISO standards in section 2 [5,6,7]. Then, the properties of the reference source are measured and shown in section 3. The effect of nearby reflection on the sound power emission is shown in the same section. In section 4 a household appliance, vacuum cleaner, was used as a text object in three different sites.

2. Theoretical background

The determination of sound power characterizing the level of noise generated by machinery was a challenge at which engineers responded already more than four decades ago. The result of their research was a sum of methods which use either the sound pressure or the sound intensity as input data for determining the sound power level (SWL). From these methods a set of ISO standards was developed and since then, additional improvements were added systematically.

The theoretical basis for the sound power determination is a particular case of the Gauss theorem, which defines the sound power as the integral of the normal component I_n of the sound intensity vector over an imaginary surface S which envelopes the sound source.

$$P = \oiint_S \vec{I}\,\overrightarrow{dS} = \oiint_S I_n dS \qquad (1)$$

where:
I is sound intensity
P is the sound power

From this formula, two distinct approaches can be followed to determine the sound power. The only one discussed in this paper is based on a far field hypothesis. In this case, v_n is proportional to the sound pressure p and inverse proportional to the acoustic impedance:

$$I_n = \frac{p^2}{\rho c} \qquad (2)$$

where:
rho is the air density;
c is the speed of sound in air.
Introducing this term in equation 1, the sound power equation will have the following shape:

$$P = \oiint_S I_n dS \approx \frac{1}{\rho c} \sum_{i=1}^{N} \widetilde{p_i^2}\, \Delta S_i \qquad (3)$$

where:
$\widetilde{p_i^2}$ is the averaged squared sound pressure over a finite equal area surface.

Relation 3 is the basis of the standard sound power measurements defined by ISO 3741, 3744 and 3747 which use the measured sound pressure as input data. The medium in which the measurements are made can be a free field, a semi-free field, a diffuse field, or a combination of all which is the most common environment for on-site measurements and for each, a different standard method is available.

2.1 Sound power level in semi-free field

According to ISO 3744 [6], to determine the sound power of a source in a free field environment over a reflective surface, the measurements of the sound pressure over a hemisphere surface around the test object have to be made. At least ten points corresponding to ten equal area patches are needed to fulfill the requirements. Then, the surface averaged pressure is calculated and then introduced into the following formula in a relation which is distance dependent. The sound power is expressed as SWL in dB over 1/3 octaves bands.

$$L_w = \overline{L_{pf}} + 10lg(S/S_0) \qquad (4)$$

Where
Lw is the band power level of the source, in dB;
Lpf is the surface sound pressure level in dB;
S is the area of the measurement surface in m²;

2.2 Sound power in reverberant condition

When doing precision measurements according to ISO 3741 [5] in reverberant environments, two methods are used to determine the SWL of a noise source.

2.2.1. Direct method

This method uses less microphones positions than for ISO 3744 to obtain a similar result. In a highly diffuse field from a reverberant room, the sound pressure level

is measured by at least 3 microphones separated by a distance smaller than half the wavelength of the smallest center frequency band of interest.
The reverberation times T on each frequency band need to be measured as well. This is done by switching off a broadband noise source and measuring the time decay, projecting this to a 60 dB attenuation.
The other parameters that need to be known are the volume of the room and the total surface of the walls, the wavelength of each center frequencies and barometric pressure. The final relations is:

$$L_w = L_p - 10lg\frac{T}{T_0} + 10lg\frac{V}{V_0} + 10\,lg\left(1 + \frac{S\lambda}{8V}\right) - 10\,lg\left(\frac{B}{1000}\right) - 14, \qquad (5)$$

Where,
Lp is the mean band pressure level;
T is the reverberation time of the room in seconds;
V is the volume of the room in cubic meters;
Λ is the wavelength at the center frequency of the octave or one-third octave band, in meters;
S is the total surface area of the room, in square meters;
B is the barometric pressure in millibars.

There are requirements to homogeneity of sound pressure in the reverberation room. The dimensions must also be large enough to have sufficient modal density in the lowest third octave band. If the requirements are no longer met it can be visible as a larger variation in the sound pressure responses and in the reverberation time estimates over different source-microphone locations. And the reverberation time is the basis of the power estimation.

2.2.2. Reference method

The reference method is an alternative way to determine the SWL of a sound source in a reverberant room. The reverberation times and all the other room and atmospheric parameters are not needed anymore if a reference power source is available. The averaged sound pressure level of the test object is measured in the same way as for the direct method. Then, a calibrated reference sound source is placed instead of the test object and the sound pressure level is measured again. The SWL equation reduces to three terms like in the following relation:

$$\boldsymbol{L_w} = \boldsymbol{L_p} + (L_{Wr} - L_{pr}), \qquad (6)$$

Where,
Lp is the mean band pressure of the source in dB;
Lwr is the band power of the reference source in dB;
Lpr is the mean band pressure level of the reference source.

In a good reverberation room, directionality of the reference source is not critical because the room will average out this effect. The stability of the output power between the calibration of the source and the application as a reference is most important.

2.3 Sound power in non-ideal environments

A survey method was also developed for on-site sound power measurements and is described in ISO 3747. This method is very similar to the reference method described by ISO 3741, but in this case the microphones have to be placed in the center of the free faces of a rectangular parallelepiped surface covering the source and with the sides parallel to those of the reference source at a distance which is bigger or equal with 1 m. The setup is visually represented in Figure 2, for an open situation and near wall situation. In the case the source has a horizontal dimension larger than 1m, additional microphones are added in the corner positions. For situations with a nearby wall another configuration with more microphone location is possible.

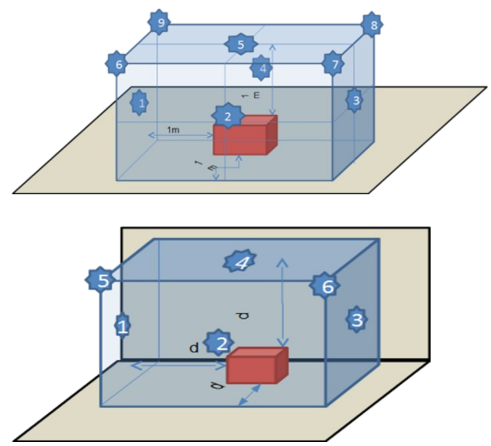

Figure 2. Test-object and microphone positioning according to ISO 3747

For the reference source measurement according to ISO 3747 the power reference source (RSS) is placed either on top of the test-object, or on the floor, replacing the test-object in the test-site.
When performed according to the described method of the standard, the measurement uncertainty is expected at a standard deviation of 4 dB for broad band noise and 5dB for discrete tone sources.
This larger uncertainty on the power estimation using the reference source method in non-ideal sound fields can be related to different effects:
1. The directionality of the test-object as well as the directionality of (traditional) RSS will differ and lead to variation in the pressure response in an arbitrary

environment at different positions, because only reverberant rooms are insensitive to this effect. And in (semi) free-field, the differences are carefully averaged out over multiple microphone locations.
2. The test-object can be large compared to the room dimensions, or large compared to the distance to the reflecting surfaces. In which case the room acoustics is significantly altered when the test-object is removed for the reference source measurement.
3. The test-object can also be large compared to the wavelength and compared to the distance to the microphones. In that case, the measured sound pressure responses when adding the reference source, will depend significantly on the choice of the location of the reference source on the test-object. This may bias the power estimate when using the proposed RSS location in the ISO standard.

According to a study on the sound power level emission in situ, performed by the Swedish National Testing And Research Institute, it's shown that ISO 3747 measurements can achieve engineering accuracy if some criteria are fulfilled [10]: no absorbing wall near the source, or if so additional microphones between the wall and source shall be used; indicators that describe the sound transmission properties of the room have to fulfill a maximum standard deviation ; if below 500 Hz, the reference sound source is calibrated in a position which is located in a similar way relative to nearby reflecting surfaces as it is in the actual test.
It seems that there is potential for improvement of the accuracy of this on-site method.

2.4 Reference power source calibration

For the calibration of a reference sound power source, a dedicated standard ISO 6926 [12] was developed.
The methodology of calibrating a sound source takes account of several uncertainty factors, like reproducibility, temporal steadiness and repeatability, spectral characteristics and directivity index. The reproducibility factor refers to the uncertainty of the sound power emission when this is performed in different laboratories. The repeatability deviations are related more to the repetition of sound power levels in the same laboratory conditions. The table below show the standard deviation limits for these of repeatability.
The spectral characteristics of a RSS are defined in such a way that a source should produce sound power levels within a frequency range of 12 dB for all one-third-octaves and will not deviate more than 3dBs in adjacent bands.

Table 1. Maximum standard deviations for repeatability ISO 6926

Frequency range Hz	Standard deviation dB
50 to 80	0.8
100 to 160	0.4
200 to 20000	0.2

The highest value of the directivity index D_{li} shall not pass +6 dB. However, if the source is meant to be used in quality reverberant rooms, this condition is not mandatory.

3. Reference sound source measurements

The sound power emission and directivity are determined for the new small reference source.
The power to a reference signal ratio was calculated to observe its variability. The effect of nearby reflectors on the sound power emission was also studied in this section.

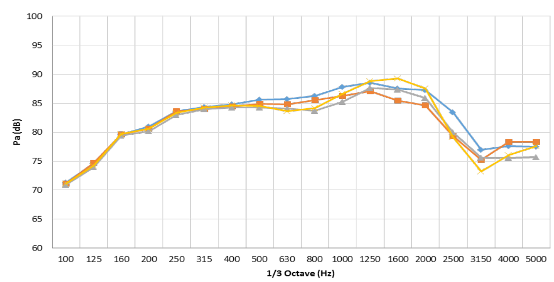

Figure 3. Spectra of the RSS in 1/3 octaves in 30 degrees angle steps from radial to axial.

3.1 Directivity measurements

Because of the symmetry of the source in the tangential direction, only the directivity in the axial direction is analyzed in detail.
The third octave spectra in Figure 3 were measured at 40 cm from the center. This was done in the axial plane of the source. It can be seen in Figure 3 that a maximum +/- 2 dB variation relative to the average third octave band level occurs up to 5 KHz.

The measurements have also been performed according to ISO 140. (Figure 4) The minimum and maximum deviations are calculated and compared with the higher and lower limits provided by the ISO 140 standard, which is more strict than the ISO 6926. The results show far lower directionality than ventilator based RSS, or even dodecahedron sources.

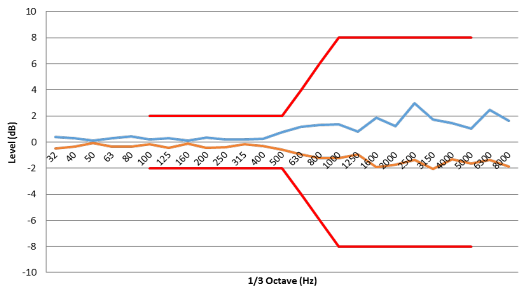

Figure 4. Spectra of the RSS in 1/3 octaves in 30 degrees angle steps from radial to axial.

3.2 Sound power stability measurements

First, the sound power level of the source was estimated in a free-field environment, measured 5.5 m high up inside a large semi-anechoic room. Using the symmetry only four microphones positions were measured around the RSS. The processing was done similar to ISO 3744 with surface proportional averaging. The setup is shown in Figure 5.

Figure 5. Free-field measurement set-up for sound power and directionality

Secondly, the source was placed inside a diffuse field in a large reverberation room of 197 m³ at the university in Leuven Belgium. To calculate the sound power level emitted by the source, the reverberation time method described in ISO 3741 was followed. Five different microphones were spread inside the room separated by a distance of half a wavelength of the smallest frequency of interest. The source was also moved in 3 different locations inside the space.

The reverberation times were calculated in three different locations and at two different moments of a the day and their average was chosen to be used in the future estimation of sound power. The room was relatively cold and humid; 13 degr. Celsius, 50%.

Figure 6. Sound power measurement set-up in a large reverberation room.

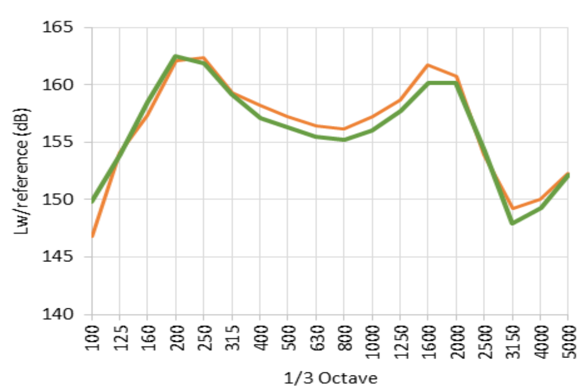

Figure 7. Sound power level of the RSS green curve in free-field, and yellow curve in the reverberation room.

The free-field measurements were done at a room temperature around 24 degr. Celsius, and 30% humidity. The resulting sound power in Figure 7 is shown as the ratio of power relative to the internal reference signal voltage squared.

A satisfactory agreement between the two observations of the power level and of the reference signal ratio was observed.

3.3 Sound power and orientation/position

Relative to free-field, any sound source will emit a higher sound power when coming near to a reflecting surface or object. Theoretically an infinitely high impedance point source will have a doubled sound power output when placed on a reflecting surface. And because RSS are intended to be used in the vicinity of floors, test-objects and potentially reflecting panels and walls in on-site measurements, this is relevant for the interpretation of power measurements using RSS. The ISO 6926 standard for the calibration of RSS has chosen for the source position on the floor as the calibration situation. To analyze the effect of the floor, the source was placed at different heights from the ground at horizontal and vertical orientation, as in Figure 8.

Figure 8. Source with height relative to the floor.

The orientation did not affect the sound power emission, but the height relative to the floor has a strong influence.

The observed sound power per unit reference signal from the internal sensor of source, for the different heights relative to the floor of the reverberant room, are shown in Figure 9.

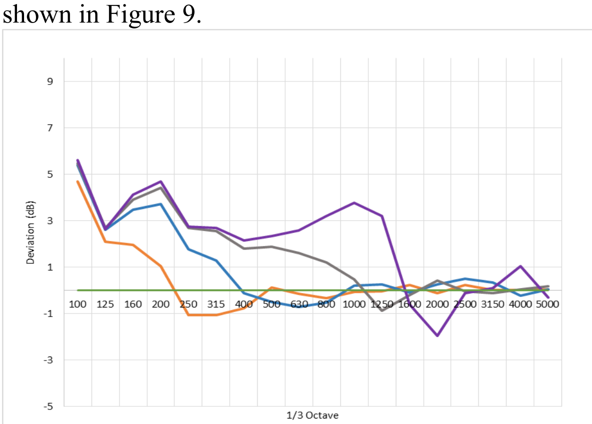

Figure 9. Increase of sound power emission. Orange at 1.0 m from the floor, Blue at 0.4 m from the floor, Gray at 0.2 m from the floor, Purple at 0.1m from the floor.

The 0 dB line in Figure 9 represents the power values for positions close to the center of the reverberation room. When the source comes closer and closer to the reflecting surface, the bandwidth on which the increase is visible expands to higher frequencies, up to 1.6 kHz for 10 cm. An average level shift up at lower frequencies of 3 dB is observed.

This result shows that the ISO 6926 calibration of RSS actually produces sound power emission values of the RSS for semi-free field condition, with the height of the acoustic center of the RSS determining the distance to the reflecting floor.

And by consequence the sound power estimation when using the reference method also produces equivalent sound power for semi-free field condition, as if the acoustic center were at the same location as the RSS.

The RSS sound power emission relative to reference signal at 20 cm height from the floor was used in the applications in the following section 4. This height is also close to the position of the common ventilator based RSS.

4. Sound power of a house hold appliance

In this section a household appliance, vacuum cleaner, was used to compare sound power determined in three different sites, in order to investigate the reliability of the method and new RSS. Based on the sound pressure levels in a constant environment, the vacuum cleaner with regulated voltage seems to be sufficiently stable over time, within +/- 1 dB. The vacuum cleaner sound power was determined in the large reverberation room using both reverberation time and the reference method. This was repeated in a very small tiled space of 13 m^3 and in a 75m3 office space with uneven absorption around the measurement location. The comparison between three cases is presented in this section. There was some variation in temperature and humidity between the different tests, but the vacuum cleaner rpm was regulated in all situations.

Figure 10. Measurement of the vacuum cleaner in the reverberant room.

4.1 Large reverberation room

The vacuum cleaner was placed inside the large reverberant room (Figure 10). The sound pressures were measured at 5 positions. Both methods from ISO 3741 (direct and comparison) were used to calculate the sound power. The result shows that both methods give very similar results with deviations well within the limits of the standard (Figure 11).

To calculate the sound power level of the vacuum cleaner using the reference source signal, equation 8 is being introduced:

$$L_w = 10lg(\overline{\frac{p_i^2}{TF^2} * W_{r/signal}/W_0}) \qquad (8)$$

Where,
P_i is the pressure measured at each microphone
TF_i is the transfer function of reference signal to pressure signal at each microphone;
Wr/signal is the sound power calibration curve of the reference source;
$W_0 = 10^{-2}$ is the reference value of sound power

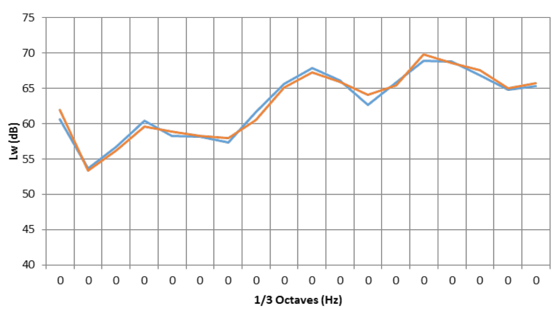

Figure 11. Sound power level of the vacuum cleaner based on reverberation time in orange and based or reference method in blue.

4.2 Small reflective tiled room

The reverberation time method was tested inside a small fully tiled room of approximately 13 m³ with strong reflections (Figure 12). This room was clearly not an ideal reverberant room, being too small and with nothing but parallel walls. On the other hand, the walls were all highly reflective.

Figure 12. Measurement set-up in a small tiled room.

Figure 13 shows large variations in reverberation time under 250 Hz, which can explain the limitation of the reverberation time method in such environments. Still, the identification of the sound power was possible with deviations of less than 3 dB from 250 Hz upwards and less than 1.5 dB on the overall level like shown in Figure 14.

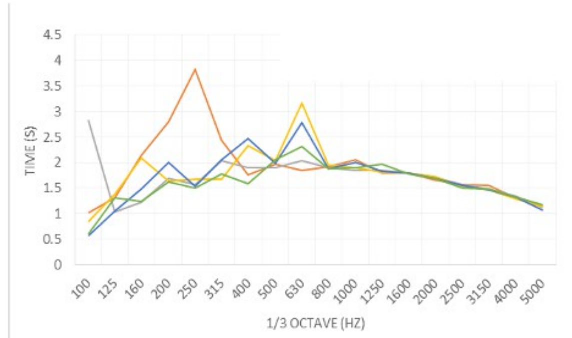

Figure 13. Reverberation times in the small tiled room at four microphone positions.

Interestingly the sound power estimation of the vacuum cleaner using the reference method in the small room was close to the large reverberation room result, even at lower frequencies.

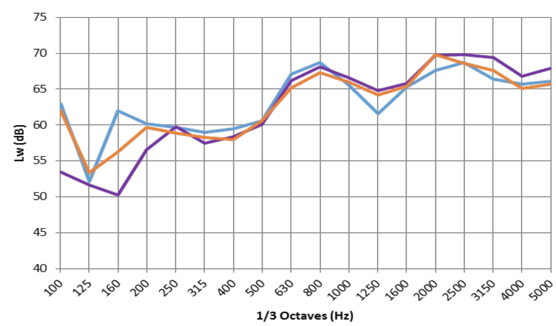

Figure 14. Sound power level of the vacuum clearer, in the small room. Blue curve using the reference source method, Orange using the reverberation time method. And in yellow the reference method curve from the large reverberation room.

Figure 15. Measurement set-up in the office space.

4.3 Office room measurements

The office space had an uneven absorption, with a highly absorbent ceiling, reflecting objects and walls, and a frequency dependent absorption from the floor. This situation was far from reverberant.

Still, in figure 16, the comparison of the sound power estimations when using the reference source also shows an agreement within +- 3 dB from 250 Hz upwards.

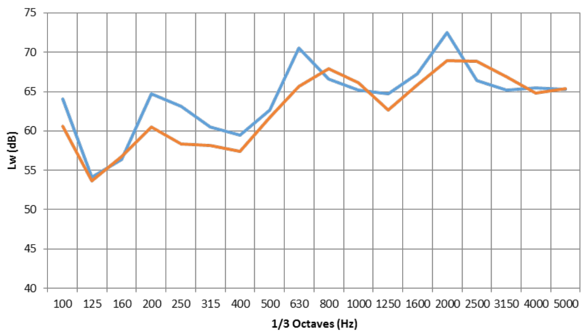

Figure 16. Sound power of the vacuum cleaner, measured in the office using the reference method, in the blue curve, and based on reference method in the large reverberation room in the orange curve.

5. Conclusion, outlook

The reference power method is attractive as an alternative to the more complex sound intensity scanning for on-site identification, because of the limited complexity and high efficiency of the power reference method.

This method, as described in ISO 3747, expects a standard deviation of up to 4 dB in an arbitrary acoustic environment.

A new omni-directional and high acoustic impedance power reference source (RSS) was developed. Being smaller and closely approximating a monopole this source allows an other way of using power reference sources.

The application of a new power reference source to a household appliance, following ISO 3747 and ISO 6926, in different environments provided sound power estimates with an accuracy which was better than the 4 dB expected by the ISO standard.

Measurements in a large reverberant room showed that the ISO 6929 calibration of RSS actually depends on the height of the acoustic center relative to the floor.

There is a potential further improvement of the method to exploit, now that it has become possible to place the acoustic center of the RSS very close to the surface of machinery, and with the feasibility of multiple positions/faces on larger machines.

On-site determined sound power of machinery remains important because it allows to compare machinery and provides reliable data for the design of a building environment for large machinery.

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