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EXPANDING THE SOUND POWER MEASUREMENT CRITERIA FOR SOUND INTENSITY P-U PROBES

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The sound power of a machine or device provides a general description of its acoustic output. Sound intensity based methods determine this quantity by integrating the normal sound intensity over an area enclosing the noise source. Current ISO standards solely regulate the use of *p-p* intensity probes. A *p-p* probe consists of two paired pressure microphones that approximate sound intensity by combining the average pressure and pressure gradient. Sound pressure is strongly affected by the measurement conditions, especially in reverberant environments or the presence of background noise, which can significantly constrain the accuracy of intensity estimations. As a result, regulations define a set of parameters or “field indicators” to guarantee the validity of measurements and control the uncertainty limits of the estimated sound power level. Alternatively, it is possible to directly obtain sound intensity from the sound pressure and particle velocity acquired using *p-u* probes. However the measurement methodology that support this approach has not yet been established. This paper adapts the current measurement standards for the use of *p-u* intensity probes. A corresponding field indicator that determines the accuracy of the computed estimations is suggested and experimental data is presented, providing evidence for the viability of the measurement methodology introduced.

1. Introduction

Sound power is one of the main characteristics defining the acoustic output of a noise source. This quantity has a fundamental role in many practical applications since it allows for the estimating of the acoustic impact of a machine or device in its operational environment. Furthermore, it is often used for benchmarking products from different suppliers. Although sound power is commonly used “as a quantitative label of acoustic output” [1], it is not completely independent of the measurement environment [2].

There are many standardised methods to determine sound power based upon sound pressure measurements in free-field conditions (ISO series 3744-3746), sound pressure measurements in a reverberant field (ISO series 3741-3743) and sound intensity measurements (ISO 9614-1, 9614-2 and 9614-3). The main limitation of pressure-based methods is the necessity to perform tests in special measurement rooms, either anechoic or reverberant chambers. Difficulties are often encountered when the test object cannot be placed in an controlled environment, possibly due to its large size, heavy weight or a requirement to operate coupled with another device. In contrast, sound intensity techniques can be used *in-situ* providing that certain measurement conditions are met, regulated by the field indicators.

Sound intensity is the time averaged product of sound pressure and particle velocity. These two quantities can be directly acquired using a *p-u* probe comprising a microphone and a particle velocity sensor (also known as a Microflown), or estimated via indirect methods [1], using a *p-p* probe to approximate acoustic particle velocity from the gradient between two microphones. Multiple research articles have been published exploring the fundamental differences between these two sound intensity measurement principles [4–6]. Nonetheless, both the IEC standard on instruments for the measurement of sound intensity [7] and the corresponding North American ANSI standard [8] only regulate the use of pressure-based solutions. The lack of calibrated acoustic particle velocity sensors at the time when the standards were proposed may be the main reason for the absence of a *p-u* measurement standard. However, a full-bandwidth calibration procedure has already been established [9], enabling *p-u* probes to be utilised for the localisation, quantification and ranking of sound sources, even in conditions where *p-p* probe cannot be used due to high levels of background noise or reverberation [10].

This paper outlines the theoretical basis of sound intensity methods using both *p-p* and *p-u* probes for the estimation of sound power. Furthermore, the standardised measurement procedure is expanded to include sound intensity *p-u* probes, introducing a new field indicator which accounts for the measurement error of a direct sound intensity approach. In addition, experimental data for both systems is compared and discussed.

2. Sound power estimation

Sound power is commonly used as a quantitative description of the acoustic output of a device [1]. It is defined by the integral of the normal intensity over the radiating noise surface, i.e.

$$\Pi = \int_S I_n dS \tag{1}$$

where I_n is the active normal intensity described as [11]

$$I_n = < p\, u_n >_t = \frac{1}{2}\text{Re}\{p\, u_n^*\} \tag{2}$$

where p is sound pressure, u_n is normal particle velocity and $< . >_t$ indicates time averaging. Taking into account the measurement errors introduced by the acquisition of sound intensity gives

$$\hat{\Pi} = \Pi \left(1 + \int_S b[\hat{I}_n]\right) \tag{3}$$

where Π is the “pure” sound power unaffected by any errors, $\hat{\Pi}$ denotes its biased estimate and $b[\hat{I}_n]$ is the bias of the sound intensity estimations. This last term depends upon the measurement principle used to acquire sound intensity: directly using a *p-u* probe, or indirectly with a *p-p* probe (two pressure microphones). Note that random errors are not considered in Equation 3, thus spatial positioning errors, electrical noise, etc, are disregarded.

2.1 Direct intensity estimation

Equation 2 can be directly calculated from the sound pressure and acoustic particle velocity acquired using *p-u* probes without any further assumptions or approximation. The measurement error introduced depends upon the reactivity of the sound field and the calibration of the probe [12]

$$\hat{I}_n = \frac{1}{2}\text{Re}\{p\hat{u}_n^*\} = \frac{1}{2}\text{Re}\{p u_n^* e^{j\varphi_{ue}}\} = I_n \left(1 - \varphi_{ue}\frac{J_n}{I_n}\right) = I_n(1 + b[\hat{I}_n]) \tag{4}$$

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[1] A novel indirect method based on particle velocity measurements has recently been introduced for the estimation of sound power [3]

where φ_{ue} is a small phase error introduced during the calibration procedure and J_n is the reactive intensity, defined as

$$J_n = \frac{1}{2}\text{Im}\{p u_n^*\} \tag{5}$$

2.2 Indirect intensity estimation

Sound intensity can be estimated by measuring sound pressure at two closely spaced positions using the "p-p measurement principle". Two fundamental quantities define the intensity at one point: sound pressure and acoustic particle velocity. Whereas the former can be easily calculated as the average of the two pressure signals, the latter is obtained by a finite-difference approximation to the pressure gradient in Euler's equation of motion [4], hence

$$\hat{I}_n \simeq \frac{1}{2\rho\Delta r}\left\langle (p_1(t) + p_2(t)) \int_{-\infty}^{t} [p_1(\tau) - p_2(\tau)]\, d\tau \right\rangle_t \tag{6}$$

where $\langle . \rangle_t$ denotes an time average operation, ρ is the density of air and Δr is the separation between the two microphones. Scattering and diffraction, instrumentation phase mismatch and finite difference approximation are the main limitations of this measurement approach. It can be shown that a small phase mismatch error gives rise to a bias error that can be approximated by

$$\hat{I}_n \simeq I_n - \frac{\varphi_{pe}}{k\Delta r}\frac{|p|^2}{\rho c} = I_n\left(1 - \frac{\varphi_{pe}}{k\Delta r}\frac{|p|^2/\rho c}{I_n}\right) = I_n(1 + b[\hat{I}_n]) \tag{7}$$

where k is the wave number and c is the speed of sound. This expression shows that the bias error $b[\hat{I}_n]$ is inversely proportional to the frequency and the microphone separation distance whilst being proportional to the ratio of absolute square sound pressure to sound intensity.

3. Field indicators

"Field indicators" are a set of parameters suggested by standards to assess measurement conditions and ultimately judge the quality of the produced results. They are calculated from acquired data, accounting for errors introduced not only by the measurement instrumentation but also by the testing environment.

3.1 Temporal variability indicator (F_1)

The temporal variability indicator is used to check the stationarity of the sound field within the measured segment by evaluating a series of short time average intensity estimates.

$$F_1 = \frac{1}{I_n}\sqrt{\frac{1}{M-1}\sum_{k=1}^{M}(I_{nk} - \overline{I_n})^2} \tag{8}$$

where $\overline{I_n}$ is the arithmetic average of I_n calculated from M short time averages I_{nk}. The criterion for this indicator is given in the standard as $F_1 \leq 0.6$. Being a statistical concept, this indicator is valid for both direct and indirect methods.

3.2 Surface pressure-intensity indicator (F_2)

The purpose of surface pressure-intensity indicator is to limit the bias error due to instrument phase mismatch. It is calculated by taking the difference in decibels between arithmetic averages of *unsigned intensity* and pressure levels. It is defined as:

$$F_2 = \overline{L_p} - \overline{L_{|I_n|}} = 10\log\left(\frac{|p|^2/\rho c}{I_n}\right) = \delta_{pI} \tag{9}$$

where

$$\overline{L_p} = 10\lg\left(\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}}\right), \ \overline{L_{|I_n|}} = 10\lg\left(\frac{1}{N}\sum_{i=1}^{N}|I_{ni}|/I_0\right) \tag{10}$$

Note that F_2 is equal to the pressure-to-intensity index δ_{pI}. There are two criteria regarding this indicator:$F_2 < L_d$, implying $\delta_{pI} < \delta_{pI_0} - K$ where K is bias error factor given in the ISO standard, the other is related with F_3 and given in the next section.

3.3 Negative partial power indicator (F_3)

This indicator is essentially the same as F_2 except the arithmetic average is evaluated using *signed intensity* so $\overline{L_{|I_n|}}$ becomes $\overline{L_{I_n}}$ whereby

$$\overline{L_{I_n}} = 10\lg\left|\frac{1}{N}\sum_{i=1}^{N}I_{ni}/I_0\right| \tag{11}$$

The criterion regarding F_2 and F_3 is given as $F_3 - F_2 \leq 3dB$. This is a measure of the ratio between partial sound power entering and leaving the segment.

3.4 Field non-uniformity indicator (F_4)

The field non-uniformity indicator is the normalised variance of segment intensity values. It is the spatial variance across the defined surface and used to control the minimum number of segments necessary, thus restricting the uncertainty of the spatial mean estimates within acceptable limits. It is defined as:

$$F_4 = \frac{1}{\overline{I_n}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(I_{ni} - \overline{I_n})^2} \tag{12}$$

where $\overline{I_n}$ is the arithmetic average of I_n using N segment measurements I_{nk}. The criterion of this indicator is defined in the ISO 9614-1 as $N > CF_4^2$. N indicates the number of segments defined and C depends on grade of accuracy. F_4 is applicable for both direct and indirect intensity methods.

3.5 Reactivity error indicator (F_5)

The reactivity error indicator is directly associated with the phase relation between pressure and velocity. The indicator can be defined as:

$$F_5 = \left|10\lg\left(1 - \varphi_{ue}\frac{|\overline{J_n}|}{|\overline{I_n}|}\right)\right| \tag{13}$$

where F_5 is the ratio of reactive to active intensity in logarithmic form and φ_{ue} is approximately 0.035 radians (2°) for the piston-on-a-sphere calibration procedure [9]. If this indicator has a large value then even a small phase mismatch φ_{ue} could cause considerable bias error (See equation 7). The criterion for $F5$ is given as $F_5 < 2s$ where s is defined in the ISO standard in terms of octave bands and engineering accuracy. Note that this criterion replaces F_2 and F_3 for controlling the bias errors introduced by the use of *p-u* probes.

4. Experimental validation

Several measurement sessions were undertaken at Hamburg University of Applied Sciences (HAW Hamburg) in two different acoustic environments: a large anechoic chamber and a conventional room. A three way AK-252 loudspeaker was used as a test object excited with a stationary white noise signal. The pictures of the test setup are presented in Figure 1.

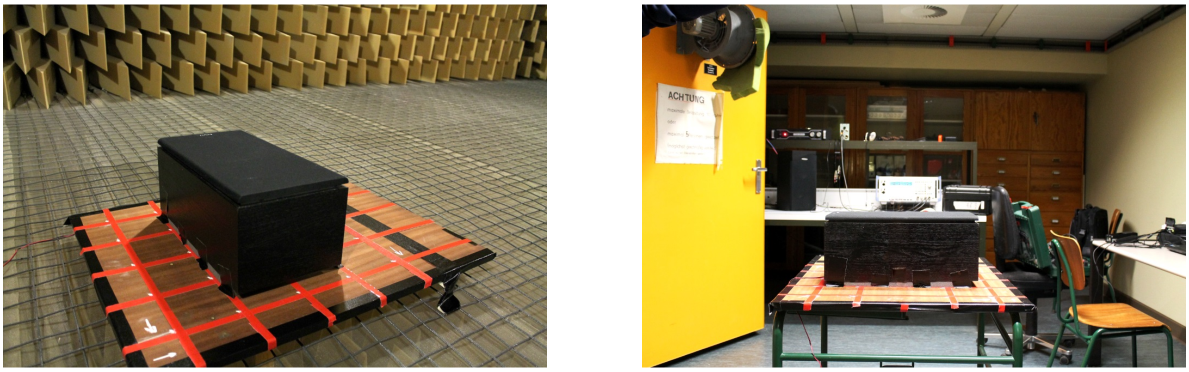

Figure 1: Loudspeaker evaluated during the sound power tests: in an anechoic chamber (left) and in a conventional room (right).

4.1 Instrumentation and measurement set-up

Measurements for the direct method were performed using the Microflown Velo Sound Power application and a Microflown *p-u* probe. For the indirect method, a Brüel & Kjær type 2270 hand held analyser and a type 4197 half inch Microphone pair (*p-p* probe) were used. The same enclosing surface is used for both sets. The surface is defined according to ISO 9614 which is chosen to be a cube with dimensions 0.6 x 0.6 x 0.6 m. Each face of the cube was divided into 25 square segments each with an area of 0.0144 m^2, resulting in a total of 125 segments per measurement set. The total recording duration for each segment is 10 seconds.

4.2 Error assessment and field indicators

As explained above, the reliability of sound intensity measurements can be assessed by computing the "field indicators" of the acquired data(see Section 3). Firstly, the two indicators that are common for the two sound intensity measurement principles, either direct or indirect measurements, are evaluated. Figure 2 presents the calculated temporal variability indicator F_1 and the non-uniformity indicator F_4 from the tests performed with a *p-u* probe.

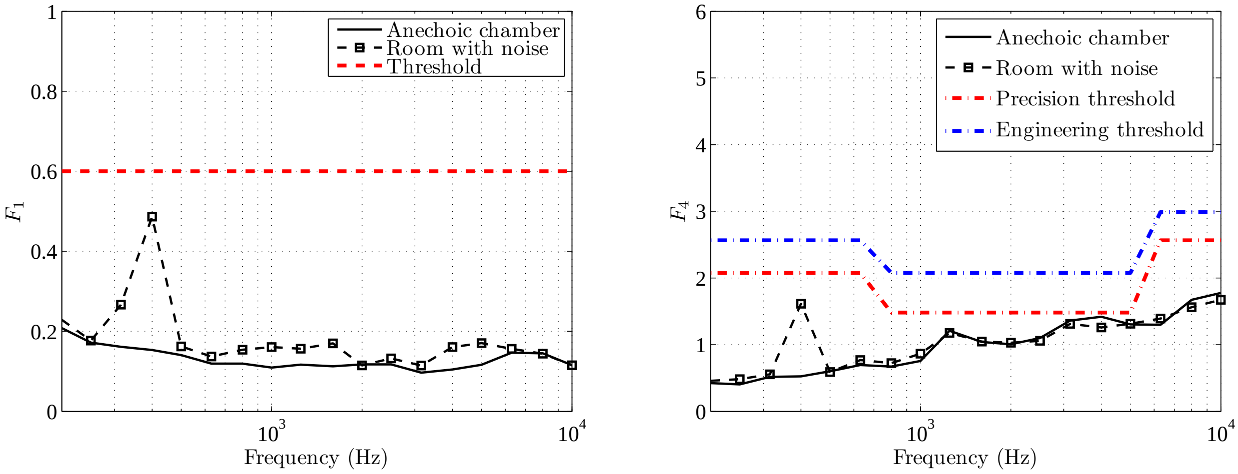

Figure 2: Temporal field indicator (F_1) and field non-uniformity indicator (F_4) in two testing environments: anechoic chamber and room with noise.

As mentioned previously, F_1 shows the stationarity of the intensity field, demonstrating that the assessed sound source works in a stationary regime during the data acquisition process of both tests. The difference between anechoic and room measurements only becomes apparent at 400 Hz, probably induced by the background noise present in the second experiment. Furthermore, F_4 indicates that the sound field is fairly uniform across the entire frequency range for both the anechoic chamber and room measurements in the evaluated surface area. These results prove that the number of segments chosen (125 points) was sufficient to fulfill the requirements given by the standards.

Once the measurement conditions are proven to be satisfactory, it is then necessary to evaluate the field indicators related to the instrumentation accuracy. The current regulations for *p-p* probes state that the measurement error introduced is assessed via the level differences between sound pressure and sound intensity, either disregarding the sign of the intensity with F_2 or taking it into account, F_3. Figure 3 displays the variation of both field indicators in the two test environments along with the pressure-to-intensity index of each measurement point, highlighted in grey.

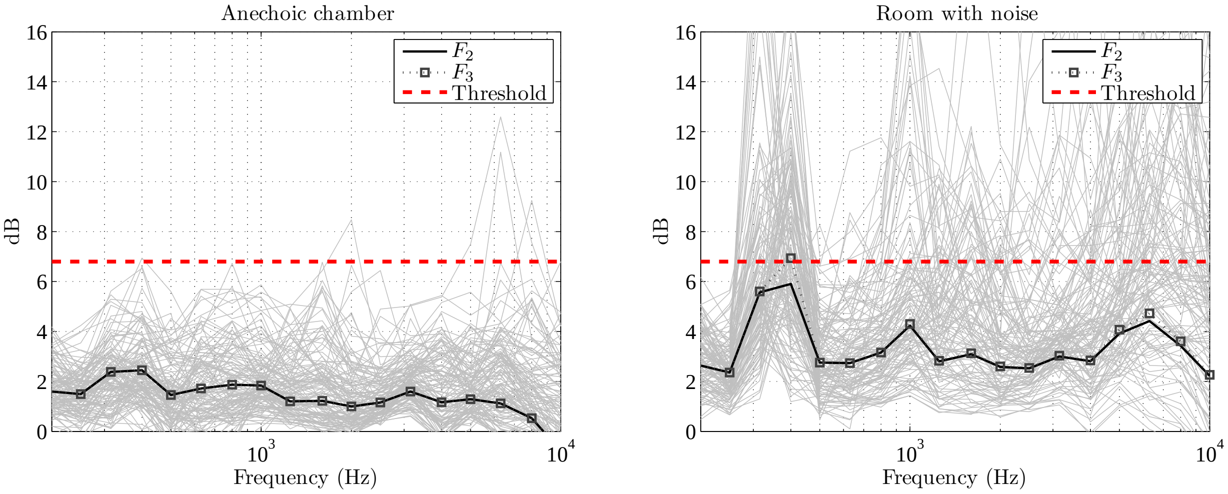

Figure 3: Field indicators F_2 and F_3 of the *p-p* probe in the two testing environments: anechoic chamber (left) and noisy room (right).

The left hand side of Figure 3 shows that by evaluating either point by point behaviour or the overall pressure-to-intensity index, results are within the accuracy limits stated in the standards. However, the measurement conditions are deteriorated significantly when the test was performed in a room with background noise. As shown on the right hand side of Figure 3, the overall indicators are significantly higher than in the anechoic test, even exceeding the accuracy threshold at 400 Hz. Furthermore, the similarity between F_2 and F_3 indicates that most of the measurement points present positive values across the entire spectra, and thus the sound intensity measured was mainly produced by the object under assessment. Regardless of having a net acoustic energy dominated by the desired source, the presence of background noise seems to have a strong effect on the measurement accuracy. This is especially true whilst assessing the local acoustic behaviour where the pressure-to-intensity index δ_{pI} reached values far above the accepted limit. The high dependence of the measurement error on the acoustic conditions of the testing environment is one of the main drawbacks of pressure-based intensity measurements for industrial applications [13].

As shown in Section 2.1, the field indicators F_2 and F_3 are not suitable for determining the reliability of data acquired with *p-u* probes. Instead, the introduction of the reactivity error indicator (F_5) enables the evaluation of data accuracy. Figure 4 shows the results found in both testing environments assuming the phase error introduced in the calibration process was 2 degrees.

The overall reactivity error F_5 shows a very similar trend in both testing environments. It is apparent that the error introduced by the reactivity of the sound field is very low despite the presence of background noise. F_5 is mainly caused by the phase difference between the sound pressure and particle velocity transducer, and therefore hardly influenced by the presence of reverberation or background noise. The reactivity error may become larger in the proximity of the sound source due to near-field effects.

In summary, the acoustic conditions of all four tests meet the accuracy requirements for a precision measurement according to the criteria given by the standards. However, the performance of *p-p*

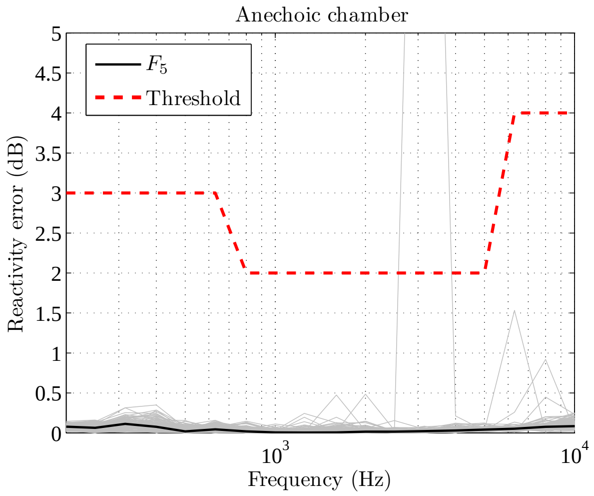

Figure 4: Reactivity index F_5 of the *p-u* probe in the two testing environments: anechoic chamber (left) and noisy room (right).

probes has been shown to be highly dependent upon the testing environment. In contrast, the error introduced by *p-u* probes is only dependent upon the reactivity of the sound field, which can usually be neglected providing the measurement surface is sufficiently far from the noise source. Therefore, while improving the accuracy of a *p-p* probe measurement involves changing the testing environment mitigating background noise sources or reducing reverberation, *p-u* only requires an increase in measurement distance from the evaluated object, a condition that is far easier to fulfil, especially in industrial scenarios.

4.3 Sound power estimation with *p-p* and *p-u* probes

The sound power of the four measurement cases is computed following Equation 1 and can be seen in Figure 5. It should be noted that very similar results are obtained using either *p-p* or *p-u* probes in both testing environments, regardless of the fundamental differences between acoustic transducers, calibration procedure or data acquisition equipment. The small discrepancies between curves were most likely due to experimental errors introduced during the measurement process, such as probe misalignments or slight variations of loudspeaker signal.

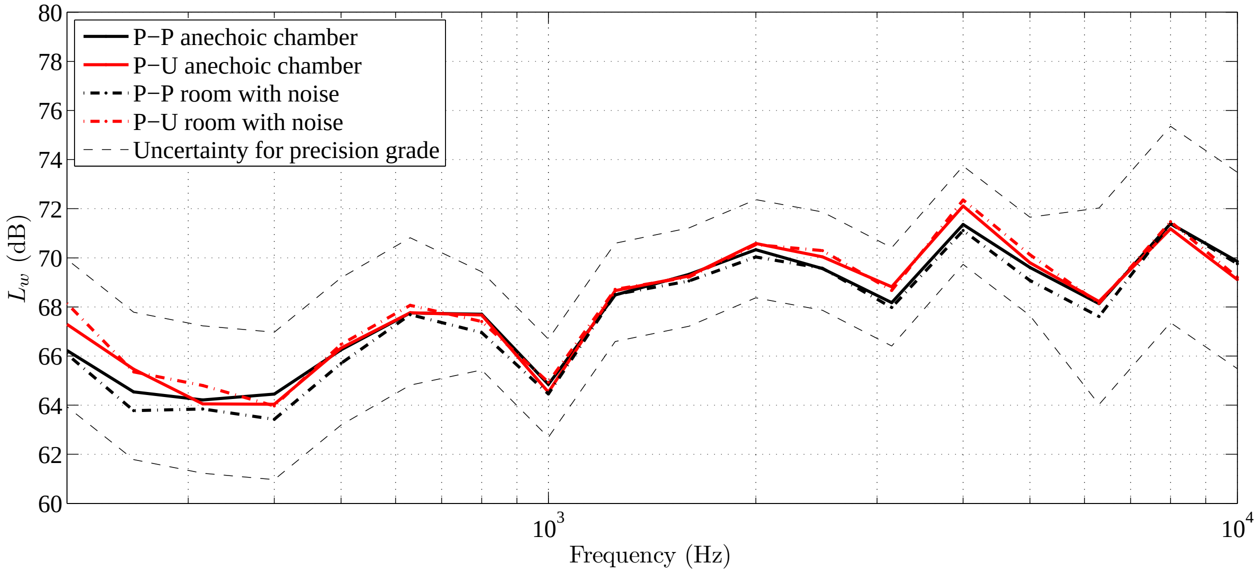

Figure 5: Sound power of a loudspeaker source, measured with a *p-p* and a *p-u* probes in two different measurement scenarios.

5. Conclusions

Sound power measurements with *p-p* and *p-u* probes have been examined theoretically and experimentally. An additional sound field indicator has been introduced to assess the reliability of the sound intensity estimations performed with a *p-u* probe. It was shown that both methods provide similar results for two different testing environments: anechoic chamber and room with background noise. However, from the results presented, it can be seen that the accuracy of *p-p* probes is highly dependent upon the acoustic conditions of the measurement environment. In contrast, *p-u* probes are mainly dependent upon the reactivity of the sound field. Consequently, *p-p* probes require changing the testing environment whilst *p-u* probes only require an increase in measurement distance from the sound source in order to improve accuracy, a much more practical solution in industry.

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