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Measuring In-Situ Sound Power Using a Simplified Acoustic Energy Density Method

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ABSTRACT

Sound power measurements are typically made in anechoic or reverberant spaces according to internationally accepted standards. However, it is often desirable to make in-situ measurements of complex sources, which makes some of these standards inapplicable. While several sound power methods have been developed that are designed for in-situ measurements, the assumptions needed to implement these standards often make them less desirable for practical implementation. An alternative has been developed to measure the sound power using acoustic energy density measurements. Energy density has been shown to have significantly lower spatial variance for enclosed fields, and this variance can be further reduced using generalized energy density. This paper will describe the use of energy density measurements to determine sound power. A “two-point” method can be used to accurately determine the sound power of compact sources in a semi-reverberant space. For more complex sources in more general environments, the method can be simplified to yield sound power estimates that have at least survey-grade accuracy. This simplified method has significant potential for making sound power measurements across a wide range of measurement conditions. Results will be presented, and both the strengths and limitations of this measurement technique will be discussed.

1 INTRODUCTION

Makers of industrial machinery components may require sound power measurements for product development purposes, or to provide their customers with sound data. Standardized tests for sound power assume somewhat idealized environments and require varying degrees of reverberant/diffuse or free-field environments. Reverberant/diffuse-field methods facilitate sound power measurements by using a highly-reverberant enclosed space as a spatial integrator. Free-field methods use discrete points around the device under test (DUT) to estimate radiated power through an imaginary enveloping surface. Some methods use a direct approach, while others use a comparison approach, where the DUT is compared to a calibrated reference sound source (RSS).

1.1 Standardized Tests

For precision work, specialized chambers are used for reverberation type tests (e.g. ISO 3741) or free-field tests (e.g. ISO 3745).[1,2] Some engineering grade tests also require purpose-built acoustic chambers (e.g. ISO 3743-2, ISO 3744).[3,4]

Because it can be very difficult to move and accommodate industrial machinery components to specialized acoustic test cells or outdoor test areas, there are test methods that utilize the principles of the more precise methods but employ practices more conducive to real-world environments.

Table 1 summarizes three standardized sound power tests that do not require a special acoustic chamber and are consequently more suitable for industrial device testing.

Standard	**Environment**	**Method**	**Measurement**	**Grade**	**Intended Scope**
ISO 3743-1	Reverberant (Hard walled room)	Comparison (RSS & DUT)	Average L_p, multiple mics at random positions in reverberant field (multiple fixed positions or moving)	Engineering	Small, movable DUT
ISO 3746	Reflecting Plane, free-field	Direct, enveloping surface with corrections ($L_I \rightarrow L_p$ and S, K_2)	Average L_p, multiple mics, reverberation time, specific positions in free field	Survey	General, fixed or movable DUT
ISO 3747	*in situ*	Comparison (RSS & DUT)	Average L_p, multiple mics, semi-specific positions in free field	Engineering or Survey	Non-movable DUT

Table 1. List of ISO sound power tests that do not require purpose-built acoustic facilities.

Implementing methods listed in Table 1 requires multiple microphones for spatial sampling. Some methods require additional equipment, such as a Reference Sound Source (RSS) or impulse generator (such as a starter's pistol) as part of the process.

Each of the aforementioned methods, including those that use purpose-built facilities, derives sound power from multiple sound pressure measurements, along with supplemental tests. This paper introduces a new method based on energy density measurements, which the authors assert can be performed with fewer spatial samples and no supplemental tests.

1.2 Energy Density and the Two-Point Method

In the late 1940s, Hopkins and Stryker published an expression that describes the temporally and locally averaged total energy density in terms of its direct and reverberant components.[5] This formulation, referred to as the Hopkins-Stryker equation, is expressed as

$$\langle w_T(r,\theta_0,\phi_0)\rangle_{t,s} = \frac{\langle \Pi \rangle_t}{c}\left[\frac{\gamma(\theta_0,\phi_0)}{4\pi r^2} + \frac{4}{R}\right], \tag{1}$$

where $\langle w_T \rangle_{t,s}$ is the temporal and local spatially averaged total energy density (TED), $\langle \Pi \rangle_t$ is the time-averaged sound power of the device under test (DUT), γ is the far-field directivity factor of the DUT at some angle (θ_0, ϕ_0), r is the distance from the acoustic center of the DUT, c is the speed of sound, and R is the room constant, which is classically defined as $R = S\bar{\alpha}/1-\bar{\alpha}$, where S is the total surface area and $\bar{\alpha}$ represents the mean absorption coefficient of the room. Here θ_0 represents the polar angle in the vertical plane and ϕ_0 represents the azimuthal angle defined in the horizontal plane. The TED is the sum of the potential energy density (local) and kinetic energy density (KED). The first term in the square brackets in Eq. (1) is proportional to the direct energy density and is referred to here as the direct term. The second term is proportional to the reverberant energy density and is referred to as the reverberant term.

The ISO 3741 standard for sound power measurements in reverberation chambers relies on Eq. (1) by using only the reverberant term and utilizing an array of microphones (or a traversing microphone) in the reverberant field to obtain a good average measurement of the squared pressure field, which corresponds to the average potential energy density in the reverberant field. However, the variance of the pressure field in the chamber is such that a number of microphones spaced in a defined manner are required in order to get a statistically accurate estimate of the average energy density. If one contemplates making such a measurement in a semi-reverberant space, such as might be typical for in-situ measurements, the variance increases further such that it is often not reasonable to obtain a good estimate of the average energy density using pressure measurements.

To overcome the challenge of spatial variance, Xu et al. proposed using the generalized energy density (GED), which is essentially a "weighted" total energy density, with the potential and kinetic energy density terms optimally weighted by a factor of β, shown in Eq. (2).[6]

$$\langle w_{G,\beta} \rangle_t = \beta \langle w_P \rangle_t + (1-\beta)\langle w_K \rangle_t\,, \tag{2}$$

For many fields, the optimum β is 0.25. It has been shown that the total energy density has a lower spatial variance than the potential energy density, which is the quantity utilized in the ISO 3741 standard, and the GED has an even lower variance. Thus, by using GED it is possible to use Eq. (1) to determine the sound power radiated from a source in a semi-reverberant space, with the GED replacing the TED in that equation.

In examining Eq. (1), there are three unknowns, in general: the sound power (which is the desired measurement), the room constant, R, and the directivity, γ. To determine these unknowns, a so-called two-point method has been developed.[7] To implement the two-point method, a reference sound source is utilized, where the sound power and directivity are known for the source. With the reference sound source operating, two GED measurements are made (measurements 1 and 2): one in the direct near field where the direct term is more dominant, and the other in the reverberant field where the reverberant term is dominant. From these measurements, the room constant can be obtained as

$$R = \frac{16\pi\left(\frac{\langle w_{2,G,\beta}\rangle_{t,s}}{\langle w_{1,G,\beta}\rangle_{t,s}} - 1\right)}{\gamma_{ref}(\theta_0, \phi_0)\left(\frac{1}{r_2^2} - \frac{\langle w_{2,G,\beta}\rangle_{t,s}}{\langle w_{1,G,\beta}\rangle_{t,s} r_1^2}\right)}. \quad (3)$$

With the measured room constant now available, the DUT is turned on and the two GED measurements are again made (measurements 3 and 4). With two measurements and two unknowns, the equations can be manipulated to yield

$$\gamma_{DUT}(\theta_0', \phi_0') = \frac{16\pi\left(\frac{\langle w_{4,G,\beta}\rangle_{t,s}}{\langle w_{3,G,\beta}\rangle_{t,s}} - 1\right)}{R\left[\frac{1}{r_4^2} - \frac{\langle w_{4,G,\beta}\rangle_{t,s}}{\langle w_{3,G,\beta}\rangle_{t,s} r_3^2}\right]} \quad (4)$$

and

$$\langle \Pi_{DUT}\rangle_t = \frac{2\langle w_{3,G,\beta}\rangle_{t,s} c}{\left(\frac{\gamma_{DUT}(\theta_0', \phi_0')}{4\pi {r_3}^2} + \frac{4}{R}\right)}. \quad (5)$$

The two-point method has been found to yield excellent results for compact sources, where the direct field radiation can be well approximated by the $1/_{r^2}$ dependence in the direct field term. However, for extended sources in more complex semi-reverberant spaces, the accuracy of the measurement is compromised.[7]

2 SIMPLIFIED GED METHOD

To estimate sound power from GED for larger sources in environments not well-suited for traditional sound power methods, a simplified GED method was developed from the principles of the two-point method.

2.1 Details, Theory, and Assumptions

To reduce the complexity of the two-point method and to address the limitations when applied to more extended sources such as industrial machinery, various simplifications have been introduced. The first simplification was to eliminate the need for the two-point method to measure the *in situ* room constant in favor of a more straightforward procedure. Instead of using a reference directivity source and solving for the room constant using the Hopkins-Stryker equation and GED measurements, one can simply determine the approximate average absorption of the room using the procedure outlined in ISO 3746 A.3.2.1.[8] This method requires the mean absorption coefficient to be referenced from a table of descriptions, ranging from an absorption coefficient of 0.05 for empty concrete or tile rooms, up to 0.5 for rooms with large amounts of sound-absorbing materials on the ceiling and walls. The room constant is then determined using the surface area of the room and the mean absorption coefficient using $R = S\bar{\alpha}/1 - \bar{\alpha}$.

The two-point method procedure consisted of using a system of equations with two instances of the Hopkins-Stryker equation based on two measurements along a line and solving for the unknown DUT power and directivity factor. This simplified method uses one or more GED measurements that are averaged together, and a single instance of the Hopkins-Stryker equation is used to calculate the sound power. This, however, leaves one equation and two unknowns, the sound power and the directivity factor of the DUT.

The true directivity factor of a DUT, especially for industrial machinery, is often more complex than the theoretical source models available and experimentally measuring the directivity factor of large sources is often not logistically feasible. Instead, the simplifying assumption of $\gamma = 1$ is applied, which is characteristic of an omnidirectional source. It is understood that any DUT does not likely radiate omnidirectionally, but this significantly reduces the error introduced by non-physical results in the directivity factor from the two-point method.[7] Thus, the expression for sound power for the simplified GED method becomes:

$$\langle \Pi_{DUT} \rangle_t = \frac{2\langle w_{G,\beta} \rangle_{t,s} c}{\left(\frac{1}{4\pi r^2} + \frac{4}{R}\right)}. \tag{6}$$

Since the errors introduced by the direct term are likely due to the difficulty in achieving direct far field conditions for large, extended sources in semi-reverberant rooms, measurement points should be away from the source in the predominantly reverberant field. This will allow the reverberant term to dominate, which increases the probability of an accurate result.

2.2 Simplified GED Method Procedure

The procedure for the simplified GED method is as follows:

1. **Define Predetermined Variables**
   Document the dimensions of the test room and calculate the room volume and surface area. Define the average absorption coefficient for the room using the method defined in ISO 3746 A.3.2.1.[8] Once the mean sound absorption has been defined, the room constant can be calculated using $R = S\bar{\alpha}/1 - \bar{\alpha}$.

2. **Measure GED of the DUT**
   Set up the energy density probe in the room at a distance of at least a quarter wavelength (of the lowest frequency of interest) from any walls or large pieces of equipment but maintain at least 2 effective DUT diameters distance from the nominal center of the DUT. The effective DUT diameter can be found by averaging the approximate length, width, and height of the DUT. This measurement method is sensitive to sensor placement if located too close the source. If both criteria cannot be satisfied, then sensor positions less than a quarter wavelength from boundaries are preferred to sensor positions near the DUT. Measurement positions near the corners of the room typically allow for these constraints to be met. Document the nominal distance from the DUT to the sensor. To minimize potential error due to sensor placement sensitivity, it is encouraged but not imperative to select additional measurement positions, meeting the aforementioned criteria, elsewhere in the room and repeat measurements. Once the DUT has reached its

steady state, take a representative time average. Repeat for all desired DUT operating conditions.

3. **Post Process Data**
   To estimate the sound power of the DUT from measured GED:
   a. Import the auto and cross spectra from each measurement.
   b. Calculate GED from the measured data according to Eq. (2).
   c. Calculate and/or define the various constants such as, measurement distance, room constant, etc.
   d. Calculate the sound power according to Eq. (6).
   e. Plot one-third-octave band sound power data.

3 VERIFICATION TESTS AND RESULTS

To assess the merit of the simplified GED method, two large industrial sound sources were each measured in situ within semi-reverberant rooms using the methodology introduced in the previous section. These results were then compared to the engineering-grade ISO standard results.

3.1 Tests

The two industrial noise sources, DUT_1 and DUT_2, were respectively located in the center of mechanical test cells, referred to as Test Room 1 and Test Room 2, shown below in Fig. 1.

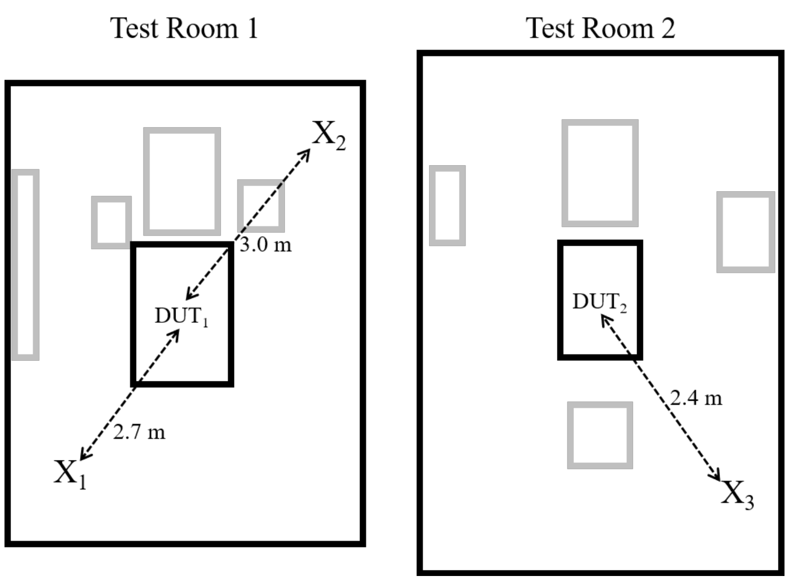

Figure 1. The layout of Test Rooms 1 and 2 showing DUT locations, sensor locations and distances, and support equipment (gray boxes) present for the measurement.

Test Room 1 had dimensions of 5.5×7×4.5 m and Test Room 2 had dimensions of 5.5×7.9×3.6 m. Both test rooms had an approximate mean absorption coefficient $\bar{\alpha}$ of 0.35. In addition to the

DUT, each room had various pieces of support equipment needed for the smooth operation of the machinery, but their acoustic contribution is minimal compared to the noise of the DUT. This support equipment is represented in Fig. 1 by gray boxes. The dimensions of DUT_1 are slightly larger than DUT_2, but both are mechanically similar.

In order to make a useful assessment of the simplified GED method, the sound power of each noise source was first estimated according to ISO 3747:2010 which is referred to as the "comparison method." This survey-grade standard measurement procedure employs the reference sound power method. A Brüel and Kjær type 4224 sound power reference source was placed around the DUT at six distinct locations and the sound pressure levels were measured by twelve free-field microphones scattered randomly about the room.[9] This was repeated for various different mechanical configurations that altered the acoustic output of the noise source.

3.2 Results

The sound power results calculated by the simplified GED method in Test Room 1 using a single sensor position approximately 2.7 m from DUT_1 are shown below in Fig. 2. This corresponds to the sensor position labelled "X_1" in Fig 1. Various operating conditions of the industrial device are shown on the same plot, which have differing acoustic outputs. These are referred to as Case 1, Case 2, and Case 3 in the legend.

For consistent comparison, the overall A-weighted sound power levels per ISO 3747 for each case have been normalized to 0 dBA, with the overall estimated sound power levels as measured by the simplified GED method being shown relative to the corresponding ISO 3747 result. Each major mark along the ordinate corresponds to a 5 dB increment with a total range of 40 dB.

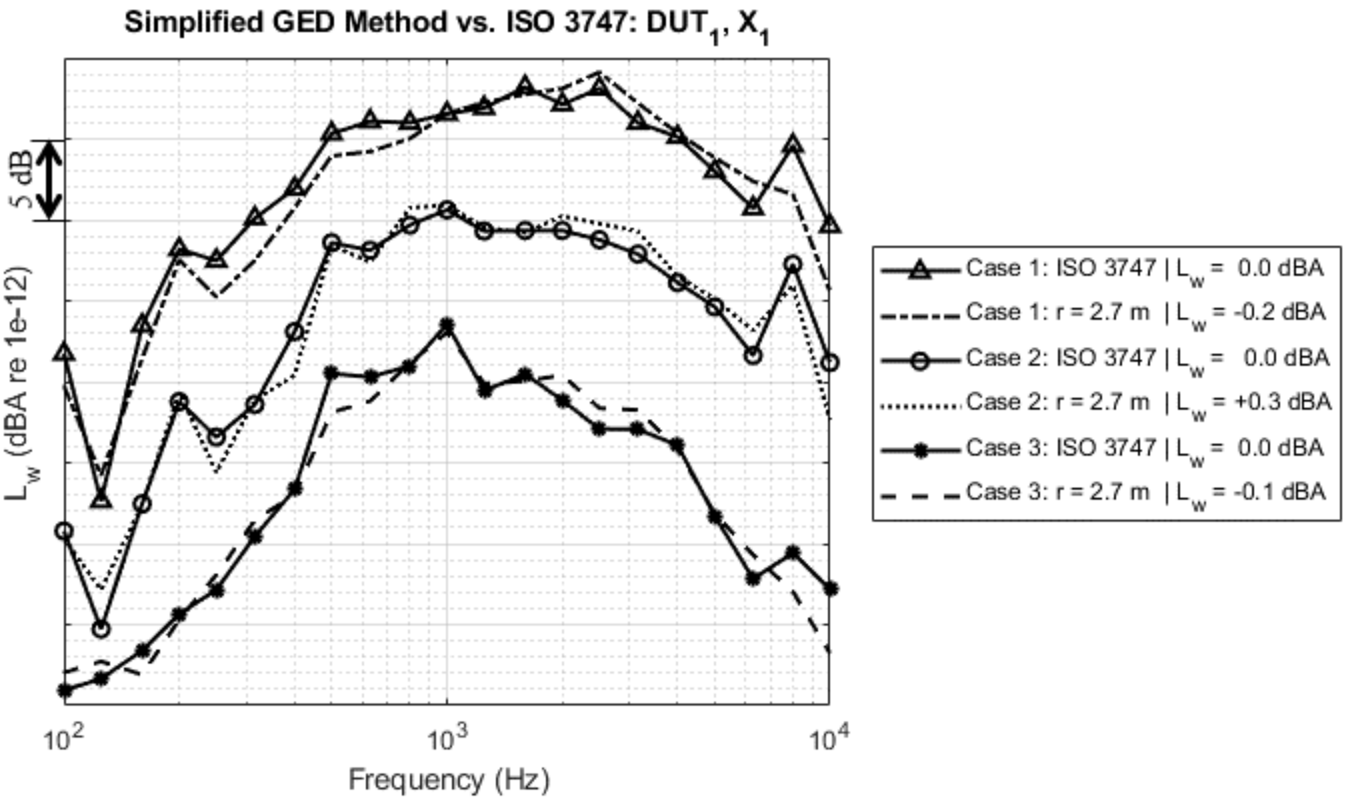

Figure 2. The sound power of DUT_1 measured at a distance of 2.7 m in Case 1, 2, and 3 using the simplified GED method compared to the sound power measured using ISO 3747.

The measurement was repeated a second time with DUT_1 operating under the same configurations but at another sensor position 3.0 m from the source, denoted by "X_2" in Fig 1. The results of this measurement are shown in Fig 3.

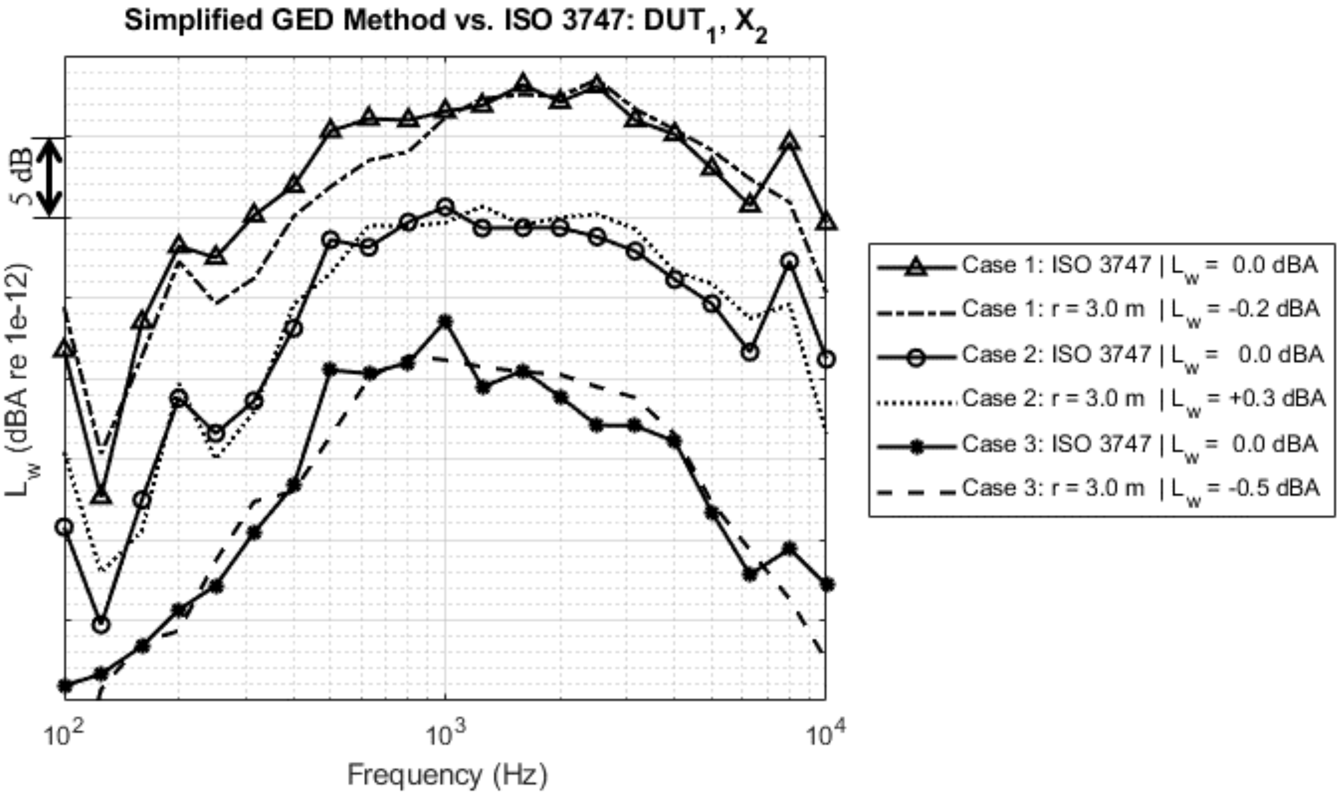

Figure 3. The sound power of DUT_1 measured at a distance of 3.0 m in Case 1, 2, and 3 using the simplified GED method compared to the sound power measured using ISO 3747.

The simplified GED method measurements were performed on DUT_2 in Test Room 2 using a sensor position 2.4 m from the source, corresponding to "X_3" in Fig. 1. Similar to DUT_1, this industrial device was measured at various operating conditions which affected the acoustic output. These conditions are not directly comparable to those of DUT_1, so they are referred to as Case 4, Case 5, and Case 6 here for clarity.

The results from this test are presented in Fig. 4 and are similarly normalized for comparison purposes. The range between major marks along the ordinate again corresponds to a 5 dB increment, but due to greater dynamic range of the spectrum, a total range of 45 dB is shown.

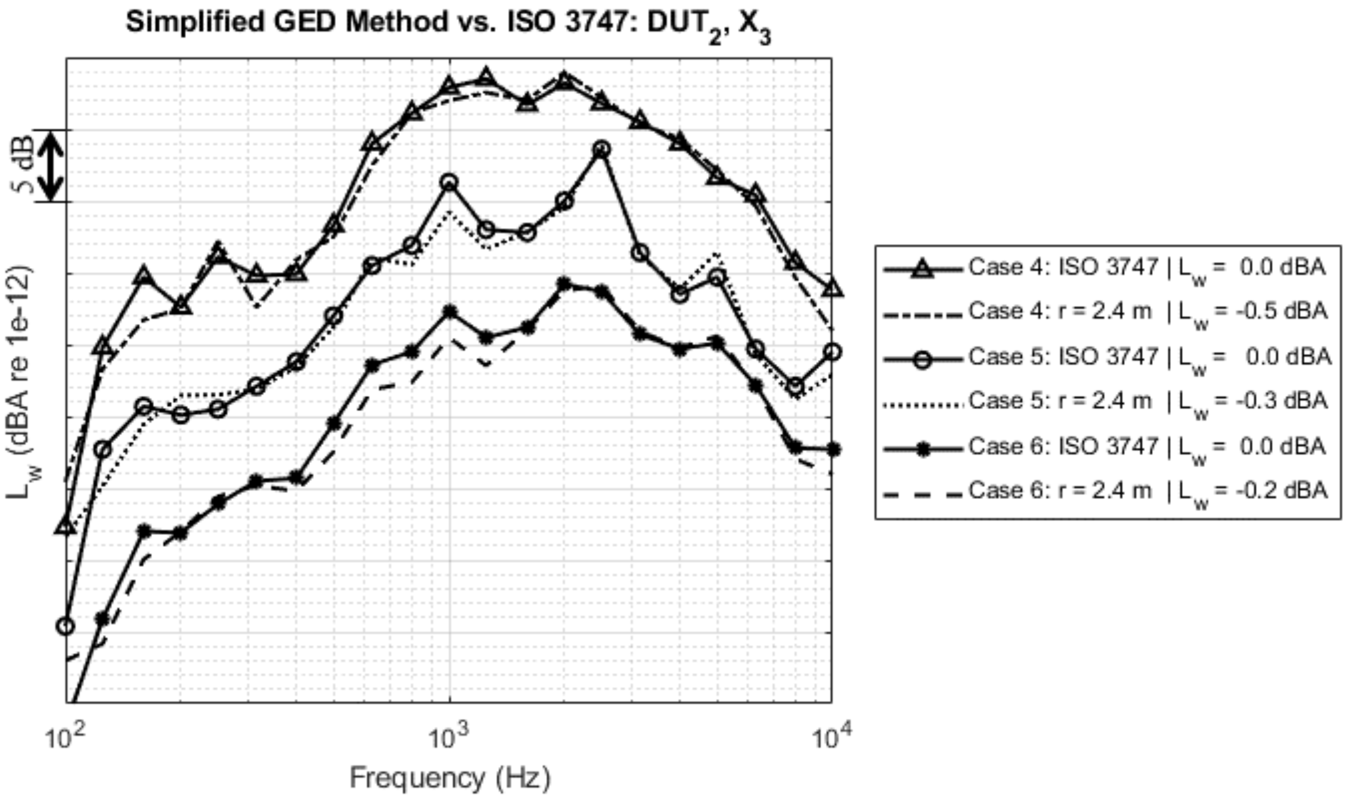

Figure 4. The sound power of DUT_2 measured at a distance of 2.4 m in Case 4, 5, and 6 using the simplified GED method compared to the sound power measured using ISO 3747.

3.3 Discussion

The single-sensor measurement results of the simplified GED method seem to converge nicely to the ISO 3747 results, resulting in overall sound power levels within 1 dB of the target ISO 3747 results. The one-third-octave band results for the simplified GED method seem to follow the shape of the ISO 3747 curve relatively well, often within +/- 3 dB of the standard. This was found to be the case for both industrial noise sources. If multiple sensor positions are averaged together, then the error can be further reduced. These results suggest that the simplified GED method can be used to estimate the sound power of a large industrial device within semi-reverberant rooms to survey-grade accuracy.

3.4 Limitations

Since it has been shown that the Hopkins-Stryker equation does not sufficiently describe the relationship between energy density and sound power when in the near field of an extended source, this method severely underestimates the sound power if the GED field is sampled too close to the DUT.[7] Therefore, for this method to perform correctly, all sensor positions must be sufficiently far from the source to be dominated by reverberant acoustic energy. However, when the distance requirements are appropriately met, the reverberant term dominates the effect of the direct term, and the overall sound power results converge to the expected result.

4 CONCLUSIONS AND DISCUSSION

Following a review of the spatially optimized GED and the two-point method, the simplified GED method was explored as an efficient and accurate measurement method to estimate the *in situ* sound power of extended sources in semi-reverberant rooms to survey-grade accuracy.

4.1 Conclusions

The simplified GED method has been shown experimentally to estimate the sound power of two industrial devices to within 1 dB of ISO sound power measurements, each with a single sensor position. When sensor locations are sufficiently far from the source, the GED, in combination with the simplifying assumptions discussed previously, allows for survey-grade accuracy *in situ* sound power measurements of industrial machinery. The method's limitations regarding sensitivity to sensor location were discussed. The simplified GED method allows for survey-grade sound power estimates comparable to international standards with fewer measurement locations and without the need for a calibrated RSS.

4.2 Consideration of a New Test Standard

Current measurement methods available for *in situ* sound power measurements of industrial sources are limited and can be cumbersome to implement in practice. The noise community would benefit profoundly from an additional survey-grade standard with more efficient implementation. While the data sets presented here are somewhat limited in scope, with a single type of source in two similar semi-reverberant rooms, the results suggest that this measurement methodology is a promising alternative to current *in situ* methods for the estimation of sound power for large industrial noise sources. It is recommended that additional resources could be used to further evaluate the merit of the simplified GED method and better define measurement uncertainties and criteria that produce the most accurate results. Such a standard would allow for significant cost and time savings and increased access to accurate sound power data.

5 ACKNOWLEDGEMENTS

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