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IN-SITU SOUND POWER ESTIMATION USING SCATTERED SOUND INTENSITY DATA SETS

Theo Lam[1*] **Matheus Lazarin Alberto**[1] **Tales Marini Storani**[1]
Engin Güven[2] **Dani Fernandez Comesana**[1]
[1] Microflown Technologies B.V., Arnhem, The Netherlands
[2] Hyundai Motor Europe Technical Center GmbH, Rüsselsheim, Germany

ABSTRACT

Accurate measurement of the sound power of individual vehicle components is essential in the automotive industry to identify and address noise, vibration, and harshness (NVH) problems. Standard intensity-based techniques, which require a complete set of regularly-spaced normal intensity values over a measurement surface, are commonly used in sound power estimation. However, in cases where datasets from sound intensity mapping procedures are non-uniformly sampled, traditional methods may not produce accurate results. This paper introduces an alternative approach that utilizes scattered datasets for sound power estimation. The proposed method expands traditional techniques and its feasibility and limitations are evaluated considering variation of the spatial distance between measured positions. The performance of the method is investigated both numerically as well as in a practical application. The proposed approach can be useful in situations where scattered datasets are available. In-situ techniques, such as the proposed method, play a significant role in reducing the need for disassembling the vehicle and performing tests in a laboratory, leading to more efficient and cost-effective sound power estimation.

Keywords: *sound power, intensity, scattered data set*

**Corresponding author*: *lam@microflown.com.*

1. INTRODUCTION

Determining the sound power of devices and machines is a crucial task in acoustics engineering. Conventional methods for calculating sound power often require specialized measurement setups meant for this specific purpose. The measurement surface used in these methods must adhere to strict standards, such as the ISO 9614 [1]. This standard dictates that the measurement surface should preferably be a cuboid or hemisphere shape, from which a measurement path following the surface must be followed. This can be difficult and time consuming to achieve in some measurement environments [2].

To address limitations, we propose a new approach for determining sound power that utilizes a 3D scattered sound intensity vector data set. Instead of relying on a measurement surface, our proposed method can use any set of 3D scattered sound intensity vectors to compute the sound power of an arbitrary sound source [3]. By utilizing a scattered dataset, our method provides a more practical measurement of sound power in a larger variation of measurement environments. This can lead to more efficient and optimized designs for devices and machines in a variety of applications. The paper describes the proposed method and shows its validity through a numerical analysis. It also demonstrates its effectiveness through an experimental investigation, comparing sound power calculations for a variety of intensity probe configurations for real-life sound intensity measurements.

2. SOUND INTENSITY-BASED SOUND POWER

Sound power is a fundamental quantity used to describe the acoustic output of a device. It is defined as the surface integral of the normal sound intensity along a surface enclosing the source under investigation [4]. Mathematically, the sound power level L_W can be expressed as

$$L_W = 10\log_{10}\left(\int_S \frac{I_n}{\mathrm{I}_0}\mathrm{dS}\right), \quad (1)$$

where I_n is the sound intensity normal to the measurement surface S, and I_0 is the reference sound intensity of $10^{-12}\frac{W}{m^2}$. The measurement surface is required to be an enclosed 3D surface surrounding the object being measured. The shape of the surface is not significant in determining the magnitude of the sound power. In practice, the continuous integral has to be discretized into a number of finite segments which combined add up to the total surface area. Consequently, the previous expression can then be formulated as

$$L_W = 10\log_{10}\left(\sum_{i=1}^{N} S_i \frac{I_{n,i}}{\mathrm{I}_0}\right), \quad (2)$$

where N is the total number of segments. Accurate measurement of sound power using this method requires precise measurements of the normal sound intensity on each sub-surface, which can be a challenging and time-consuming task. A hemisphere or cuboid geometries, with varying densities are most commonly used as the shape of the enclosing surface [5].

3. PROPOSED METHOD

The method proposed in this paper uses 3D scattered acoustic intensity vectors to calculate the sound power of an arbitrary object, this data can be acquired using measurement solutions like *Scan and Paint 3D* or *Acoustic Shape* [3, 6]. When 3D scattered intensity vectors are acquired, an algorithm is used to create a enclosing 3D surface around the measured pointcloud, represented as a triangulated mesh. The algorithm discretizes the input coordinates in 3D cells and uses the marching cubes algorithm, along with a surface smoothing method, to ensure that the input positions are located on the surface [7]. This surface is further partitioned into smaller sub-surfaces using a nearest neighbor method, which is applied along the surface shape. This technique ensures that the computed surface shape is subdivided into smaller sub-surfaces that are related to specific measurement vectors. Figure 1 illustrates a visualization of the constructed surface and its sub-divisions. Each face of the triangulated mesh is assigned to its nearest measurement position.

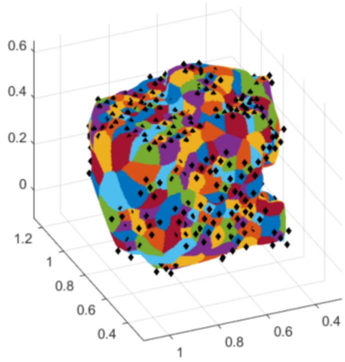

Figure 1: Patch-based spatial discretization using a set of scattered measurement positions (black diamonds) as input.

To calculate the total sound power of a sound source, the contribution of each sub-surface to the total sound power must be calculated first. The sound power contribution of a sub-surface is calculated by multiplying the surface area of the sub-surface by the scalar product of the corresponding 3d intensity vector and the surface normal vector. The equation used to obtain the sound power contribution of the sub-surface is

$$W_i = A_i(\mathbf{I}_i \cdot \mathbf{S}_i), \quad (3)$$

where A_i is the surface area of the face corresponding to the 3D acoustic intensity vector $\mathbf{I}_i$ and $\mathbf{S}_i$ is the surface normal of the sub-surface. The total sound intensity is then calculated as

$$L_W = 10\log_{10}\left(\sum_{i=1}^{N} \frac{W_i}{\mathrm{I}_0}\right). \quad (4)$$

4. NUMERICAL INVESTIGATION

A numerical investigation using a simulated data set was conducted to assess the validity of the proposed method. In this investigation, a set of measurement points are randomly generated around an ideal sound source, specifically a monopole. For each of the points, the radial component I_r of the 3D sound intensity was calculated as [8]

$$I_r(r) = \frac{10^{L_W} I_0}{4\pi r^2}. \quad (5)$$

In practice, the amount of measurement points around a sound source can largely vary, depending on the target application and nature of the source. To investigate the impact of spatial variance between the distance of measurement locations, the sound power is calculated using fractions of the input point cloud. A subset of input measurements was randomly removed from a set of 360 points and the sound power was calculated based on the remaining measurement points, the number of points which are removed are varied during the experiment. The performance of the proposed method was evaluated based on the variance in the sound power levels obtained for different average spacing between the measurement locations. Because the distance between measurement points is not evenly distributed, the average inter-spacing distance, denoted by δ, was calculated as

$$\delta = \sqrt{\frac{N}{A}}, \tag{6}$$

where A is the total surface area of the computed surface in m^2. To ensure the reliability of the results, the random removal of measurement points was repeated for 100.000 iterations. This approach provided a comprehensive assessment of the proposed method, allowing for a thorough evaluation of its robustness and accuracy in predicting the sound power levels under ideal measurement conditions. Surfaces and sub-surfaces with an increasing amount of randomly removed points, are illustrated in Figure 2.

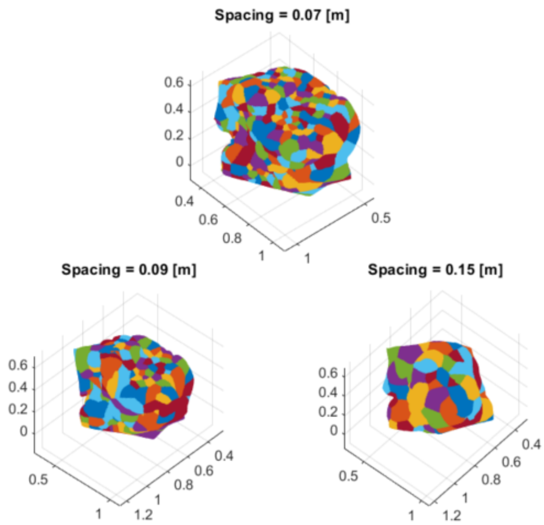

Figure 2: Examples of spatially discretized volumes with different average inter-spacing measurement points

The numerical investigation assessed the consistency of the proposed method in calculating the sound power for inter-spaced distances between measurement points ranging from $\delta \approx 0.075$m to $\delta \approx 0.155$m. Figure 3 depicts that the computed sound power is relatively consistent for an ideal sound source, the data is normalized to 0dB using the theoretical sound power as reference. The proposed methodology achieves accurate results, achieving a sound power estimation level less than 1 dB difference with respect to the target theoretical value. However, there seems to be a slight bias, leading to a 0.2 dB error. The spatial discretization caused by the algorithm seems to be responsible of introducing the bias, so further research is required to improve the estimations The largest variance in the computed sound power is lower than 0.5dB, which means that the method works for ideal sound sources.

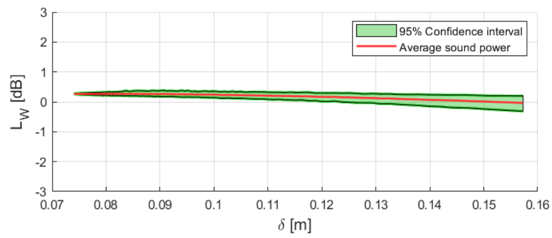

Figure 3: Average sound power and confidence interval for an ideal sound source

5. EXPERIMENTAL INVESTIGATION

To further investigate the performance of the proposed method, we conducted a similar investigation to the numerical study using a real sound source. We randomly removed an increasing number of points and calculated the sound power based on the remaining points.

To obtain a 3D scattered sound intensity data set, we utilized the *Acoustic Shape* sound visualizing system. This system employs a 3D camera and an array of 3D sound intensity probes to capture a scattered sound intensity data-set in 3D space. *Acoustic Shape* is particularly useful for capturing non-stationary sound fields, such as an engine run-up. By using a tripod, we positioned the probe array at desired locations around the sound source. The sound intensity values in this study were captured during an engine run-up. However, due to confidentiality reasons, we only computed the sound power for the engine running at 5800 rpm. The measurement locations were the same as those used in the numerical investigation. Figure 4 presents a picture of the probe array and a 3D model of the powertrain, indicating the measurement locations [9].

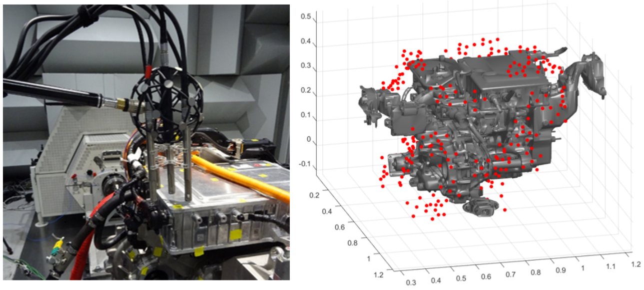

Figure 4: Picture of the experimental setup, including a 3D sound intensity probe array (left) and measurement locations relative to the powertrain (right)

The results of the experimental investigation demonstrate a pattern that is comparable to the results observed in the numerical investigation. However, the graph in Figure 5 shows a larger variance, which can be attributed to the non-uniformity of the sound field. The acquired sound power levels are normalized to 0 dB by subtracting the average of all computed values. It should be pointed out that this way of normalizing potentially masks any biased offset. The experimental investigation assessed interspaced distances ranging from $\delta \approx 0.07$m to $\delta \approx 0.155$m. While the proposed method appears to be reliable and consistent, additional experimental and numerical analyses with larger data sets are required to further validate the performance of the method. Additionally, comparing the method's performance with other metrics, such as the field non-uniformity indicator $(f4)$ from the ISO 9614 [1], would provide further insight into its effectiveness.

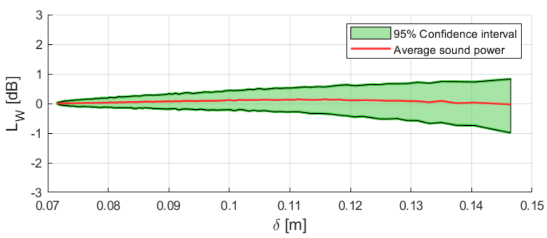

Figure 5: Average sound power and confidence interval for experimental sound intensity measurements

6. CONCLUSION

The proposed method for determining sound power using 3D scattered sound intensity vector data is a more flexible and adaptable approach that can be used in a larger variation of measurement environments than conventional methods.The proposed method was validated through a numerical analysis and demonstrated its effectiveness through an experimental investigation, comparing sound power calculations for a variety of intensity probe configurations for real-life sound intensity measurements. Compared to conventional methods for calculating sound power that require specialized measurement setups, the proposed method does not rely on a strict measurement surface

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