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Determinig of the Sound Power of the Fan in *In Situ* Conditions Using the Virtual Reference Source Method

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Abstract Sound power is one of the basic parameters characterizing the sound source and has a direct impact on the acoustic climate in its surroundings. Therefore, the determining of the sound power of machines is a practical problem. While there are many methods of determining the sound power, each of them has its own limitations. The authors presented the implementation of a comparative method of determining the sound power with the use of a virtual reference source. The method was used to test a high-efficiency flue gas exhaust fan installed on a laboratory stand. The sound source was placed in the geometric centre of the fan and the acoustic field distribution in the room was determined using geometrical methods. After determining the influence factors, the value of the source sound power of the source was calculated by means of the Moore-Penrose pseudo-inverse. Since the problem under study belongs to the inverse problems, the Tikhonov regularization was used, where the value of the parameter α was determined by the L-curve method.

Keywords: fan as a sound source, sound power, noise, reference source, regularization

1. Introduction

Every machine is a source of sound that is usually treated as noise. Since acoustic waves are radiated by all vibrating surfaces, a precise description of the acoustic field around such a source is not possible due to the complexity of the wave pattern. Taking into account the fact that the reflections from the walls of the room constitute a background noise disturbing the measurements, this issue becomes a big challenge. Therefore, one of the most important characteristics of a sound source, and therefore a machine, is the sound power. The sound power is defined as the energy radiated by a source per unit time and is an energy indicator describing the total emission of the source. Based on the sound power value and the source directivity characteristics, simulation methods can be used to determine the acoustic field distributions around such sources and the impact of these sources on the environment.

There are currently two approaches to determining the sound power of a source: in the first approach, measurements are made in the direct field, in the second approach, the measurement points are in the reverberation field. When measuring in a direct field, the values of a sound pressure or sound intensity can be measured, and the reverberant acoustic field, which consists of the reflections from the surfaces delimiting the measuring space, constitutes a disturbance. Due to the sensitivity on the disturbance of the reverberation field, this group of methods gives the best results in open spaces or rooms with high acoustic absorption. The anechoic or semi-anechoic chamber performs particularly well here.

In the case of measurements performed in a reverberation field, the sound pressure level is determined. With these methods, the acoustic field should be characterized by a sufficiently large degree of dispersion. For this reason, special rooms called reverberation chambers are mainly used for these measurements.

In industrial conditions or even in industrial laboratories, the implementation of such tests is difficult due to the complex nature of the acoustic field. The solution in such cases can be intensity methods, which can be used in close proximity to the sound source.

The existing standards regulate the performance of such measurements and specify the requirements that must be met in order for the obtained results to have the assumed accuracy class. The conditions imposed on the measurement refer to:

- the size of the laboratory room,
- distance from background noise,
- changes in temperature and humidity ,
- the size of the source ,
- acoustic characteristics of laboratory rooms,
- number of sound sources,
- number of measurement points
- localization of measurement points,
- type of generated noise,
- type of measurement parameters.

Among the standardization documents, it is worth mentioning the ISO 3741, ISO 3743 and ISO 3747 standards. The PN-EN ISO 3741 standard describes the methods of accurate determination of the sound power in reverberation chambers, and the PN-EN ISO 3743 standard describes the technical comparative method. On the other hand, PN-EN ISO 3747 describes a comparative method for the determination of the sound power in *in situ* conditions.

As the described methods cannot always be applied, the authors decided to present a method for determining the sound power of the source using the virtual reference source method. The described method belongs to the group of comparative methods and requires additional equipment in the form of software for modelling the acoustic field distribution. The authors used the open source software I-Simpa [1, 2, 3], which uses the ray method to determine the acoustic field distribution. The selected software can be an alternative to programs such as Catt-Acoustic, Odeon or EASE.

The described method consists of two stages, the first of which, consisting in the development of a sufficiently accurate numerical model of the tested room, requires a significant amount of work. In order to implement the virtual reference source method, it is necessary to develop a geometric model of the room and adjust this model to real conditions. The construction of such a model requires measurements of the existing room, taking into account the objects located in the room and which may affect on the acoustic field distribution. Of course, the basic criterion to be followed when selecting objects to be included in the model is their size and the expected impact on the distribution of the acoustic field.

After developing a geometric model, which also takes into account surfaces that are covered with various materials, one can proceed to the second stage of model development, i.e. fine-tuning. To fine-tune the numerical model, it is necessary to measure the acoustic parameters of the room. In general, the impulse response or reverberation time measurements should be made at as many as evenly spaced points in the room as possible at different sound source positions. It is worth making verification measurements with the reference sound source and measuring the sound pressure levels in the reverberation field for the given reference source locations. Based on the impulse response measurements, it is possible to determine not only the reverberation times, but also other measures describing the acoustic field at measurement points.

The next step is to select the values of the absorption coefficients inside the room model in frequency bands so as to minimize the differences between the acoustic field characteristics obtained from the model and measurements. Of course, the size of the room determines the analyzed frequency band.

It should be emphasized that the described stage of building a numerical model is extremely laborious and is an iterative process that should be repeated until the differences are sufficiently small. During this process, not only the values of the absorption coefficients are changed, but also the detail of the room equipment. Once a correctly developed numerical model of a laboratory room can be repeatedly used to test various sound sources.

The stage of building of a numerical model should be performed each time when significant changes occur in the room. After each change, control measurements of the acoustic field distribution should be carried out to verify the assumption of the correctness of the numerical model. These measurements correspond to the calibration process of the measurement path.

The next step is to measure the acoustic field distribution around the tested sound source. During measurements, the values of the sound pressure level in frequency bands at selected measurement points are determined.

The next step, which is carried out in the software for numerical determination of the acoustic field distribution, is to replace the real sound source with a source of known sound power, which acts as the reference source. Then the so-called influence factors that can be interpreted as gains in the sum of the acoustic energy transmission paths from the source to the individual receivers. On this basis, a system of equations can be formulated, which, after solving using, for example, the least squares method, will allow to determine the sound power of the tested source.

The generally accepted limit of the applicability of geometrical methods for modeling the acoustic field distribution in rooms is the Schroeder frequency [4], which allows to estimate the frequency range in which single modes dominate. For the analyzed room, the Schroeder frequency is 77 Hz.

2. Research object and description of the laboratory room

The object of the research was a high-efficiency exhaust gas fan installed on a measuring stand in a laboratory room. The geometrical model of the discussed room is shown in Fig. 1.

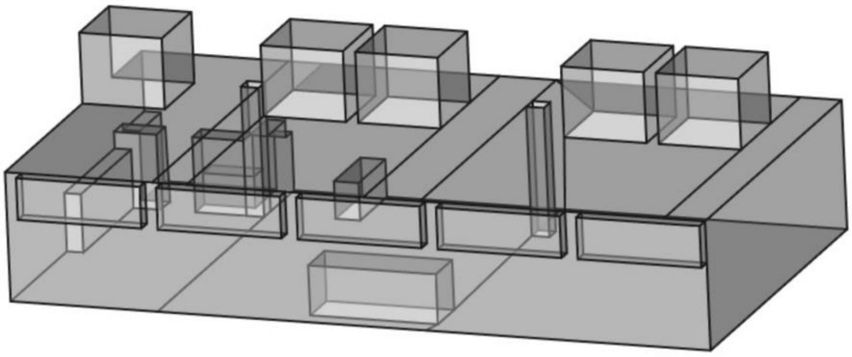

Fig. 1. Geometric model of the laboratory.

In order to fine-tune the numerical model of the laboratory room, acoustic measurements were taken in the real room. These measurements were made based on the PN-EN ISO 3382-1: 2009 standard. Mean value of sound absorption coefficient in this room is less than 0.15, volume is about 500 m^3. Sound power of the source is estimated by minimizing sum of squared differences of sound pressure in measurement points. Reverberation time measurements were conducted on the basis of decay curve obtained by inverse integration of impulse response obtained by a sweep signal. The sound source was located in the geometric center of the room. Measurements were made at 10 points (Rec 1 - Rec 10), the schematic arrangement of which is shown in Fig. 2.

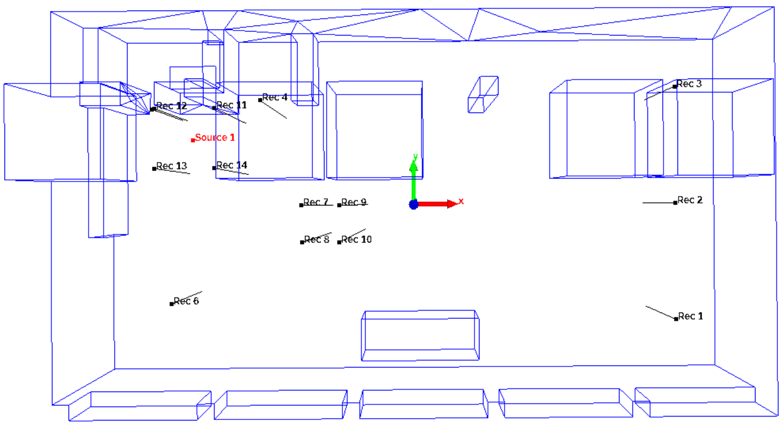

Fig. 2. Distribution of measuring points in the real room.

As can be seen, the MSE values for frequencies above 160 Hz are below 0.01. Globally, MSE was equal to 0.0018 and RMSE was equal to 0.0424. Taking into account the fact that the Schroeder frequency for this object is approx. 77 Hz and bearing in mind the limitations imposed on the geometrical methods, it can be concluded that the tuning of the numerical model of the room was correct.

Fig. 2 also shows 4 additional measurement points (Rec 11 - Rec 14) and the "Source 1" sound source, which were then used for the proper calculations related to the determination of the sound power of the fan. These localizations corresponded to an analogous measuring points and the real sound source in a real room.

Since the authors do not have complete information on the acoustic properties of the materials used in the room, apart from the precise mapping of the shapes of objects inside the room, it was also necessary to fine-tune the absorption coefficients used in the numerical model. The analyzes were performed in one third octave bands. Fig. 3 shows the average absorption coefficient of the real room. The fit index was the mean square error, and assessments were made both for individual third octave bands as well as globally. Fig. 4 shows the MSE and RMSE plots in one-third octave bands, demonstrating a good tuning of the numerical model of the room.

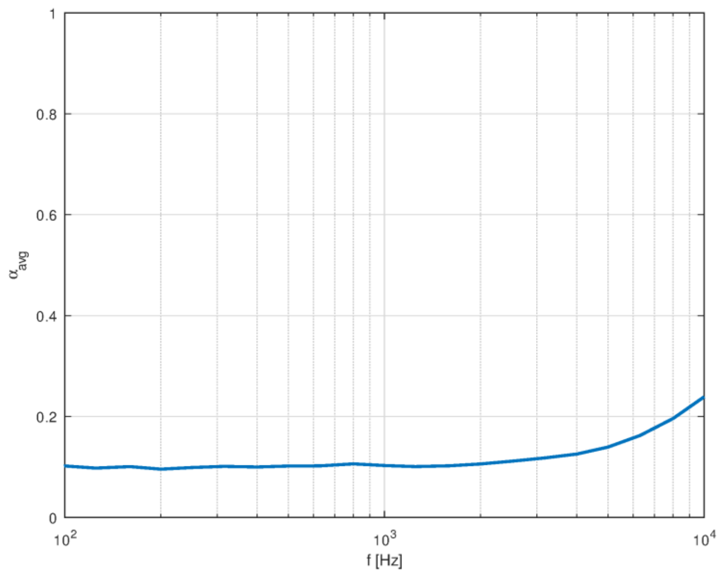

Fig. 3. Average absorption coefficient of the laboratory room.

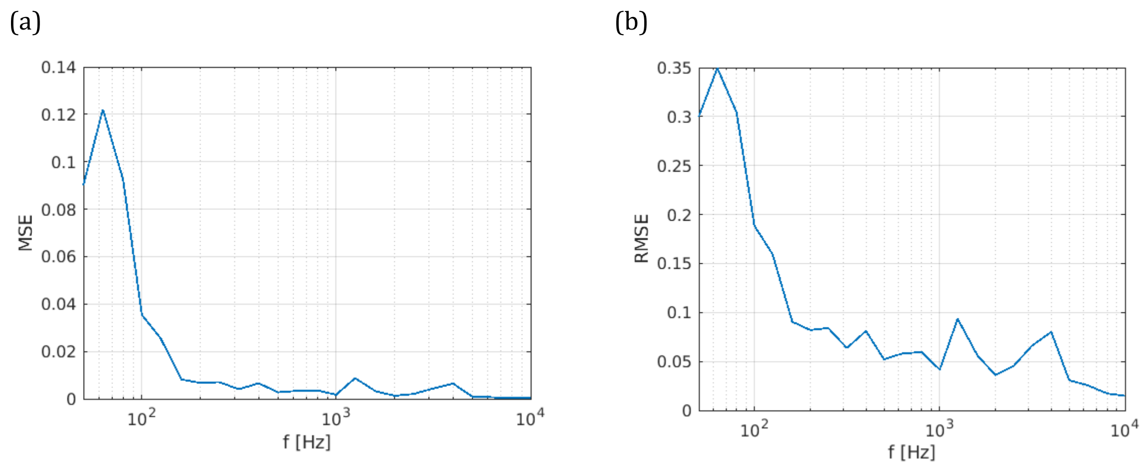

Fig. 4. Laboratory room numerical model tuning indicators
a) MSE, b) RMSE.

3. Determining of the sound power of the fan

The actual works related to the determination of the sound power of the fan started with the acoustic measurements of the real facility. These measurements were made at 4 points around the fan, for different speeds (operating points), in 1/3 octave bands.

The next stage of the work was to determine the value of the acoustic pressure at analogous measuring points in a virtual room with the use of a virtual reference sound source. These calculations were made in the I-Simpa program with the use of a sound source with an sound power equal to 1 W. Numerically determined values of the acoustic pressure were then used to build the matrix of influence factors.

Determining the sound power of a source based on the measured values of the sound pressure generated by this source is a problem that belongs to the group of inversion problems. In order to determine the sound power of the fan, two methods were used: Moore-Penrose pseudo-inversion and Tikhonov regularization.

The Moore–Penrose inverse is the most widely known generalization of the inverse matrix [5, 6]. It is a direct application of the SVD. A common use of the pseudoinverse is to compute a "best fit" solution to a system of linear equations that lacks a solution. To find the pseudoinverse the following formula can be used:

$$\mathbf{P} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{I}_\mathrm{N}\,, \tag{1}$$

where $\mathbf{P}$ is the sound power of the fan, $\mathbf{I}_\mathrm{N}$ is the sound intensity based on the measurement in the measurement points, and $\mathbf{A}$ is the matrix of the influence factors. Sound intensity values were calculated on the basis of sound pressure level.

Regularization is the process of adding information in order to solve an ill-posed problem or to prevent overfitting. Tikhonov regularization is a method of regularization of ill-posed problems. In the simplest case, the problem of a near-singular moment matrix is alleviated by adding positive elements to the diagonals, thereby decreasing its condition number [7, 8, 9, 10]. One can use the following formula:

$$\mathbf{P} = (\mathbf{A}^T\mathbf{A} + \alpha\mathbf{I})^{-1}\mathbf{A}^T\mathbf{I}_\mathrm{N}\,, \tag{2}$$

where $\mathbf{I}$ is the identity matrix, and α is the ridge parameter.

Regularization parameter controls how much filtering is introduced by the regularization. Correct value of this parameter is one of the problems of Tikhonov regularization. It can be calculated based on the L-curve [10, 11, 12]. For presented problem the L-curve is shown in Fig. 5.

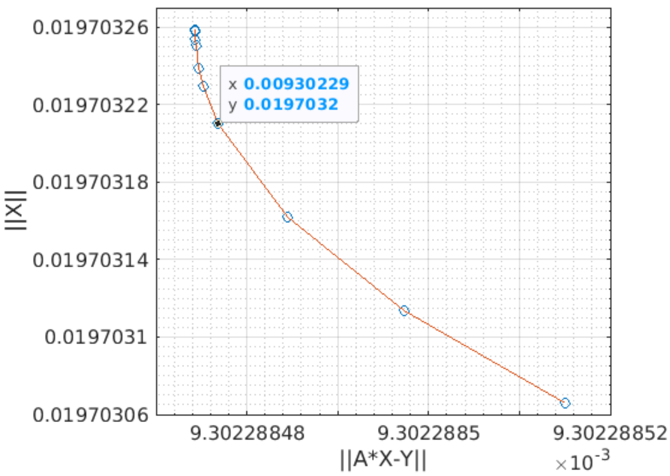

Fig. 5. L-curve for Tikhonov regularization.

The optimal solution can be obtain by using regularization parameter, which is connected with the values of the corner of the L-curve. The presented L-curve is not of a traditional L-curves' shape. But based on the article [13] Authors decided to assume α regularization parameter related to the point marked in Fig. 5. So the regularization parameter is equal to 5e-5.

As a result of the calculations, the values of sound power and the sound power level of the fan were obtained at 11 operating points. The results are shown in Fig. 6.

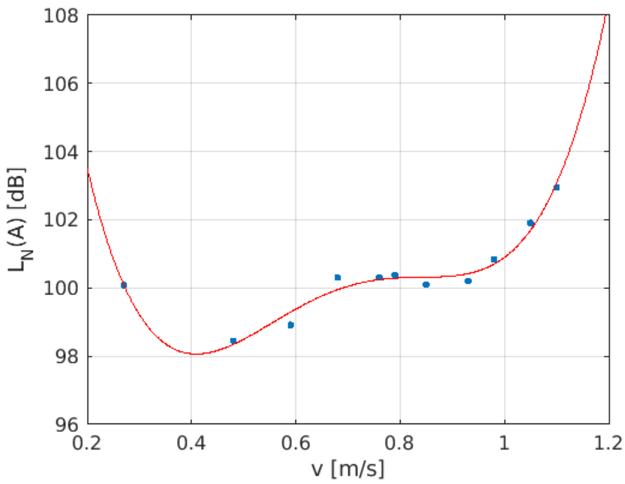

Fig. 6. Fan sound power level at 11 operating points.

There is only one curve on the chart, because the values of sound power levels obtained with both presented methods differed very slightly, the values of the differences amounted to approx. 1.0e-5.

4. Summary

The article presents a method of determining the sound power of a sound source at a laboratory stand based on a virtual reference source. The presented problem belongs to the group of inversion problems. Two methods were chosen to determine the sound power value: Moore-Penrose pseudo-inverse and Tikhonov regularization. In the presented case, both methods obtained similar sound power values.

To confirm the obtained results, it would be advisable to perform additional measurements with a reference source in a real laboratory room. Another element is the even more precise tuning of the room model, for which it would be advisable to perform additional measurements of the acoustic parameters of the room in a larger number of measurement points. The third element that could also refine the results is a greater number of measurement points around the analyzed fan. Nevertheless, the method seems to be promising, especially considering that the nature of the sound power level values obtained is consistent with the observations.

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