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Estimation of Sound Power Level of Machine by Inverse Method

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Abstract The paper presents the inverse method to estimate the sound power level of machines operated in industrial environments. Values of the partial sound power sources of machine components could be predicted based on the distribution of sound field parameters measured around the machine. Assigning partial sound power levels of machine components allows for the effective selection of efficient noise protection solutions for this machine. Measurements were carried out in an actual mechanical workshop. The multichannel measurement system for simultaneous recording of sound pressure levels and the angle of phase angle shift was used in measurements. Based on the determined the sound power of partial sources, the A-weighted sound pressure levels at the operator's workplace were determined.

Keywords: inverse method, sound power, sound pressure level, sound measurement

1. Introduction

Two complementary acoustical quantities describe the noise emission by a machine. They are the sound power level of the machine and the emission sound pressure level. International standards, which described the basic methods for determining sound power level, are standards from PN EN ISO 3740 to PN EN ISO 3747 and PN EN ISO 9614-1 and PN EN ISO 9614-2 (intensity methods). Various methods for determining the emission sound pressure levels of machinery and equipment are described in the international standards PN EN ISO 11200 to PN EN ISO 11204. In the study of acoustic parameters of machines working in industrial conditions may be used, among other methods, acoustical inverse methods [1, 2, 3]. They allow the noise rating of machinery based on an analysis of the sound field parameters in its environment. These methods are associated with the modelling of acoustic energy transmitted from the source to the point of observation. The sound field parameters in the observation points governed based on measurements allow determining of parameters of the sound source by reversing the modelled way of propagation.

The development of the inverse methods associated with other computational methods, such as finite element method (FEM) and boundary element method (BEM), geometrical acoustic methods for determining the acoustic wave propagation in rooms allows for more efficient ways of locating partial sources for complex sound sources.

Reconstruction of the sound sources using boundary element methods (BEM) and inverse methods is an important tool to identify the sources of any shapes. One of the essential advantages of these methods is identifying the zones of increased vibroacoustic emission of the machine body or functional elements.

After the experience in determining the sound power level of a single machine using the inversion method [4, 5, 6, 7], the method was applied to determine the sound power level of the series of types of machines (Fig. 1).

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Fig. 1. Series of AC generators ready to test.

The machines selected for the experiments were standalone, portable electrical generators with different output power.

2. Formulation the problem

In the inverse method, the actual sound source is replaced by a system of substitute sources. Substitution of the machine as the main source of noise by partial substitute sources (which could be functional components of the machine such as a motor, a fan, gears, and others) is associated with the supposition of their location in space and the characteristics of the sound radiation direction. Then, certain parameters of those sources are simulated to obtain the sound field distribution generated by the substitute sources' system as much as possible corresponding to the sound field distribution around the real source [8, 9].

Inverse methods in vibroacoustics can be practically applied in the identification of vibroacoustic energy sources in sound radiation by vibrating surfaces, as well as allow the acoustic rating of machines based on an analysis of the sound field parameters (Fig. 2).

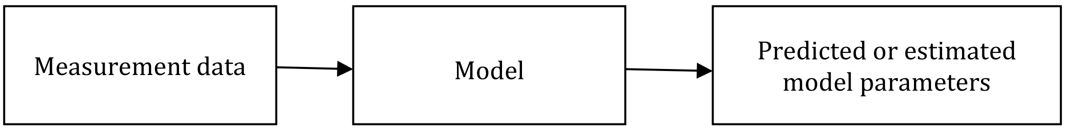

Fig. 2. Modeling of inversion process.

When the observation point is relatively far from the actual sound source, the influence of geometric dimensions of the source can be disregarded and the sound source treated as the quasi-point one. The acoustic field generated by the substitute quasi-point sources can be presented as a superposition of elementary waves emitted by individual sources. When we limit our investigations to mono-harmonic stationary processes, the acoustic pressure in observation points around the sound source can be determined from equation (1). This equation is the matrix product of vector **N** (m-dimensional vector of the sound power of sound sources) and vector **H** presented as a matrix of the influence function of the i^{th} source on the acoustic pressure value in the j^{th} point [3, 5]:

$$\mathbf{p}^2=\mathbf{HN}+\mathbf{e} \tag{1}$$

where $\mathbf{e}$ is the m-dimensional unknown errors vector, which is the difference between the pressure determined from the noise propagation model and the actually measured value in the observation point.

Determination of parameters of sound sources in the model was carried out for the omnidirectional sources placed on the acoustical hard surface. Knowing the phase shift angle between microphones we can present the source model in the following way [2]:

$$p = \sqrt{\frac{N\rho_0 c}{\pi}} \frac{\exp(ikr)}{r} \tag{2}$$

where p is the sound pressure, [Pa], k is the wavenumber, [m^{-1}], N is the sound power of the source, [W], ρ_0 is the air density, [kg/m^3] , c is the sound speed [m/s] and r is the distance from the source to the observation point, [m].

As a result of measurements in the industrial room and acoustical calculations, we had got the sound power of generator elements (partial sources) and phase shift angle between sound sources.

Based on the obtained acoustic parameters of substitute partial sources, we can reconstruct the sound field around the machines. The distribution of sound pressure levels around the working generator was determined, assuming the omnidirectional characteristics of the equivalent sound sources, the phase shift, and the location of these sources.

The sound pressure level at the point of measurement is calculated using formula (3):

$$L_p(\theta,\varphi) = 10\log\left(\sum_{i=1}^{n} A_i R_i(\theta,\varphi)\frac{\exp(-jkr_i+\psi_i)}{r_i}\right) \tag{3}$$

where A_i is the source momentum of the i-th substitute source, [Pa/m], Ψ_i is the phase shift angle of i^{th} source and $R_i(\theta,\varphi)$ is the directivity characteristics of i^{th} source,

$$R_i(\theta,\varphi) = \exp[jk(x_i\cos\varphi\sin\theta + y_i\sin\varphi\sin\theta + z_i\cos\theta)] \tag{4}$$

where x_i, y_i , z_i are the coordinates of the position of the i^{th} source, [m].

3. Experimental Part

3.1. Sound measurements

In experimental tests the inverse method was used for estimation the sound power level of four AC generators in the mechanical workshop of dimensions 14.9 x 7.8 x 6.6 m.

Measurements were provided using the National Instruments apparatus, chassis NI PXI-1042Q, with installed two eight channels measuring cards type NI PXI-4472B. The measurements and analyses were performed using LabVIEW software. Virtual instruments enabling the simultaneous multichannel registration signals were created. Then, the amplitude and phase shift angle of the measuring signals were simultaneously recorded in the files.

Sound pressure values were measured by twelve microphones G.R.A.S. 40PQ placed at a distance of 1 m to 2 m from the measuring unit in different directions and altitudes above the floor (Fig. 3). Generators were tested successively, placed at the same point of industrial spaces, and geometric projection of the center of each of the test generator is at the same point.

Measurements were performed for the idle (no load) (0) and three types of unit loads (I – III). Each of the AC generator's supplies of electricity was loaded by the electrical spiral heating element, adjustable heating power (I) 350W, (II) 700W, and (III) 1500W). All the generator units were cooled by air, produce electricity with standardized voltage 230V and 50 Hz frequency.

Fig. 3. Measurement of noise in the mechanical workshop using 12 microphones.

The mean square of the sound pressure p was determined from the power spectral density of signals G_{22} measured by measuring microphones M1 – M12:

$$\overline{p^2} = G_{22} \tag{5}$$

and

$$\overline{p^2} = \int_{f-\frac{1}{2}\Delta f}^{f+\frac{1}{2}\Delta f} G_{22}(f)df, \tag{6}$$

where $G_{22}(f)$ is the power spectral density function, [N^2 m^{-4}], f is the test frequency [Hz]; Δf is the frequency bandwidth [Hz].

The phase shift angle ψ was determined by the ratio of the imaginary part to the real one of the cross-spectral density function G_{12}:

$$\psi = \arctan\left(\frac{\mathrm{Im}(G_{12})}{\mathrm{Re}(G_{12})}\right) \tag{7}$$

where

$$G_{12} = \int_{f-\frac{1}{2}\Delta f}^{f+\frac{1}{2}\Delta f} G_{12}(f)df \tag{8}$$

where G_{12} is the cross-spectral density function, [N^2 m^{-4}] .

3.2. Discussion results

The measurements were made for the CMI C -G series of generators. All measurements took place after the generator's operation had stabilized. The primary purpose of the measurements was to determine the power of substitute sound sources for each generator. With these parameters of the sound sources, it is possible to determine the total sound power of the device and determine the acoustic field parameters at a selected point around the machine. Such calculations can be performed by taking appropriate directional characteristics of substitute sources and their locations and phase shifts.

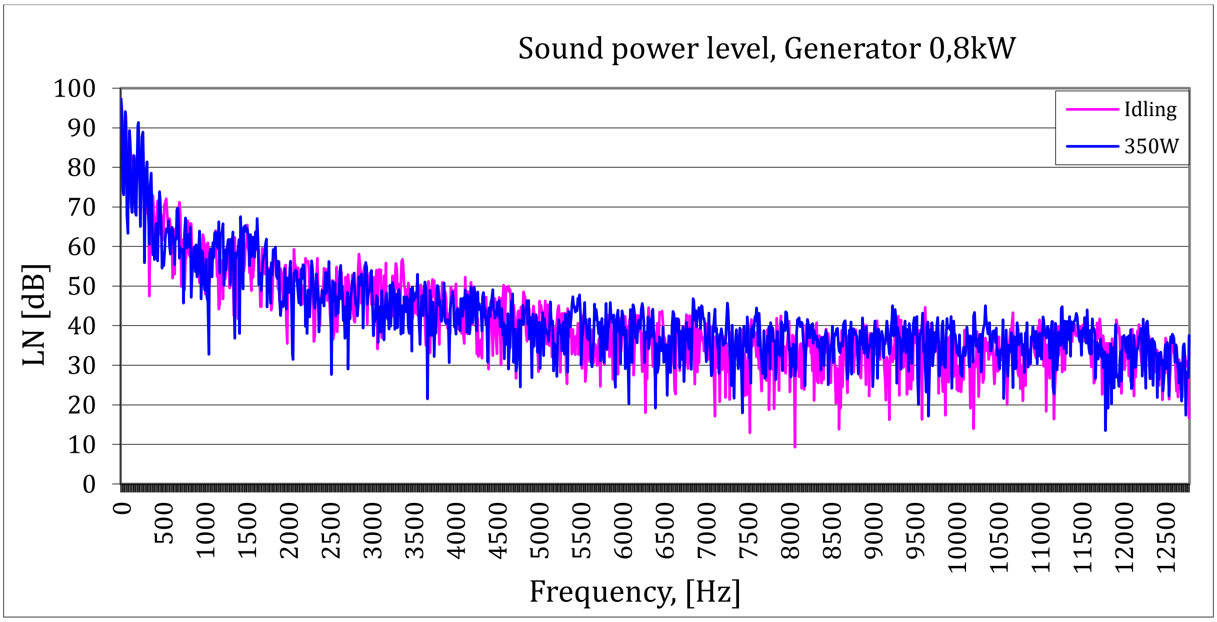

Fig. 4. Sound power levels for frequency bandwidth Δf= 10 Hz of generator CMI C-G800 0,8 kW for different variants of power loads.

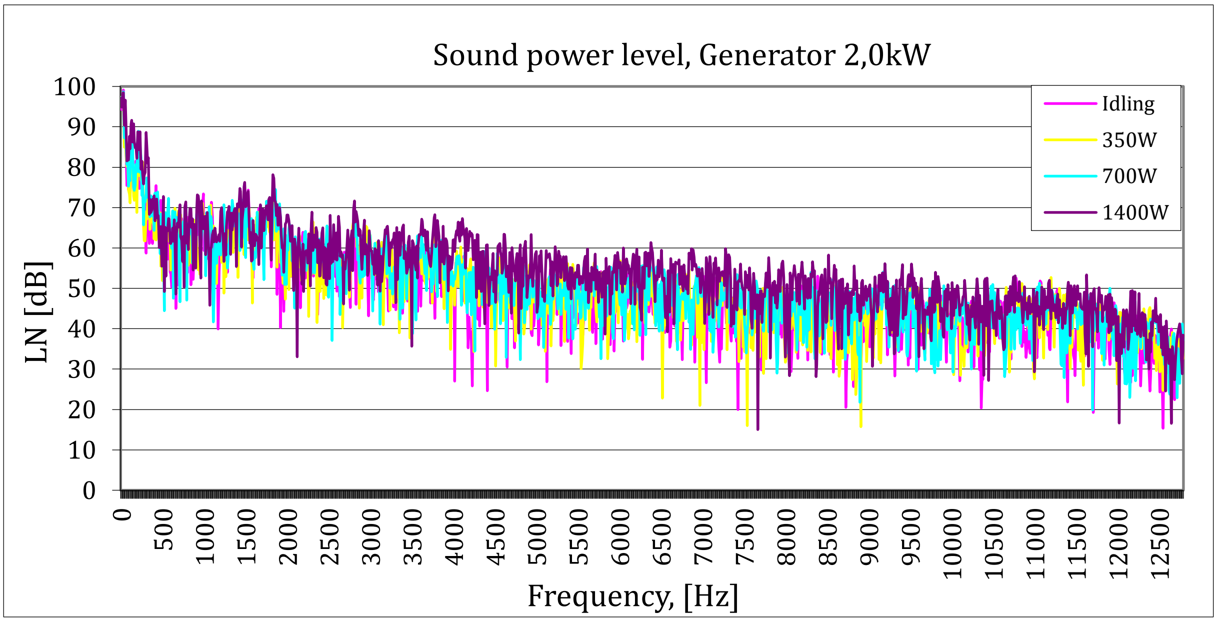

Fig. 5. Sound power levels for frequency bandwidth Δf= 10 Hz of generator CMI C-G2000 2 kW for different variants of power loads.

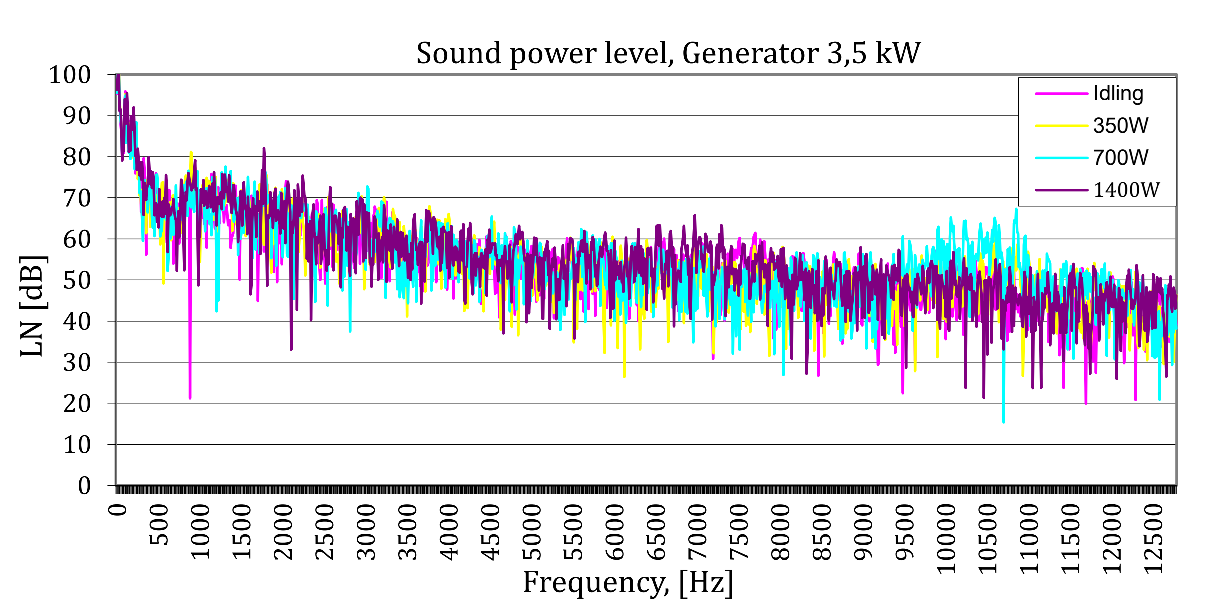

Fig. 6. Sound power levels for frequency bandwidth Δf= 10 Hz of generator CMI C-G3500 3.5 kW for different variants of power loads.

The summary results of the series of measurements and calculations are shown in Figures 4-6 (Figure 4, Figure 5, and Figure 6). They present the results of estimates of the generator sound power value for various quantities consumed by the power load. These results are shown in the form of a narrowband spectrum analysis with a width frequency band Δf = 10 Hz from 20 Hz to 12,500 Hz.

The signals recorded from 12 microphones placed around the tested device made it possible to determine the partial power of the generator sound sources with the locations assumed a priori. The graphs (see Fig. 4 – Fig. 6) of the sound power levels for different types of AC generator loads show the similarity of the spectral distributions of each noise generator. The sound pressure level differences are already much higher for different kinds of loads in the narrowband frequency spectra. In computer simulations, an operator's position was established at a distance of 1 m from each machine, i.e., a position related to supervising the machine's operation. Table 1 shows the calculated values of noise levels for the tested series of generators for different output loads. The numerical values of the sound pressure level for each generator do not differ by more than ± 2 dB for the different types of load.

Tab.1. The A-weighted equivalent continuous sound pressure levels L_{AEQ} at the workplace-surveillance of the generator.

No	Generator type	Heater load mode	A-weighted equivalent continuous sound pressure levels at the workplace (1 m from the current generator), dB L_{AEQ}
1	CMI C-G800 0,8 kW	0	74.4
		I	77.5
2	CMI C-(G) 2000 2.0 kW	0	80.2
		I	80.8
		II	81.7
		III	83.1
3	CMI C-G 3500 3.5 kW	0	84.9
		I	85.6
		II	84.9
		III	86.4

Many machines and devices can participate in the industrial process, and each machine, equipment, or means of transport has many partial noise sources. The identification of partial sources must precede any activities aimed at reducing noise emissions from noise sources. The identification tasks include the location of sources, determination of the sound power level emitted by the source, and determination of radiation directivity. Using various measurement techniques, the author has repeatedly examined the parameters of the sound field in industrial rooms. The research results were used, among others, for modelling noise sources, determining the location of sound sources and determining their sound power, acoustic evaluation indicators for determining the acoustic quality of machines.

4. Conclusions

To investigate and evaluate acoustic parameters of machines can be used various test methods: the inversion method, the reciprocity method, intensity methods. The most frequently used methods for determining the sound power level are methods using sound pressure.

Each of these methods has advantages and disadvantages that make them more useful or the possibility of use in specific industrial circumstances. The advantage of this method is the possible use for the identification, localization, and then determine the partial sound power level of noise sources, in situ conditions. Difficulty in applying this method is complicated measurement and mathematical apparatus necessary for the calculations. The survey and engineering methods are more accessible measuring methods of determining sound power levels of machines using sound pressure. However, the resulting value of the sound power level is the global value for the whole machine [10].

This paper presents an experimental phase of work leading to a broader analysis of acoustic phenomena in industrial rooms. Also, the acquisition of measurement data to implement the inverse method in studying acoustic parameters of machines in industrial environments is presented.

The inverse method also allows the reconstruction of compound sound sources and identifies areas of the body machines or their functional nodes of excessive vibroactivity. It is related to the method of modeling a sound source consisting of elementary monopoly substitute sources. The study is part of a research program associated with inverse methods in determining the acoustic parameters of machines in industrial environments and comparing the results with those obtained by using other research methods.

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Additional information

The author declare no competing financial interests.

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