

ACOUSTIC MODELLING OF MACHINES USING THE INVERSION METHOD FOR THE PURPOSES OF THE ACOUSTIC ASSESSMENT OF MACHINES

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Issues related to the development of acoustic models of machines are important factors both in the design of low-noise machines and in the prediction of machines noise. The acoustic modelling of machines may be carried out using a set of omni-directional substitute sound sources, located in points related to the functional elements of machines. The optimal parameters of these sources may be determined using an inversion method. To calculate these parameters by using the inversion method one must know the real distribution of sound pressure around the machine. This requires the determination, on the surface of hemisphere, of both the distribution of the amplitude of sound pressures, as well as the distribution of phase shift angles between acoustic signals. Computer simulations yield optimal parameters (sound power) for the individual omni-directional sound sources. Using the calculated parameters of the substitute sources it is possible to determine the radiation characteristics and to carry the acoustic assessment of the machine.

Keywords: machinery noise, acoustic model, emission sound pressure, sound power.

1. Introduction

Facilitating the understanding of the complex mechanisms of sound generation and propagation in machines calls for the development of simple acoustic models. These models are the basis for the inclusion of noise-control measures at the respective stages of design. Sound generation mechanisms in dynamic processes may be related to the properties of elementary sound sources of known properties, e.g. monopoles. In such a case, the results of the sound source modelling of machines may be used to determine the acoustic parameters necessary to carry out the acoustic assessment of machines [1].

Based on parameters of a substitute model of machine, it is possible to determine the emission sound pressure level at a work station or at other specified position. This

level, together with the sound power level, should be taken into consideration during the process of the machine conformity assessment carried out pursuant to the Machinery Directive 2006/42/EC [2].

2. Application of inversion methods to acoustic modelling

Inversion may be one of the methods used in acoustic modelling for the acoustic assessment of machines on the basis of the analysis of acoustic field parameters. By modelling the process of the radiation of vibro-acoustic energy from source to receiver and knowing the real values of sound pressures at measuring points, one can inverse the model of the propagation path and thus determine the parameters of the sound source.

The scheme of the determination of the parameters of substitute sources by using the inversion method is presented in Fig. 1 [3].

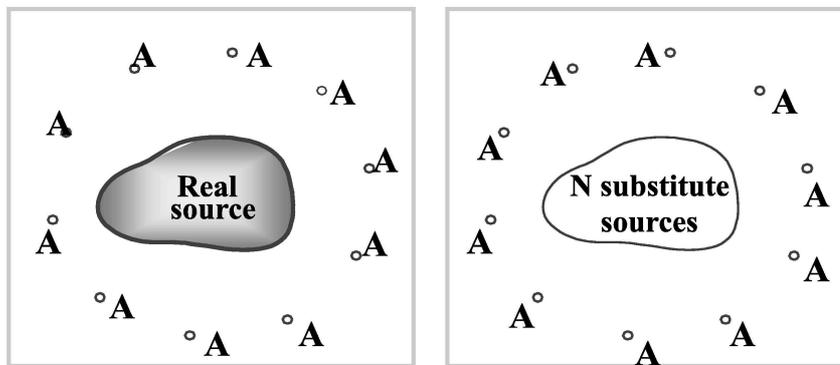


Fig. 1. Scheme of the determination of parameters of substitute sources.

The sound pressure at observation points A can be determined from following dependence:

$$\boldsymbol{\pi} = \mathbf{G} \boldsymbol{\alpha} + \mathbf{e}, \quad (1)$$

where $\boldsymbol{\pi}$ – m -dimensional vector of measured complex amplitudes of sound pressure at observation points, $\boldsymbol{\alpha}$ – n -dimensional vector of complex parameter values of the model source, \mathbf{G} – matrix $m \times n$ defining the complex value of sound pressure at observation points, determined on the basis of parameters of substitute sources, \mathbf{e} – m -dimensional vector of error.

To calculate the parameters of substitute sources by using the inversion method [3] one must know the real distribution of acoustic pressure around the machine. This requires the determination, on the surface of a hemisphere, of both the distribution of the amplitude of acoustic pressures, as well as the distribution of phase shift angles between acoustic signals.

3. Distribution of sound pressure levels

The parameters of substitute sound sources can be used to determine the distribution of sound pressure levels around the machine. The distribution of sound pressure levels can be calculated using the following relationship [4, 5]:

$$L_p(\theta, \varphi) = 10 \log \left(\sum_{i=1}^n A_i R_i(\theta, \varphi) \frac{\exp(-ikr_i)}{r_i} \right) \quad [dB], \quad (2)$$

where A_i – moment of the i -th substitute source [Pa m], $R_i(\theta, \varphi) = \exp[ik(x_i \cos \varphi \sin \theta + y_i \sin \varphi \sin \theta + z_i \cos \theta)]$ – directional radiation characteristics of the i -th source, x_i , y_i , z_i – coordinates of the location of the i -th source [m].

4. Results of experimental tests

4.1. Acoustic measurements

The measuring set-up used to determine the distribution of sound pressure emitted by an industrial vacuum cleaner in an anechoic chamber is presented in Fig. 2.

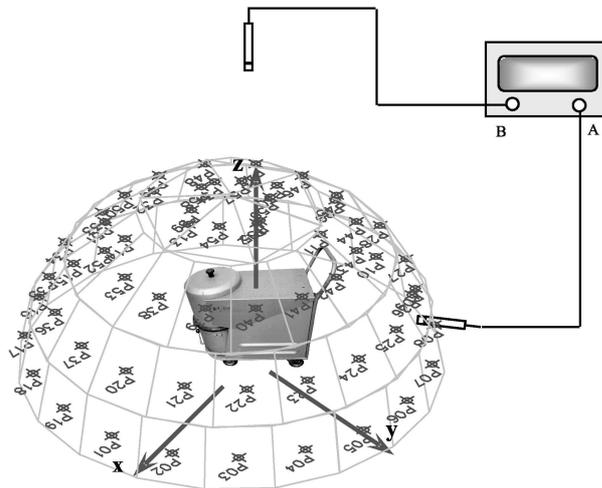


Fig. 2. Chart of the measuring set-up and location of measuring points.

Sound pressure was measured by means of a microphone connected to channel A of a bi-channel analyser. Measurements were taken in 59 measuring points, evenly distributed over the surface of a hemisphere. Another microphone and a preamplifier were connected to channel B of the analyser. The simultaneous measurement of signals from both microphones has made it possible to measure the angles of phase shift between sound pressures in the measured direction (determined by the angle θ and sound source rotation angle) and the reference direction.

Measurements were taken in 801 bands 4 Hz wide in a range of up to 3200 [Hz]. Examples of measurements of sound pressure levels and phase shift angles in one of the measuring points point P01 have been presented in Fig. 3 (amplitude) and Fig. 4 (phase).

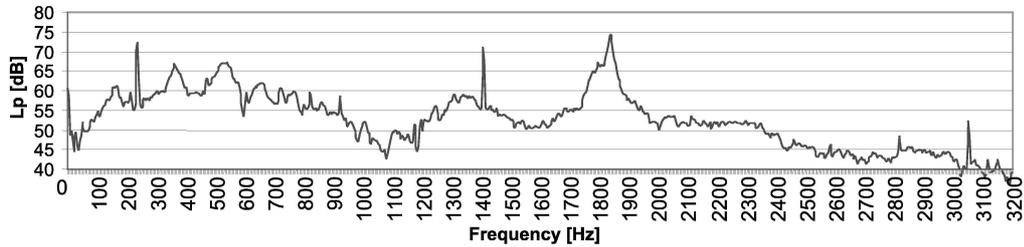


Fig. 3. Sound pressure level – point P01.

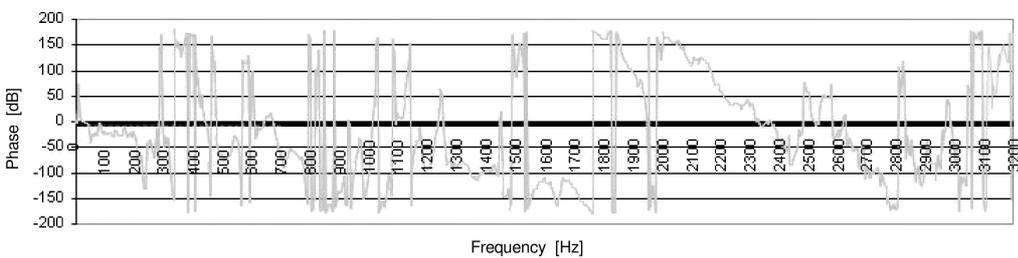


Fig. 4. Phase shift – point P01.

4.2. Acoustic model

In line with the methodology developed in [3] it was assumed that the location of omni-directional substitute sources corresponded to the functional elements of the machine. The individual elements of the industrial vacuum cleaner (turbine, suction, left side, right side) have been replaced with omni-directional sources (Fig. 5).

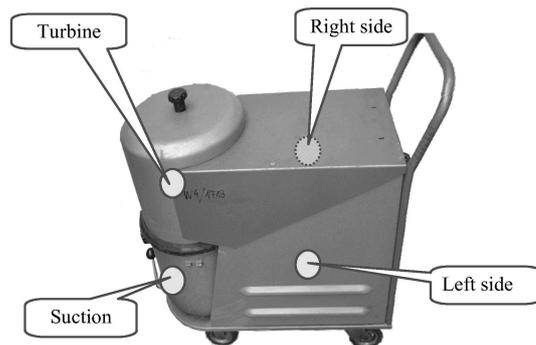


Fig. 5. Location of substitute sources.

The accuracy of calculations was determined using the inversion method on the basis of the mutual configuration of substitute sources and observation points and on the basis of Greene's function values for substitute sources.

Computer simulations have yielded optimal parameters (sound powers) for the individual omni-directional sources corresponding to the individual elements of the vacuum cleaner. The sound power levels of the sources are presented in Fig. 6.

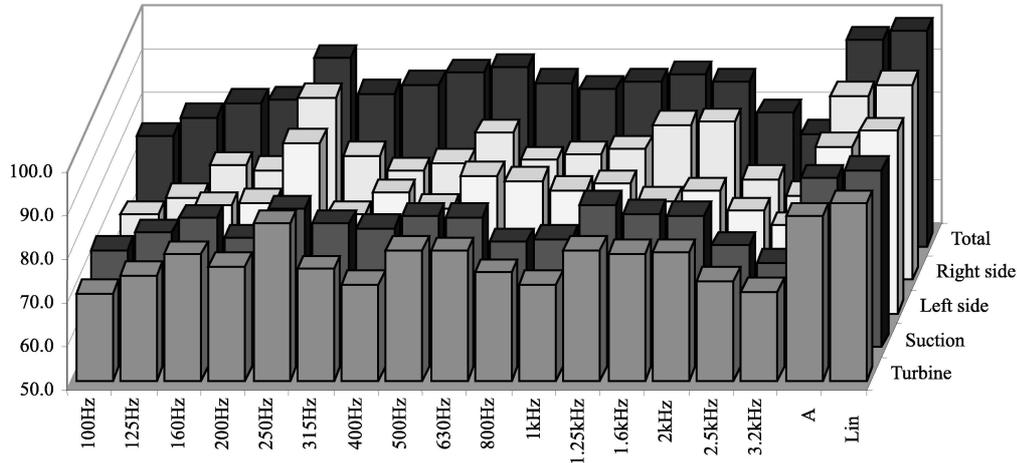


Fig. 6. Sound power levels of substitute sources and total sound power level.

4.3. Distribution of sound power levels

On the basis of the parameters of the substitute sources, the directional radiation characteristics were obtained using the formula (2).

The directional radiation characteristics obtained (as expected) were smooth for low frequencies and, as frequency increased, they became less regular and more fuzzy. Examples of directional radiation characteristics have been presented in Fig. 7.

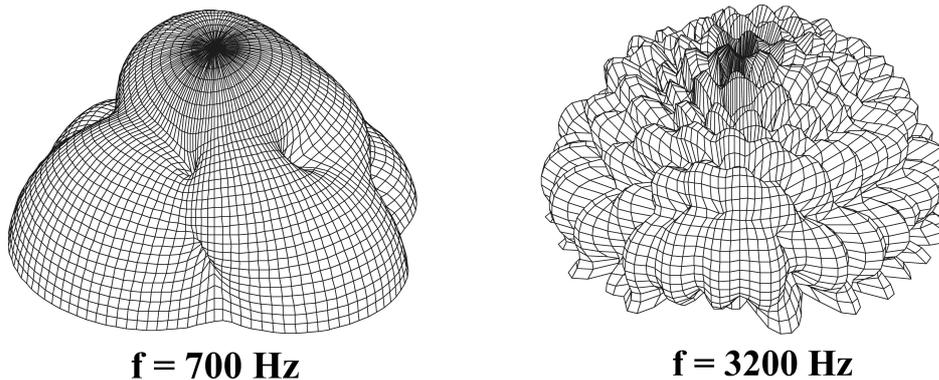


Fig. 7. Radiation characteristics – industrial vacuum cleaner.

4.4. Emission sound pressure level and sound power level

The Machinery Directive 2006/42/EC [2] defines basic requirements relating to safety of machinery, including requirements concerning protection from noise. An instruction manual must contain among others the following information on airborne noise emission: the A-weighted emission sound pressure level at the workstation, the A-weighted sound power level. These values are necessary for the purpose of the acoustic assessment of the machine. The comparison of the emission sound pressure levels at the work station obtained on the basis of the parameters of the substitute sound sources and determined according to the method specified in the European Standard EN ISO 11202 [6] have been presented in Table 1. This table contains also the comparison of the sound power level obtained on the basis of the parameters of the substitute sources and determined according to the method specified in the European Standard EN ISO 3746 [7].

Table 1. Results of determination of the emission sound pressure level and the sound power level.

Machine	A-weighted emission sound pressure level [dB]		A-weighted sound power level [dB]	
	Modelling	EN ISO 11202	Modelling	EN ISO 3746
Industrial vacuum cleaner	84.7	81.9	97.3	97.1
Vibrating conveyor	90.3	90.5	92.2	92.2

The results of simulation tests regarding the effect of the distance between the substitute sources of the industrial vacuum cleaner (“left side” and “right side”) on the emission sound pressure level and on the sound power level have been presented in Table 2.

Table 2. Influence of the distance between the substitute sources of the vacuum cleaner on the emission sound pressure level and the sound power level.

Parameter	Distance between the substitute sources: “left side” and “right side” [m]					
	0.1	0.2	0.3	0.4	0.5	0.6
A-weighted emission sound pressure level [dB]	82.7	83.2	84.3	84.5	84.7	84.7
A-weighted sound power level [dB]	95.8	95.8	95.9	95.9	95.7	95.7

5. Conclusions

Inversion methods are increasingly often used in various areas of acoustics, including those dealing with the minimisation of the vibro-acoustic activity of machines and equipment. They may have a practical application for the calculation of the parameters of substitute machine sources (made up of omni-directional sources). The optimal

values of these parameters (sound power) for the individual omni-directional sources corresponding to the individual elements of the machines are obtained through computer simulations.

Using the parameters thus calculated for substitute sound sources it is possible to calculate the distribution of acoustic pressure levels around the machine.

The results of the experimental tests confirmed the correctness of the acoustic modelling of machines using the inversion method. Even in case of sound sources with complicated radiation characteristics, the model accuracy is usually satisfactory.

Acknowledgment

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- [7] EN ISO 3746 Acoustics – Determination of sound power levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane.