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INVESTIGATION OF EMISSION SOUND PRESSURE USING INVERSIVE METHOD

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According to the Machinery Directive 98/37/EC the emission sound pressure level must be taken into consideration, together with the sound power level, in carrying out the acoustic assessment of machines. However the European Standard series EN ISO 11200 specifies methods for determining emission sound pressure the authors worked out the inversive method of the determination of emission sound pressure levels using sound source modelling by means of many substitute sources. The value of this level at specified position in the vicinity of the machine is calculated from the following parameters of the substitute sources:

- the amplitude characteristic,
- the phase characteristic.

The results of the determination of emission sound pressure levels using the inversive method are presented in the paper.

1. Introduction

In principle, sound source modelling of machines and devices is applied for the purposes of vibro-acoustic synthesis as well as vibro-acoustic process studies and analysis. It enables to replace the real sound sources with elementary sources with preset directivity patterns and includes a stage of working mathematical models out as well as a stage of computer calculations. One of the methods for sound source modelling used in industry is to apply for that purpose substitute sources, which consist of elementary monopoly sources. 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 specific 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 98/37/EC [6]. The directive 98/37/EC defines basic requirements concerning safety of machinery, including requirements concerning protection from noise. According to this directive, technical materials describing a machine should contain information on the equivalent emission sound pressure level and peak C-weighed instantaneous sound pressure value at work station, and, if some cases, the sound power level.

2. Standardized methods of determining emission sound pressure levels at a work station

The European Standard series EN ISO 11200 (PN-EN ISO 11200) [7–11] specifies methods to determine emission sound pressure level at the work station and other specified positions. Apparently, determination of this pressure level at workplace may seem a very easy task, consisting only in determining the sound pressure level at one point of space. In reality it is not so. Result of a single measurement of the sound pressure level will simultaneously be the value of the emission sound pressure level only when the test environment fulfils the conditions of an ideal free field over the surface reflecting the sound. Due to that, it can be distinguished the following methods of determining the emission sound pressure levels at work station:

- methods of free field over the sound reflecting surface — requiring measurements of the sound pressure levels to be conducted [7, 8, 10],
- methods using the values of sound power levels of machinery [9],
- intensity methods [11].

In the case of the methods of free field over the reflecting surface, the A-weighted emission sound pressure level at the work place L_{pA} in dB, is calculated with the following formula:

$$L_{pA} = L'_{pA} - K_{1A} - K_{3A} \tag{1}$$

where L'_{pA} is the A-weighted sound pressure level measured at the work place A, in dB, K_{1A} is the correction for background noise, in dB, K_{3A} is the local environment correction, in dB ($K_{3A} = 0$ dB in the method in accordance with [7]).

In the case of the method using the sound power level, the emission sound pressure level L_p, is calculated from the sound power level L_W using the following formula:

$$L_p = L_W - Q \tag{2}$$

where L_W is the sound power level in dB, Q is the quantity experimentally determined or calculated, in dB.

The quantity Q may be determined experimentally ($Q = Q_1$) or calculated from a measurement surface surrounding the machine under test ($Q = Q_2$). Due to this, determination of the emission sound pressure level can be done by means of one of the following methods:

- method with Q, determined experimentally ($Q = Q_1$),
- method with Q calculated ($Q = Q_2$).

The first of the above methods is applicable only when there exists a noise test code for the family of machines, to which the machine under test belongs. In such case, the noise test code should give the values of Q_1. These values are determined on the basis of experimental investigations carried out during preparation of noise test code, consisting in determining the correlation between the sound power level and the emission sound pressure level at a given point for the whole family of machines. As a result, the value of Q_1 is associated with a specific point, where the emission sound pressure level is to be determined and is valid only for that point. Exemplary values of Q_1 for hand-held machines range from 4 to 12 dB (depending on the machine dimensions), whereas for hand-held screwers and impact wrenches $Q = 8$ dB. However, there are not many machines for which values of Q_1 have been determined.

In the second of the above methods the value of Q_2 is calculated from the following relation:

$$Q = 10 \lg \frac{S}{S_0} \qquad [\mathrm{dB}] \tag{3}$$

where S is the area of a rectangular, box-shaped surface enveloping the machine at a given measurement distance d from the reference box on which the work place or other specified place is located, in m^2, $S_0 = 1$ m^2.

In order to determine the emission sound pressure levels using sound intensity method, it is necessary to carry out measurements of sound intensity levels in octave bands with mid frequencies from 63 to 4000 Hz (or in third bands with mid frequencies from 50 to 5000 Hz) in three Cartesian directions. Taking into consideration the measured sound intensity levels, the emission sound pressure level at the work station L_p is calculated from the following formula:

$$L_p = 10 \lg \sqrt{\left(10^{\frac{L_{I,x}}{10}}\right)^2 + \left(10^{\frac{L_{I,y}}{10}}\right)^2 + \left(10^{\frac{L_{I,z}}{10}}\right)^2} \qquad [\mathrm{dB}] \tag{4}$$

where $L_{I,x}$, $L_{I,y}$, $L_{I,z}$ are the sound intensity levels in the three Cartesian directions x, y and z.

3. The general principle of sound source modelling

Determination of optimum parameters of the substitute sources requires that the sound pressure amplitude distribution and the distribution of the phase shift angles in the octave or narrower bands should be determined followed by the sound source modelling carried out for every frequency band [2, 3]. The real noise source, for which the sound field distribution in the Fraunhofer's is zone is known (that means that the real source radiation directivity coefficient $R_0(\theta, \varphi)$ is known), is most often replaced with a omnidirectional source set with the radiation directivity coefficient $R_n(\theta, \varphi) = 1$. The replacement of the noise source is carried out by selecting substitute source set parameters (pressure amplitude and phase shift angle) so that there will be highest similarity of the distribution of sound fields generated by real sources and substitute source set. The quality functional defined by the following formula is adopted as one of possible similarity criteria:

$$K = \frac{1}{4\pi A^2} \iint |p - p_z|^2 \, dS \tag{5}$$

where $p = \frac{A}{r} e^{\frac{-i2\pi r}{\lambda}} R_0(\theta, \varphi)$ — the sound pressure generated by real source, in Pa, $p_z = \sum_{n=1}^{m} \frac{A_n}{r} e^{\frac{-i2\pi r_n}{\lambda}} R_n(\theta, \varphi) e^{i\varphi_n}$ — the summary sound pressure generated by substitute source set, in Pa, A — the sound pressure amplitude of the real source, in Pa, r — the distance between the observation point and the source, in m, λ —- the sound wave length,

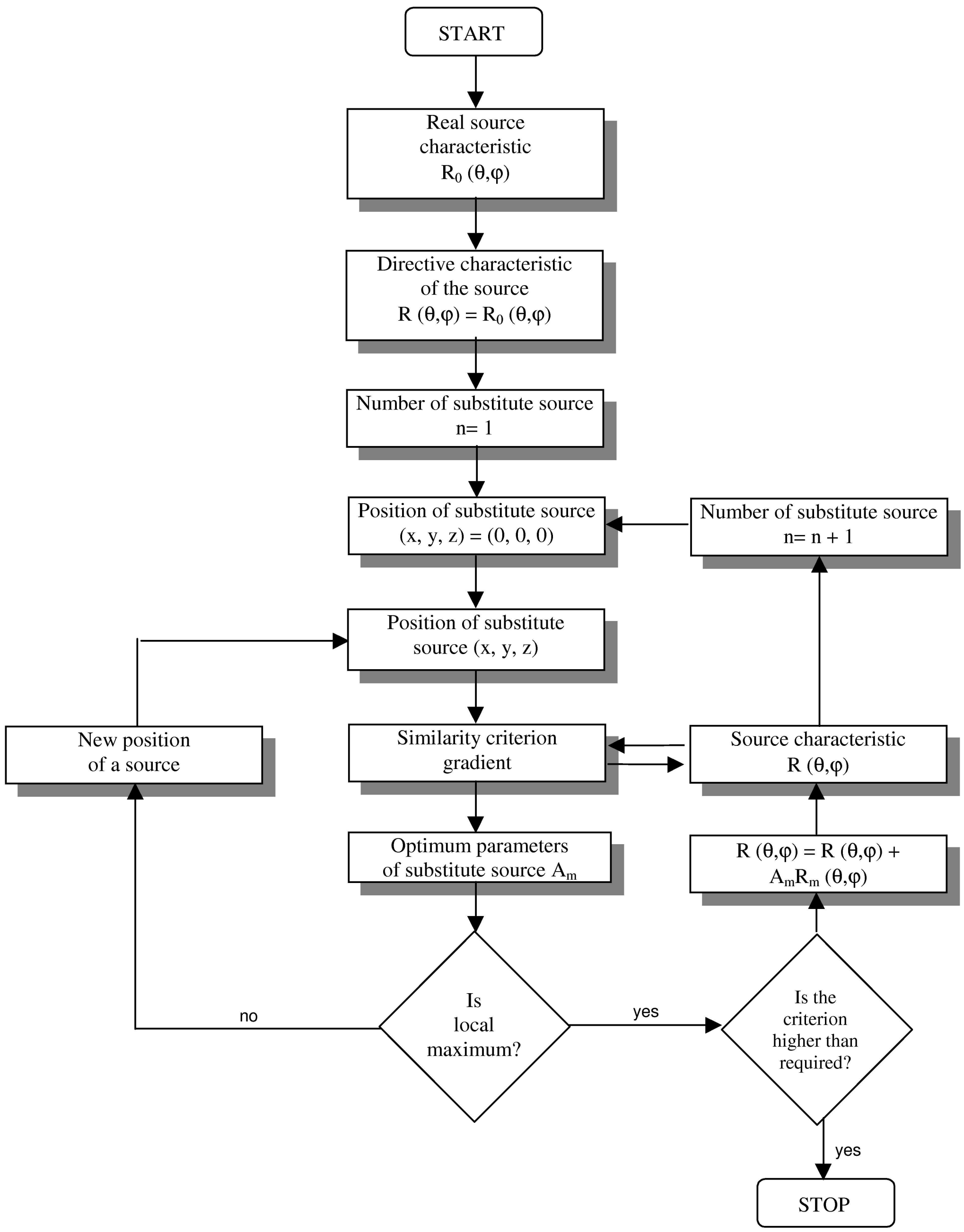

Fig. 1. Algorithm of sound source modelling with many substitute sources.

in m, (θ, φ) — the coordinates of the observation point, A_n — the sound pressure amplitude for the n-th substitute source, in Pa, m — the number of substitute sources, φ_n — the angle of the n-th substitute source phase shift in relation to the reference vibration, in deg, S — the surface of a sphere with the radius r, in m.

When there is no substitute source, the quality functional K takes the value 1, while in case of perfect substitute source, the functional value is 0.

By using the measuring results of the sound pressure distribution around the noise source, the modelling in accordance with the algorithm illustrated in Fig. 1 is carried out. First of all, the real noise source is replaced with one substitute omnidirectional source, placed in the geometric centre of the real source (in the midpoint of the co-ordinate system). At this place, an approximate similarity criterion gradient and the optimum parameters of the substitute source are determined. Then the substitute source is moved towards the maximum gradient and the operation is repeated until the local maximum is obtained, after which it is checked whether the criterion is higher than the required one or not. If not, the source characteristic is changed in accordance with the principle given in the algorithm in Fig. 1 and the new substitute source is assumed to be placed in the midpoint of the co-ordinate system. Next all the calculations are carried out once again from the beginning until the similarity criterion reaches the required value. As a result of this procedure, the minimum number of optimally distributed substitute sources (the position of the substitute sources) with optimum parameters can be obtained. The parameters are the sound power levels of the substitute sources and the source phases.

4. Inversive method

As a result of the sound source modelling, we obtain the number (m) of the substitute sources, their sound power or sound pressure amplitude (A_n), phase shift of every source (φ_n) and the position of every source $(x_n,\ y_n,\ z_n)$.

The inversive method consists in determination of the sound field distribution around the sound sources based on the substitute source set parameters having been determined before. In case of the criterion K, the emission sound pressure around the real source, which consists of omnidirectional sources, can be determined from the following dependence:

$$p(r, \Theta\varphi) = \sum_{n=1}^{m} \frac{A_n}{\lambda} \exp\left(\frac{-i2\pi}{\lambda} (x_n \cos\varphi \sin\Theta + y_n \sin\varphi \sin\Theta + z_n \cos\Theta) \right) \exp(i\varphi_n) \tag{6}$$

where x_n, y_n, z_n — the coordinates of the omnidirectional source position.

5. The results of experimental tests

The following machines have been selected for the experimental tests: saw, grinder, air compressor and water pump. In order to determine optimal parameters of the model, the knowledge of amplitude distribution in the space and phase shift angles around actual sound sources was necessary.

For all machines, the measurements of sound pressure levels in 37 measurement positions located on the surface of a hemisphere (Fig. 2), above the sound-reflecting surface, were performed. Simultaneously with the measurements of sound pressure levels, the easurements of phase shift between the signals obtained from the microphone located in a given measurement position and a reference microphone (marked as R) were performed.

The examples of the test results for a compressor, i.e. the amplitude and phase characteristics is presented in Fig. 3.

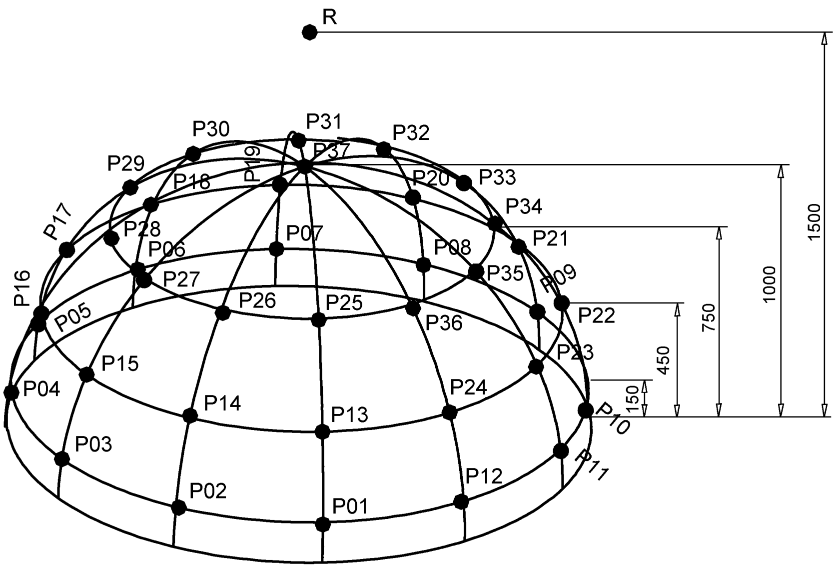

Fig. 2. Location of measurement positions.

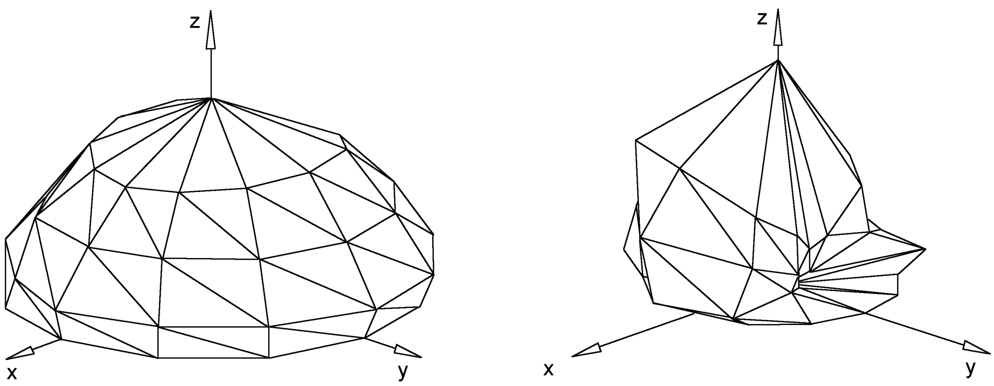

Fig. 3. Amplitude and phase characteristics at frequency 1000 Hz for the compressor.

During the modeling, the number of substitute sources was assumed in advance — there were 4 substitute sources. The locations of individual substitute sources were assumed to overlap with the functional elements of the machines. The locations of the substitute sources are presented in Table 1.

An additional assumption made in sound source modeling in order to determine emission sound pressure levels was the condition of coincidence between the acoustic power of tested machine and that of substitute sources set. Because of this condition, it was not possible to determine optimal parameters of the model in an analytical way. The optimal parameters were determined numerically with the maximum gradient method. The determined parameters of the substitute sources are presented in Tables $2 \div 5$.

Table 1. Locations of the substitute sources.

Machine	Substitute source number	x [m]	y [m]	z [m]
Pump	A1	0	0.1	0.15
	A2	0	0.3	0.15
	A3	0	−0.1	0.15
	A4	0	−0.3	0.15
Grinder	A1	0	0.1	0.2
	A2	0	0.3	0.2
	A3	0	−0.1	0.2
	A4	0	−0.3	0.2
Compressor	A1	0.2	0.1	0.2
	A2	−0.2	0.1	0.2
	A3	0.2	−0.1	0.2
	A4	−0.2	−0.1	0.2
Saw	A1	0	0.2	0.6
	A2	0	−0.2	0.6
	A3	0	0	0.6
	A4	0	0	0.2

Table 2. Results of modelling of the saw.

Frequency [Hz]		63	125	250	500	1000	2000	4000	8000
Substitute source No		Sound power levels of the substitute sources [dB]							
	1	78.0	75.7	89.6	76.3	80.7	96.3	85.1	73.7
	2	80.1	82.3	86.0	78.1	84.0	95.1	88.5	72.1
	3	77.9	9.9	91.0	86.1	80.6	8.7	88.0	63.7
	4	77.8	78.2	81.0	86.0	85.4	88.1	0.7	64.3
		Phase of the substitute sources [deg]							
	1	145.9	208.6	141.3	237.2	89.6	289.7	110.4	74.3
	2	30.1	88.6	25.7	202.3	−166.1	153.9	179.9	13.2
	3	318.0	281.7	311.2	66.6	232.0	54.4	−17.9	52.8
	4	−120.6	28.7	−40.0	−28.8	−143.8	142.6	−19.1	97.0

Table 3. Results of modelling of the grinder.

Frequency [Hz]		63	125	250	500	1000	2000	4000	8000
Substitute source No		Sound power levels of the substitute sources [dB]							
	1	30.9	38.9	56.7	70.3	59.7	48.6	48.4	42.0
	2	29.1	28.2	53.8	63.6	57.6	50.9	43.1	42.6
	3	39.8	35.7	63.3	59.6	67.8	52.0	57.0	42.9
	4	40.8	29.1	59.4	52.7	67.5	62.4	42.3	44.2
		Phase of the substitute sources [deg]							
	1	291.8	361.9	204.4	237.3	69.0	59.0	135.8	323.9
	2	−77.7	−19.3	−49.9	48.9	145.4	88.9	73.8	150.6
	3	313.9	348.3	218.0	76.0	162.2	80.6	48.5	357.2
	4	−20.1	−62.8	39.3	−71.2	−168.2	148.1	−98.5	177.7

Table 4. Results of modelling of the compressor.

Frequency [Hz]		63	125	250	500	1000	2000	4000	8000
Substitute source No		Sound power levels of the substitute sources [dB]							
	1	52.2	62.9	64.5	72.8	59.3	65.0	59.1	65.3
	2	52.2	64.1	66.1	73.9	66.5	68.0	58.6	65.9
	3	51.7	58.2	62.6	70.1	75.6	62.1	51.8	61.3
	4	54.1	62.2	64.0	67.1	68.0	49.8	51.5	65.0
		Phase of the substitute sources [deg]							
	1	398.9	312.1	282.9	323.0	416.0	10.3	339.0	213.8
	2	5.0	−46.9	−57.8	−45.4	203.2	160.6	−26.9	−162.0
	3	339.6	99.8	213.6	71.5	43.0	106.2	355.0	314.7
	4	−64.1	−129.5	−177.0	73.7	−71.1	116.0	13.0	−38.6

Table 5. Results of modelling of the pump.

Frequency [Hz]		63	125	250	500	1000	2000	4000	8000
Substitute source No		Sound power levels of the substitute sources [dB]							
	1	51.5	55.5	53.2	52.0	54.9	38.4	47.5	44.2
	2	56.5	53.1	29.8	35.0	44.3	54.3	54.1	33.5
	3	57.7	55.6	20.4	56.3	55.0	47.7	45.2	44.1
	4	57.2	55.9	61.9	49.4	50.3	52.5	53.7	26.2
		Phase of the substitute sources [deg]							
	1	372.5	263.1	62.6	345.0	286.2	51.2	60.5	186.6
	2	−60.8	−89.6	22.4	35.6	110.7	177.0	−113.5	−111.2
	3	309.6	261.8	222.0	325.3	250.7	89.4	74.1	184.4
	4	125.3	−93.9	−121.6	122.9	107.0	162.4	−109.6	−78.9

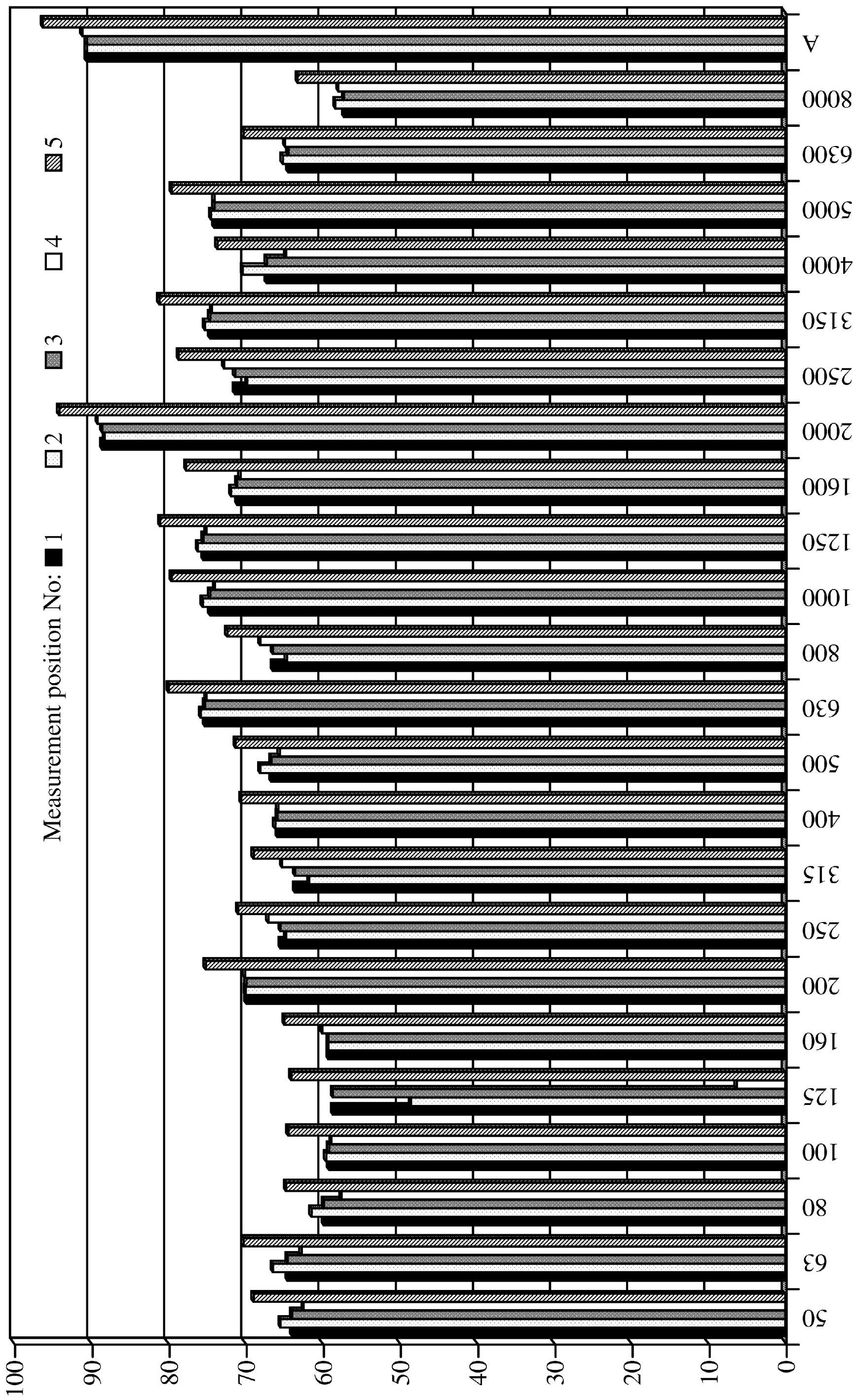

Fig. 4. Results of determination of the emission sound pressure levels of the saw obtained by the inversive method.

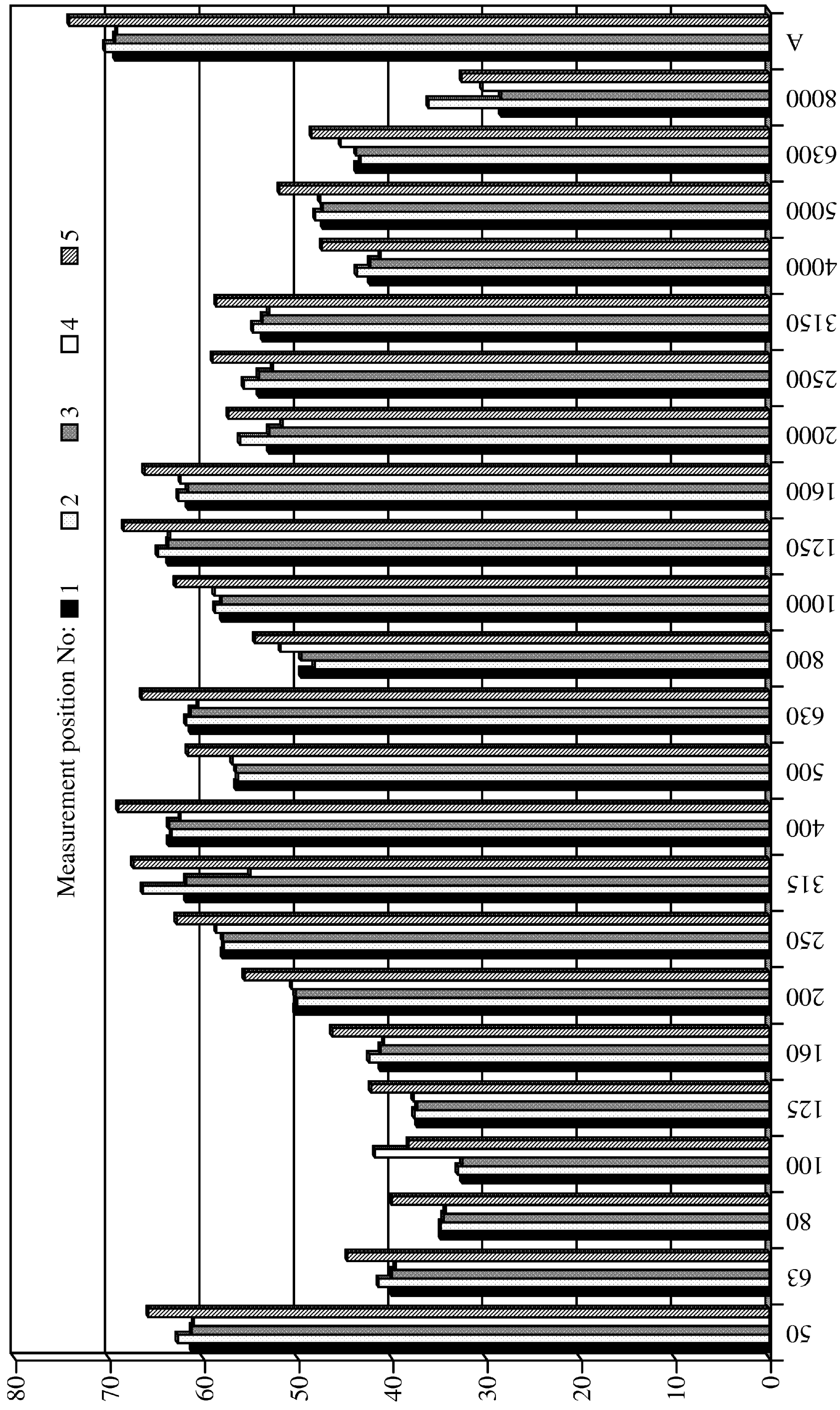

Fig. 5. Results of determination of the emission sound pressure levels of the grinder obtained by the inversive method.

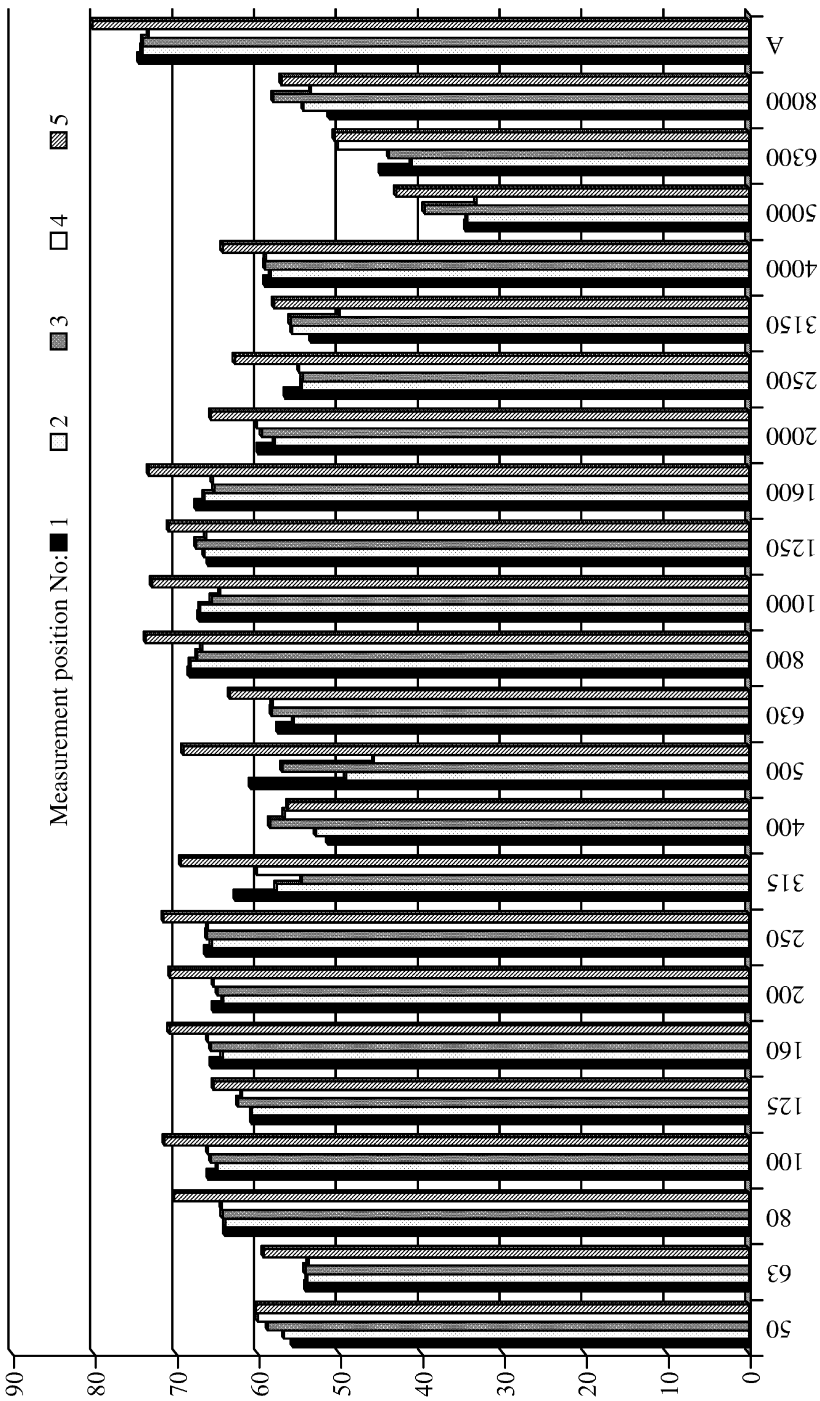

Fig. 6. Results of determination of the emission sound pressure levels of the compressor obtained by the inversive method.

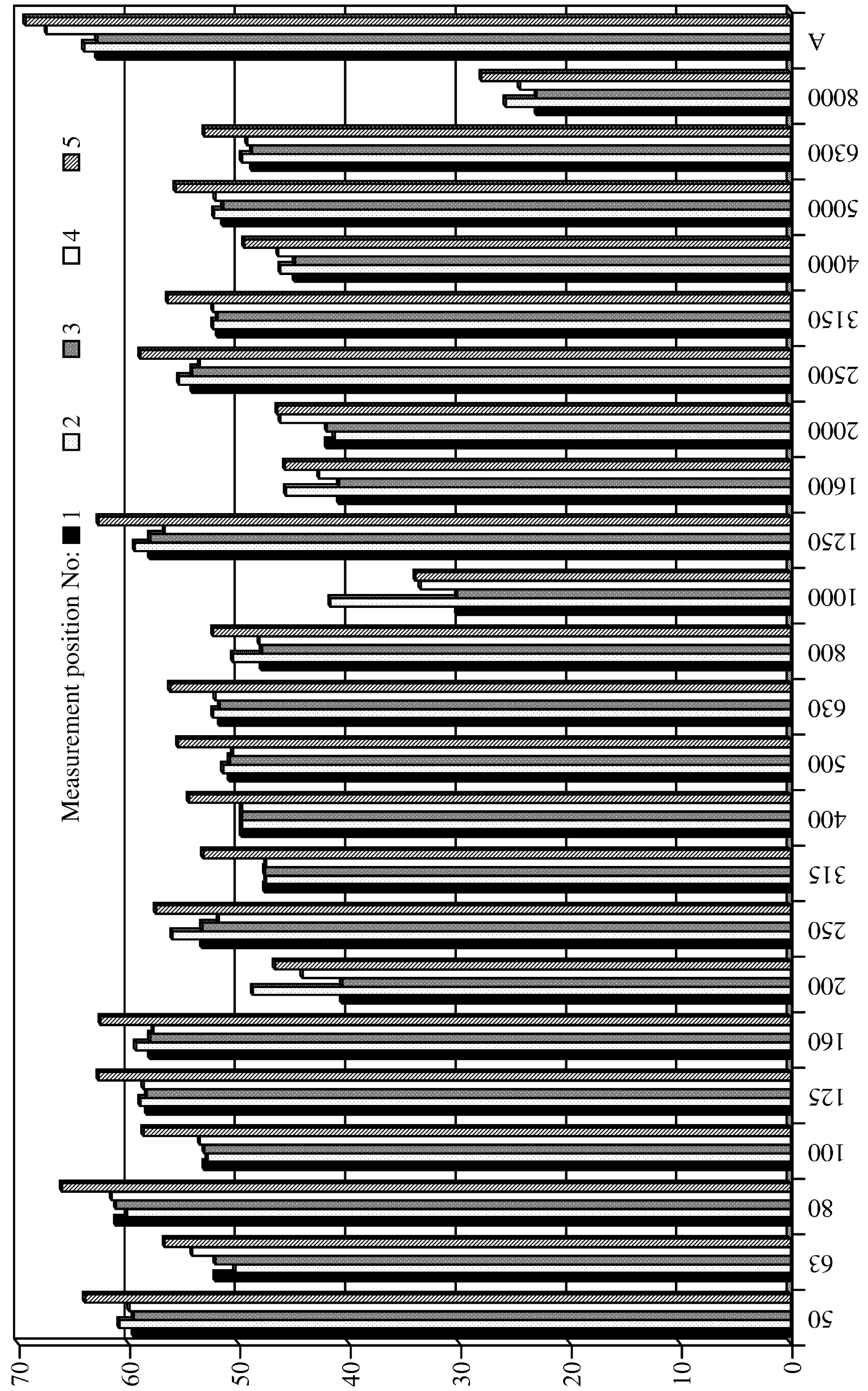

Fig. 7. Results of determination of the emission sound pressure levels of the pump obtained by the inversive method.

On the basis of the parameters of the substitute sources, emission sound pressure levels in 5 measurement positions were determined using the inversion method for each of the tested machines. The results of the calculations of emission sound pressure levels are presented in Figures $4 \div 7$.

Whereas the Table 6 presents a comparison of the emission sound pressure levels obtained on the basis of substitute sound models by the use of the inversive method and the methods specified in the European Standard series EN ISO 11200.

Table 6. Comparison of A-weighted emission sound pressure levels.

Machine	A-weighted emission sound pressure level [dB]				
	Inversive method	EN ISO 11201	EN ISO 11202	EN ISO 11203	EN ISO 11204
Pump	62.8	62	63	63.5	63
Grinder	69.3	69	68	70.5	67.5
Compressor	74.5	74	74	75	75.5
Saw	91.1	90.5	90	90	90.5

6. Conclusions

The results of the experimental tests have confirmed the correctness of the inversive method of determination of emission sound pressure levels. The emission sound pressure levels values, obtained as a result of carrying out the inversive method, are consistent with the level values obtained following the methods specified in the European Standard series EN ISO 11200. The inversive method allows to determine the emission sound level distribution around the real sources, with the use of relatively low number of the substitute sources with the simplest radiation directive characteristics. Even in case of

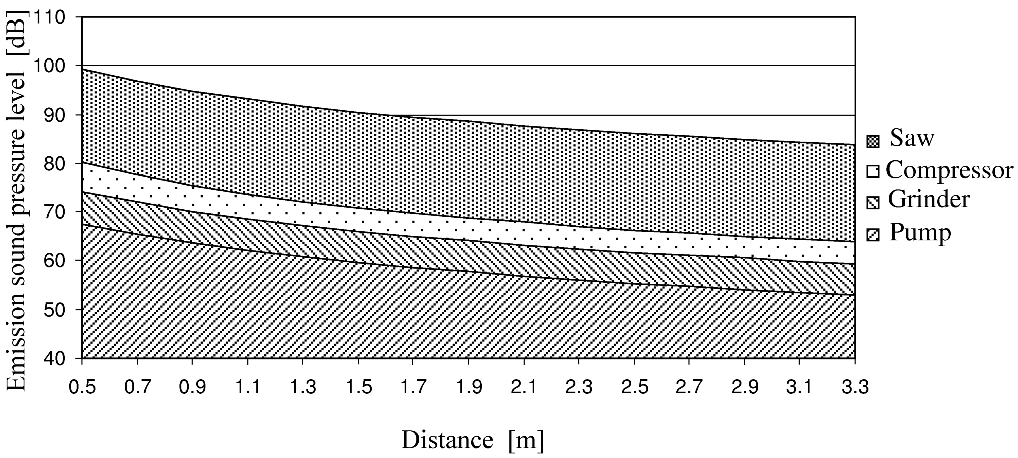

Fig. 8. Influence of the distance on the emission sound pressure levels determined by the inversive method.

sound sources with complicated radiation characteristics, the model accuracy is usually satisfactory. It should be also noted that the optimum position of the substitute sources is usually connected with the location of the sound sources in a machine.

In addition, the method, the authors have worked out, allows easy predication of the emission sound pressure level as a function of the distance between a work station and a machine. Fig. 8 presents the results of simulation tests regarding the effect of the distance on the emission sound pressure levels determined by the inversive method.

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