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EXPERIMENTAL MODELLING AND RESEARCH ON VIBROACOUSTIC PHENOMENA IN MACHINES

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Issues related to the development of acoustic models and determinations of energetic balances of phenomena, which occur in machines, are important factors both in the design of low-noise machines and in the prediction of machine noise. The acoustic modelling of machines may be carried out using a system of omni-directional substitute sound sources, deployed in points related to the functional elements of machines. The parameters of these sources may be determined using inversion methods.

New indices – the energy transmission index and the energy radiation index, have been proposed for application in the quantitative analysis of energetic phenomena occurring in machines. Determining these indices calls for the measurement of specific vibro-acoustic parameters of machines, acoustic pressure levels and the vibration acceleration levels or vibration velocities of the surfaces of selected machine elements.

The paper presents the results of experimental research in the acoustic modelling of machines with the use of inversion methods, as well as the analysis of energetic phenomena, which take place in machines.

1. Introduction

Reducing the emission of machine noise is one of the priority tasks and, at the same time, one of the most effective means of limiting risks derived from exposure to noise. The obligation to assess and reduce noise emission by machines is also derived from a fundamental European directive, i.e. directive 98/37/EC on the safety of machines [7].

The above directive mandates that machines be designed and produced, so as to reduce risks derived from the emitted noise to the lowest possible level, taking account of technological progress and the available noise control measures, especially at source.

Developing the conceptual and detailed design is an important stage in designing low-noise machines [8, 9]. Ensuring noise reduction at this stage of the design of a machine with a number of different sources calls for a separate analysis of all prospective noise sources, the transmission path, the determination of the energy balance and of the radiating surface, in order to determine the noise risk for the particular source.

The rapid development of computer calculation methods has made it possible to apply well-known acoustic theorems and equations to the problems of the prediction of acoustic fields and acoustic energy radiated and transmitted through structures. Most of the practical issues dealing with the prediction of acoustic fields prevent the application of deterministic methods (which results from the inability to determine border conditions in mathematical form), which calls for the development and application of survey methods. Determining the acoustic power radiated and transmitted by structures are another important problem involved in vibro-acoustic prediction.

New calculation methods in vibro-acoustics rely to a large extent on the balancing of energy in vibro-acoustic phenomena. This is derived from the broader trend of balancing the energy of all physical phenomena, including vibrating movement, which can be found in the surrounding world. Especially significant are the methods used to provide the quantitative assessment of vibration energy cumulated in various construction elements, as well as the assessment of acoustic energy transmitted between various objects. This is related to the development of the theoretical foundations of energetic models of various phenomena, experimental and measurement methods. Energetic models are more and more frequently used in methods based on the discretisaton of vibrating surfaces designed for the calculation of radiated and transmitted acoustic power.

2. Application of inversion methods to acoustic modelling

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. Inversion [2, 3] 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 value of sound pressure at measuring points, one can inverse the model of the propagation path and thus determine the parameters of the sound source.

To calculate the parameters of substitute sources by using the inversion method [2, 3] one must know the real distribution of sound pressure around the machine. This requires the determination, on the surface of a hemisphere, of both the distribution of the amplitude of sound pressures, as well as the distribution of phase shift angles between acoustic signals.

2.1. Acoustic measurements

The measuring set-up used to determine the distribution of sound pressure in an anechoic chamber [1] is presented in Fig. 1.

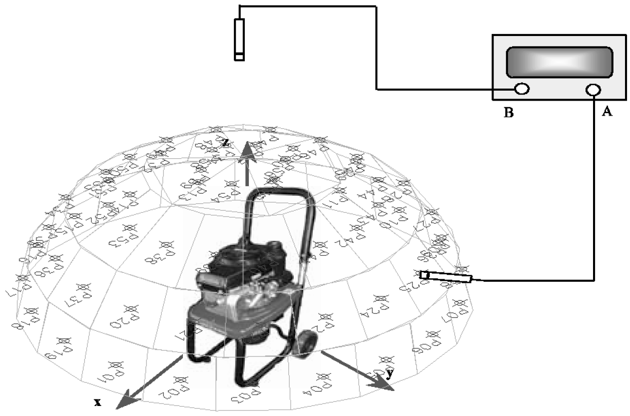


Fig. 1. Chart of the measuring set-up and location of measuring points.

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]. The amplitude of sound pressure p was read from the function of the function of the auto power spectrum of the signal from microphone A:

$$\overline{p^2} = G_{22} \ \ [\mathrm{N}^2/\mathrm{m}^4], \tag{1}$$

where

$$G_{22} = \int\limits_{f-\frac{1}{2}\Delta f}^{f+\frac{1}{2}\Delta f} G_{22}(f)\, df,$$

$G_{22}(f)$ – function of the auto power spectrum; f – tested frequency [Hz]; Δf – frequency bandwidth [Hz].

The function of the auto power spectrum between the signals of microphones A and B was used to determine phase shift angles between the signals. The phase shift angle ψ was calculated from the ratio of the imaginary to the real part of that function:

$$\psi = \arctan\left(\frac{\mathrm{Im}\,(G_{12})}{\mathrm{Re}\,(G_{12})}\right), \tag{2}$$

where

G_{12} – function of the auto power spectrum:

$$G_{12} = \int\limits_{f-\frac{1}{2}\Delta f}^{f+\frac{1}{2}\Delta f} G_{12}(f)\, df.$$

Examples of measurements in one of the measuring points point P01 have been presented in Figs. 2 (amplitude) and 3 (phase).

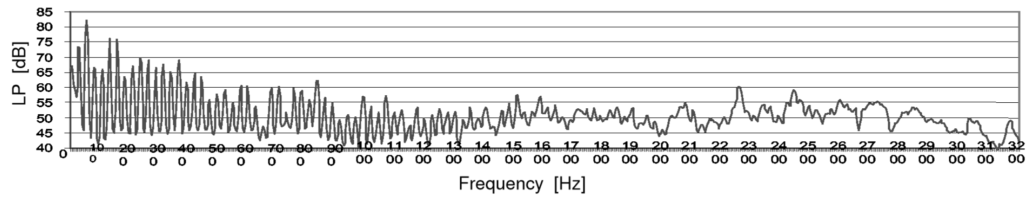


Fig. 2. Sound pressure level – point P01.

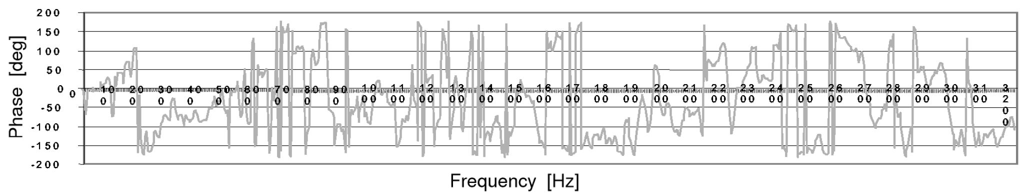


Fig. 3. Phase shift – point P01.

2.2. *Acoustic model of a power generator*

In line with the methodology developed in [2, 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 machine (radiator fan, engine cylinder, generator, exhaust) have been replaced with omni-directional sources (Fig. 4).

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.

The elements of the **G** matrix (Greene's functions) for omni-directional sources can be expressed as:

$$G_{ij} = \frac{\text{Exp}\,(-ikr_{ij})}{r_{ij}}\,, \tag{3}$$

where r_{ij} – distance between source i and observation point j; k – wave number.

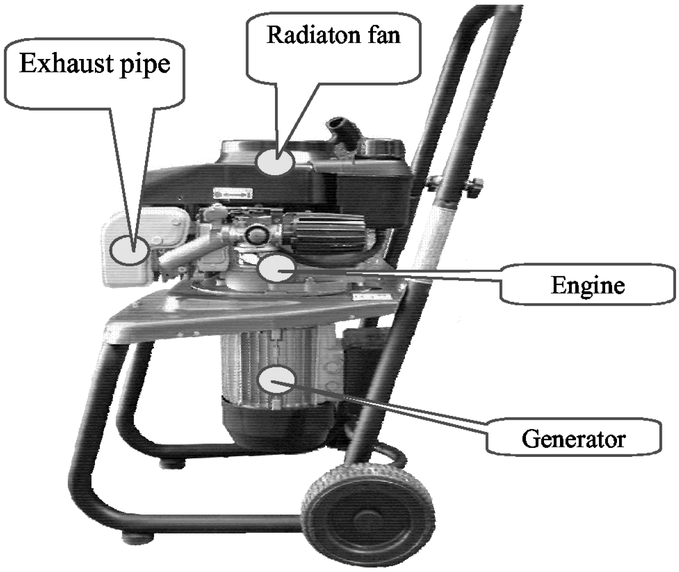


Fig. 4. Location of substitute sources.

The accuracy of the model thus obtained (determined for only 59 measuring points) has been presented in Fig. 5.

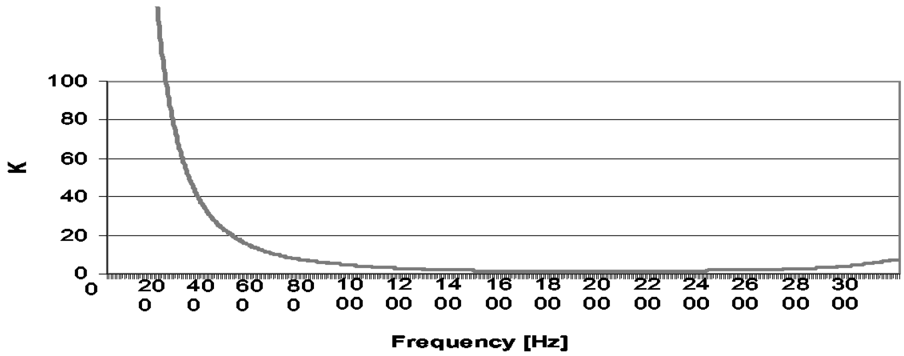


Fig. 5. Computing accuracy.

Computer simulations have yielded optimal parameters (sound power) for the individual omni-directional sources corresponding to the individual elements of the power generator. The sound power of the sources are presented in Figs. 6 through 9.

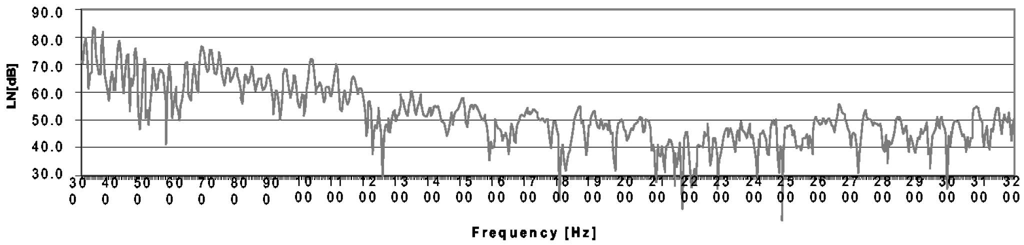


Fig. 6. Fan – sound power level [dB].

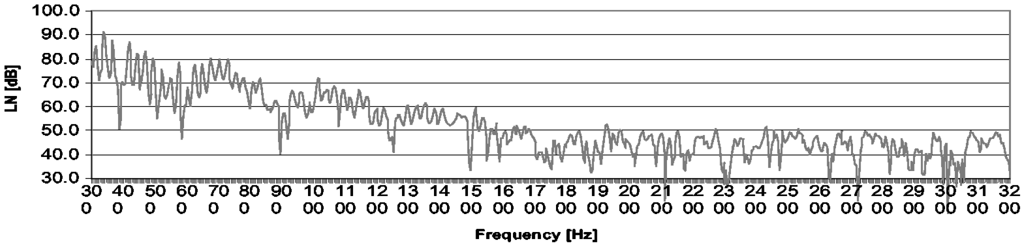


Fig. 7. Cylinder – sound power level [dB].

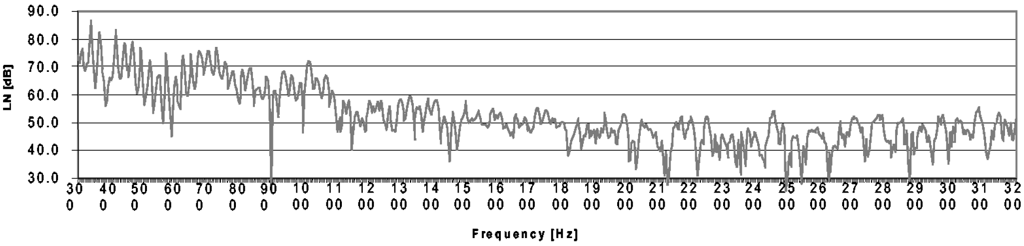


Fig. 8. Generator – sound power level [dB].

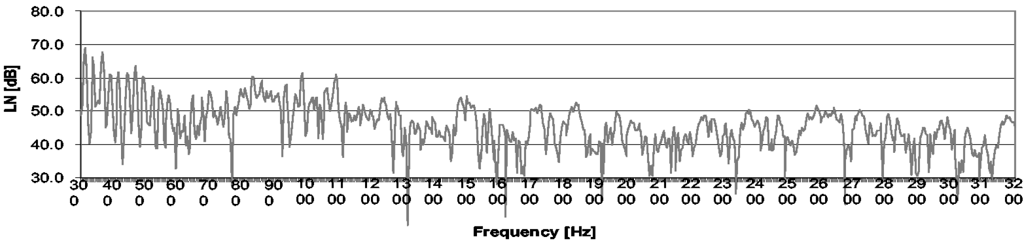


Fig. 9. Exhaust – sound power level [dB].

2.3. *Distribution of sound pressure levels*

The parameters of substitute sound sources were used to determine the distribution of sound pressure levels around the power generator. The distribution of sound pressure levels was calculated using the following relationship [4, 5]:

$$L_p(\theta, \varphi) = 10 \log 10 \left(\sum_{i=1}^{n} A_i R_i(\theta, \varphi) \frac{\exp(-ikr_i + \psi_i}{r_i} \right) \quad [\mathrm{dB}], \tag{4}$$

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 – co-ordinates of the location of the i-th source [m], ψ_i – phase shift angle of the i-th source.

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 Figs. 10 through 11.

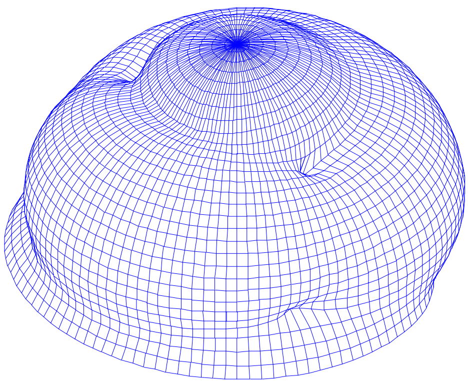


Fig. 10. Radiation characteristics – power generator – 700 [Hz].

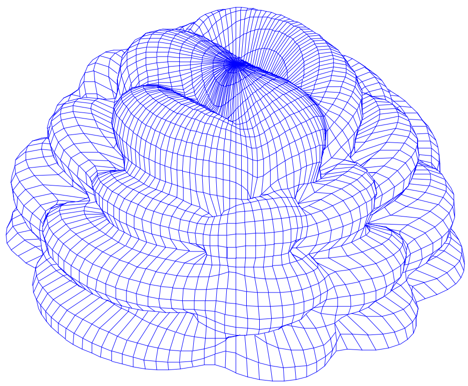


Fig. 11. Radiation characteristics – power generator – 3200 [Hz].

3. Experimental research on the determination of the energy balance

3.1. Energy transmission and radiation indices

Creating energetic balances for all physical phenomena in the surrounding environment makes it possible to simultaneously record various energies present in the environment. Knowing the value of energy stored, dispersed and transmitted by the individual elements of these constructions is essential in the testing of complex technical systems (building structures, machinery and equipment, means of transportation). These values are used to assess material effort, fatigue, to carry out diagnostic tests and to predict noise. Furthermore, they facilitate systems design, the design of connections between individual elements, the design of appropriate sound and vibration isolation systems, such as housings, partitions, cabins, etc.

Machine component properties with regard to radiation and transmission of vibroacoustic energy can be characterised using indices: the radiation index and transmission index.

The energy transmission index WTR can be defined as follows:

$$\mathrm{WTR} = 10 \lg \frac{E_2}{E_1} \quad [\mathrm{dB}], \tag{5}$$

where E_2 – total energy of the element receiving energy, E_1 – total energy of the element transmitting energy.

The energy radiation index WRD is defined by the following relationship:

$$\mathrm{WRD} = 10 \lg \frac{W_c}{\rho c S \langle v^2 \rangle} \quad [\mathrm{dB}], \tag{6}$$

where W_c – total radiated acoustic power, ρ – air density, c – sound velocity in the air, S – radiation surface area, $\langle \nu \rangle$ – mean value of the radiation surface velocity squared.

3.2. Testing methodology

To calculate the acoustic energy radiation and acoustic energy transmission indices it is necessary to measure the sound pressure levels and levels of the acceleration or velocity of the vibrations of machine surfaces. These parameters have been determined using set-up presented in Fig. 12. This set-up allowed the simultaneous measurement of sound pressure and the acceleration of surface vibrations of selected machine elements.

Sound pressure measurements have made it possible to calculate the acoustic power of the machines tested, while the measurements of the acceleration of machine elements yielded, by integration (velocity of surface vibrations), the spectral power density and ultimately – both indices, i.e. of energy radiation and transmission, as well as the energetic balance for the machines tested.

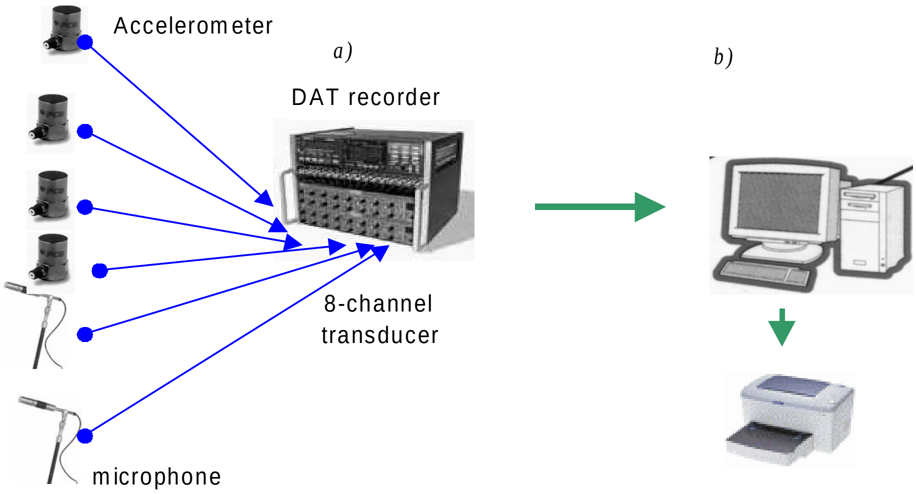


Fig. 12. Measuring set-up a) and analysis set-up b) fot the calculation of the vibro-acoustics parameters of machines.

3.3. Energetic balance of a forge hammer

Using testing methodology described in Sec. 3.2 it was possible to determined the spectral densities of acceleration and the pressures on the impact of a forge hammer (Fig. 13).

To calculate the energetic balance the tested forge hammer was subdivided into five conventional parts (Fig. 14). A block diagram showing the flow of acoustic energy was developed for a forge hammer (Fig. 15), divided as shown in Fig. 14. The ram is the source of the hammers impact energy. On the one hand, impact energy is transmitted to the anvil, then to the anvil block and is dispersed in the foundation of the hammer and, on the other, the cylinder transmits it to the frame. In each of the hammer's elements energy is dispersed and acoustic energy is radiated.

The equations of the energy balance can be expressed with the following set:

$$\begin{aligned}
E_B &= E_{BK} + E_{BC} + E_{AB} + E_{DB},\\
E_{BK} &= E_{KS} + E_{AK} + E_{DK},\\
E_{KS} &= E_{AS} + E_{DS},\\
E_{BC} &= E_{BR} + E_{AC} + E_{DC},\\
E_{CR} &= E_{AR} + E_{DR}.
\end{aligned} \tag{7}$$

Vibration energy was calculated from the following relationship:

$$E_i = m_i \langle v_i^2 \rangle, \tag{8}$$

where $\langle v_i^2 \rangle$ stands for the root mean square vibration velocity.

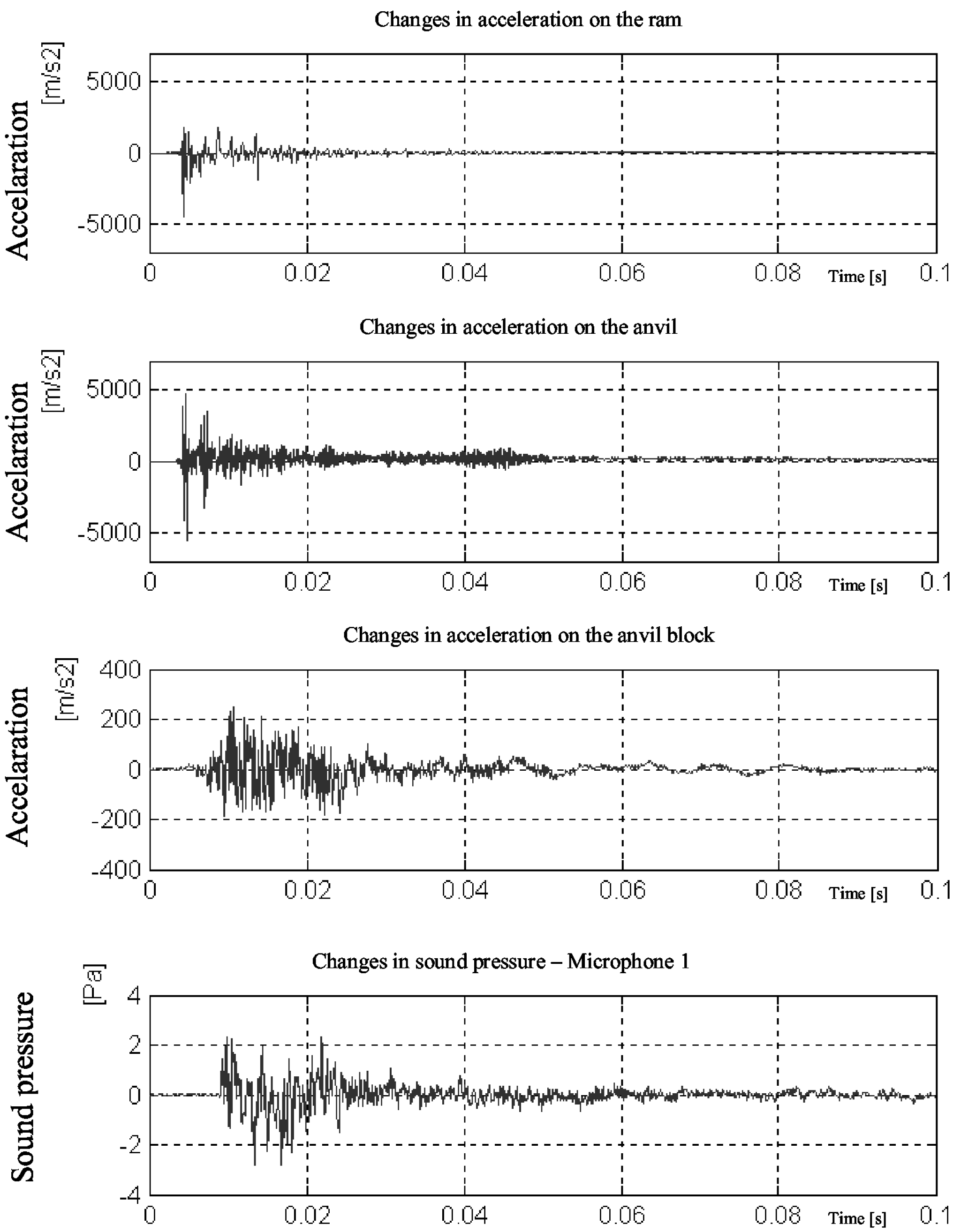


Fig. 13. Spectral density of the power of impact signals.

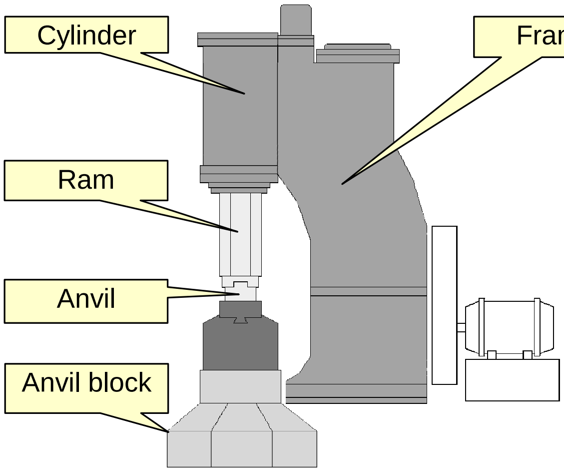
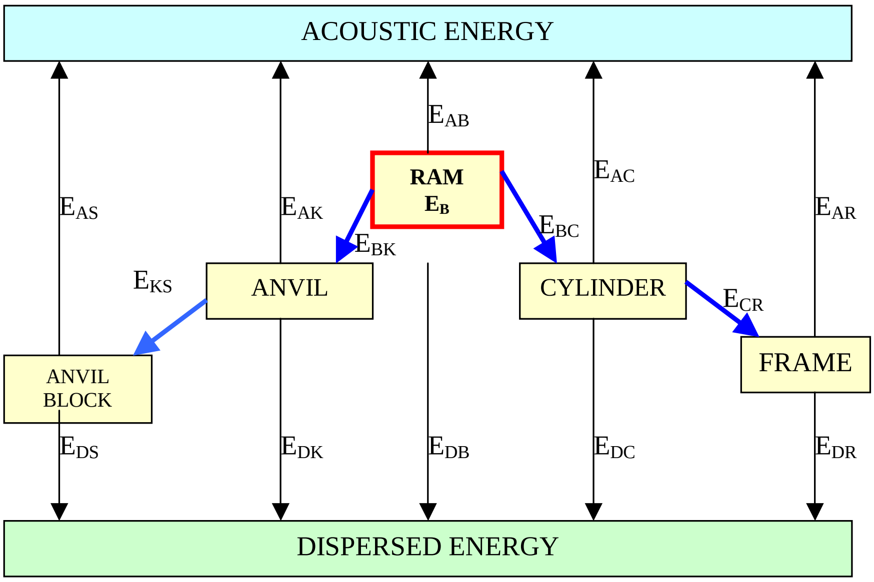


Fig. 14. Block diagram of the location of the elements of the forge hammer.



E_{B} – kinetic energy supplied by the ram
E_{BK} – energy transmitted from the ram to the anvil
E_{BC} – energy transmitted from the ram to the cylinder
E_{AB} – acoustic energy radiated by the ram
E_{DB} – energy dispersed by the ram
E_{AK} – acoustic energy radiated by the anvil
E_{DK} – energy dispersed by the anvil
E_{KS} – energy transmitted from the anvil to the anvil block
E_{AS} – acoustic energy radiated by the anvil block
E_{DS} – energy dispersed by the anvil block
E_{AC} – acoustic energy radiated by the cylinder
E_{DC} – energy dispersed by the cylinder
E_{CR} – energy transmitted from the cylinder to the frame
E_{AR} – acoustic energy radiated by the frame
E_{DR} – energy dispersed by the frame.

Fig. 15. Block diagram of energy flow during the operation of the hammer.

Examples of the coefficients and indices (WTR, WRD) of energy transmission and radiation, as well as the spectral densities of the energy of the elements of the hammer have been presented in Figs. 16–17.

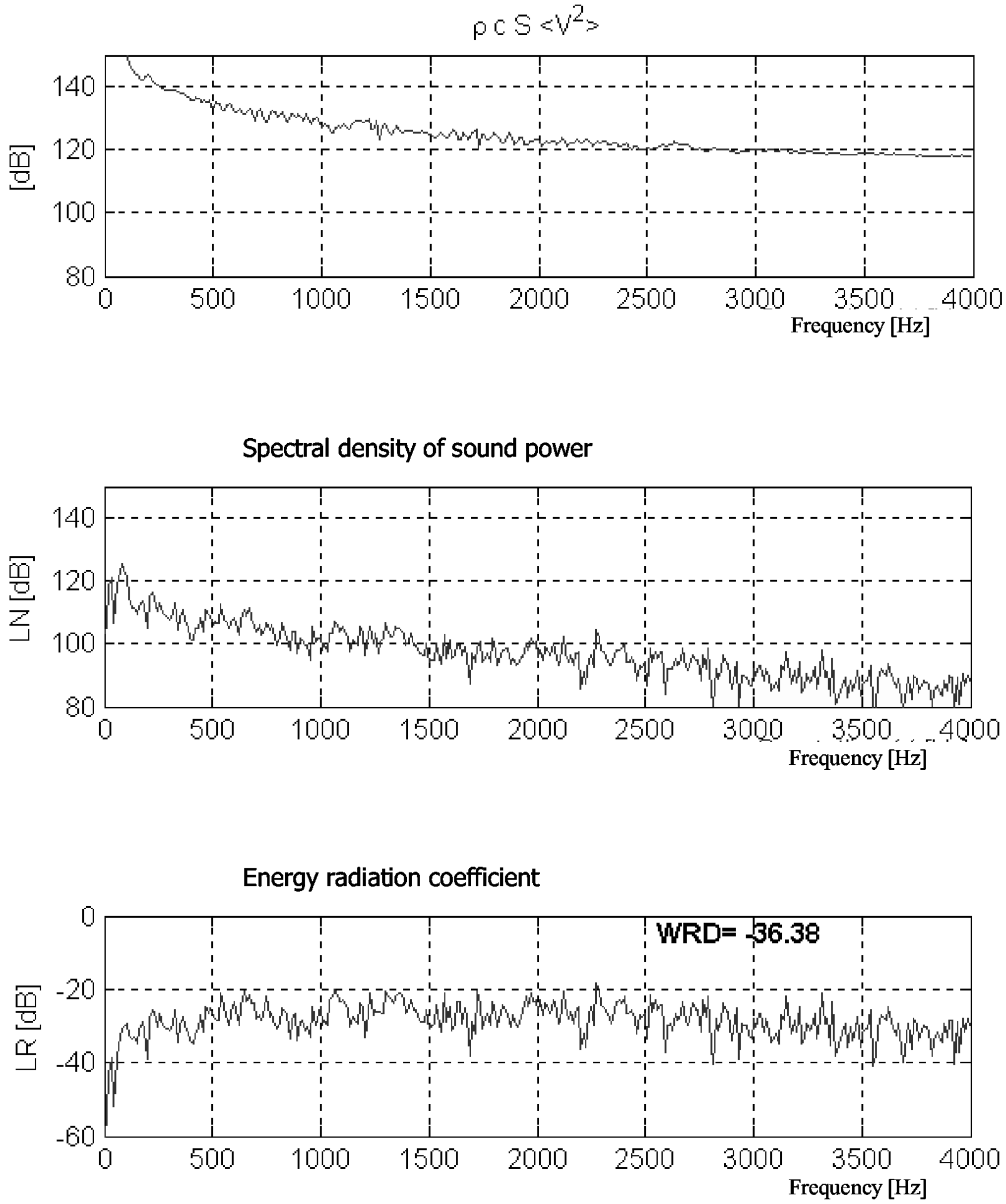


Fig. 16. Mean energy radiation coefficient and index.

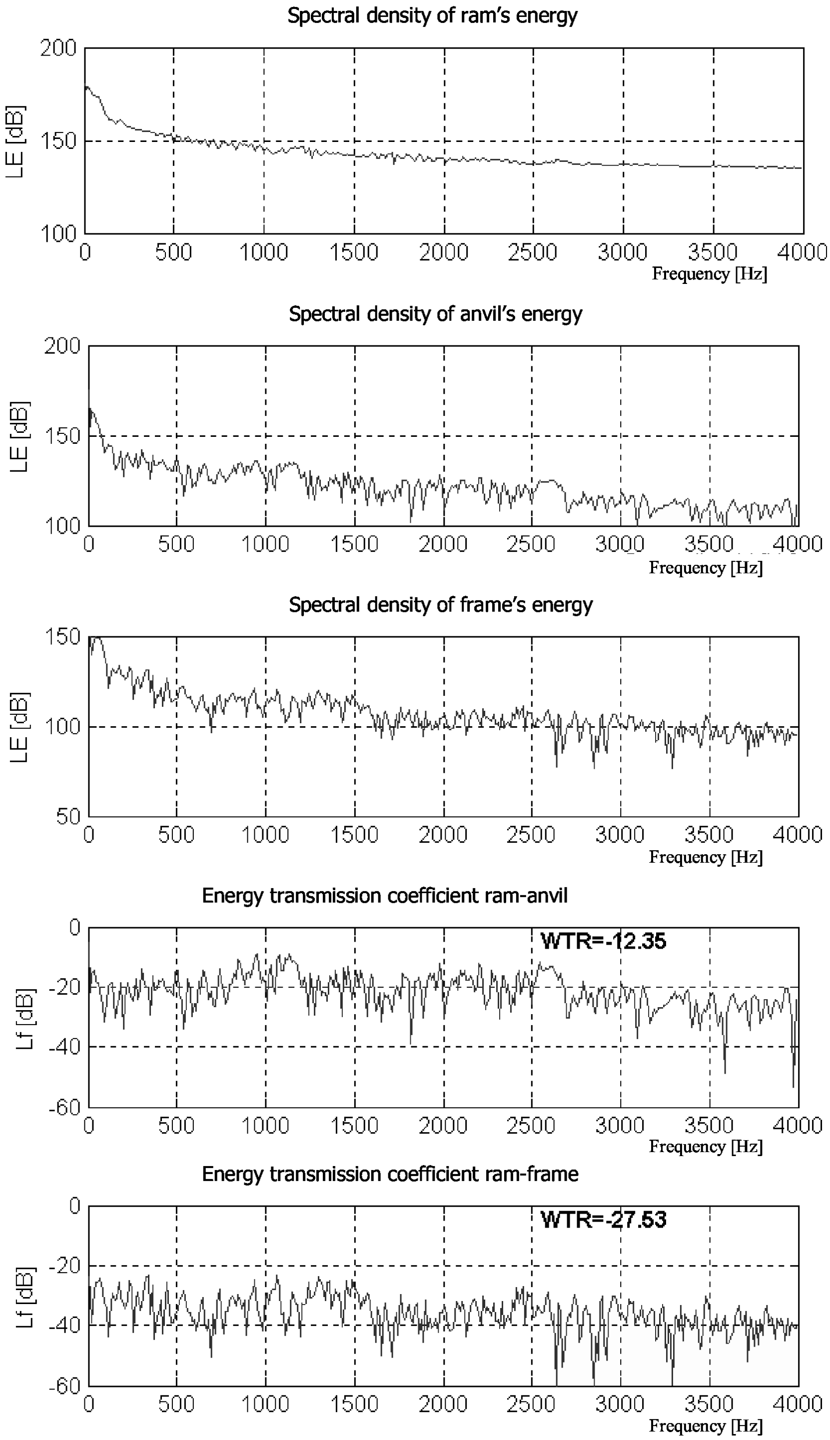


Fig. 17. Spectral densities of the energy and energy transmission coefficients and indices.

4. 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.

However, in certain cases the total sound power of individual substitute sources may be greater than the actual acoustic power of the modelled machine. This is due to the fact that the individual elements of the machine have a kinematic relationship (their vibrations are synchronised) and that there is interaction between the elements.

Using the parameters thus calculated for substitute sound sources it is possible to calculate the distribution of sound pressure levels around the machine. The radiation characteristics obtained, as anticipated, became increasingly fuzzy as frequency increased. A method has been developed to calculate the new proposed indices describing the vibro-acousticity of machines (energy transmission index and energy radiation index). These indices, along with the machine acoustic assessment indices – energetic and emission indices [6] will be used in subsequent work to develop a method of machine modelling designed to minimise vibro-acoustic phenomena in machines.

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