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DESIGNING MACHINERY AND EQUIPMENT IN ACCORDANCE WITH THE PRINCIPLE OF SUSTAINABLE DEVELOPMENT

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Abstract:
The paper presents a designing scheme based on the main criterion of optimisation, which is to minimize the vibrations and noise generated by machinery. This concept takes into account the deterioration of the strength and operational properties of constructions, which should be brought to a satisfactory level by applying additional measures. The considered design approach was examined on the example of the gearboxes, for which it is extremely difficult to achieve a noise reduction due to their highly advanced technology.

Key words: *design, noise, gearboxes*

INTRODUCTION

The development of computer computational and graphical techniques allows speeding up the development work, which causes that results of the technical, technological and social criteria assumed are obtained faster. One of the effects of such a development is a faster implementation of modified solutions of existing products or entirely new types of products, which leads to a faster replacement of the existing products. Such a situation causes higher demand for natural resources.

One of the concepts used for counteracting such processes is sustainable development [14] of the industry and service sector. A very important aspect of implementing this concept is a technological platform oriented towards: "the creation of goods and services that do not pollute the environment, but conserve energy and natural resources is economically viable, healthful and satisfying for the producer, community and consumers" [3]. It is possible to achieve these goals by including them already at the stage of designing, while the inclusion of the environmental aspects at an early stage of the product manufacture will affect the properties and functioning of the product in later stages of its life cycle. The establishment of appropriate design strategies determines the achievement of the desired results, e.g. a reduction of environmental costs and minimization of the impact on the natural environment and human health.

In many cases it is relatively easy to achieve an improvement in the environmental impact of the product, but there are many groups of products (this applies especially to machinery and equipment), for which it is difficult to obtain a design solution different from the existing one. This results from high requirements to be met by technical devices, which include primarily the durability, reliability and safety. The requirements imposed and thus the materials and technologies used greatly narrow the possibilities of so-called eco-designing.

The area, in which an improvement in the impact of machinery and equipment on the environment and human health can be particularly sought for, is a reduction in the acoustic emissivity. An improvement in acoustic properties of machinery and equipment takes place primarily at the design stage by making changes in the design, so it actually depends on the designer's approach to the problem as well as his knowledge and experience in creating designs characterized by a reduced vibroactivity.

The working conditions of operators depend on the values of sound levels generated by machinery and equipment used in the production process. These conditions affect the health of workers, their efficiency and above all the permissible working time resulting from the applicable laws.

The permissible sound level value at the workplace for the eight-hour working time, i.e. 85 dB (A), is often exceeded due to the character of the operation of machinery and equipment. The probability of exceeding the permissible values of the factors in question also increased recently due to a significant increase in the power of motors installed in drives of machinery and equipment (the acoustic power of the sound generated by the equipment depends on the value of the mechanical power supplied to the system). An explicit example of this is the mining industry, where the total power rating of drives increased at least twofold in the last decade. Excessive noise values at workplaces are observed in many industries. The industries that are most at risk include in particular the mining industry, the machine building industry, metallurgical industry and construction industry.

A noise level exceeding the standard values causes the necessity to use additional personal hearing protectors and reduce the working time, which significantly affects the economic performance of the entire company. It should also be added that noise emissions are also associated with an environmental impact and this fact caused legislative changes that resulted in imposing penalties for such emissions [9].

The importance of reducing vibrations and noise emissions has also been emphasized in the following provision of the currently applicable Machinery Directive [10]: "Machines must be designed and constructed in such a way that risks resulting from vibrations produced by the machines are reduced to the lowest level, taking account of technical progress and the availability of means for reducing vibration, in particular at source".

THE ROLE OF DESIGNING IN THE PRODUCT MANUFACTURING PROCESS

As a part of the engineering activity, designing is one of the most important stages of the process of manufacturing technical means. The final result of designing, i.e. a finished product, determines whether the expectations assumed in terms of the cost-effectiveness, reliability and durability are met. The term "designing" [2] is defined as the development of information about the manner of meeting the needs, while technical designing consists in the development of the manner of meeting these needs as an outcome of a technical activity. As a result, technical documentation is created which contains e.g. drawings, descriptions and instructions concerning the operation. Machine designing can be defined as devising a concept of the machine operation, the selection of the energy, material and information processing systems, an appropriate use and association of properties of materials and physical phenomena, development of structures of mechanisms and the creation of desired links and relations between objects [2].

Interrelations between various stages of technical designing and machine designing processes [2] are shown in Figure 1. The diagram takes into account all the necessary factors required to meet the social needs. However, when designing a specific device or machine, generally the existing infrastructure and available technical resources should be taken into account and therefore it is enough to focus on the machine designing process itself.

In the presented diagram of a machine designing process there is a stage of defining the criteria to be met by the device being designed. These criteria provide a basis for a structure optimization aimed at the fulfilment of the goal function assumed.

The concept of optimization is understood as determining the best solution from the point of view of a given factor. There are single- and multi-criteria optimizations (polyoptimization). In the case of multi-criteria optimization there are many criteria that often exclude each other. Therefore the design decisions constitute the product of many goal functions. It often happens that the leading criterion determines the further designing process (actually constructing process, i.e. detailed designing that consists in selecting the construction characteristics of the proposed device).

In practice, companies use different approaches to designing and developing their products. This results primarily from the specific character of a given product and their technological back-up facilities. In recent years there occurred a development in computer simulation methods that use CAD software and rapid prototyping techniques.

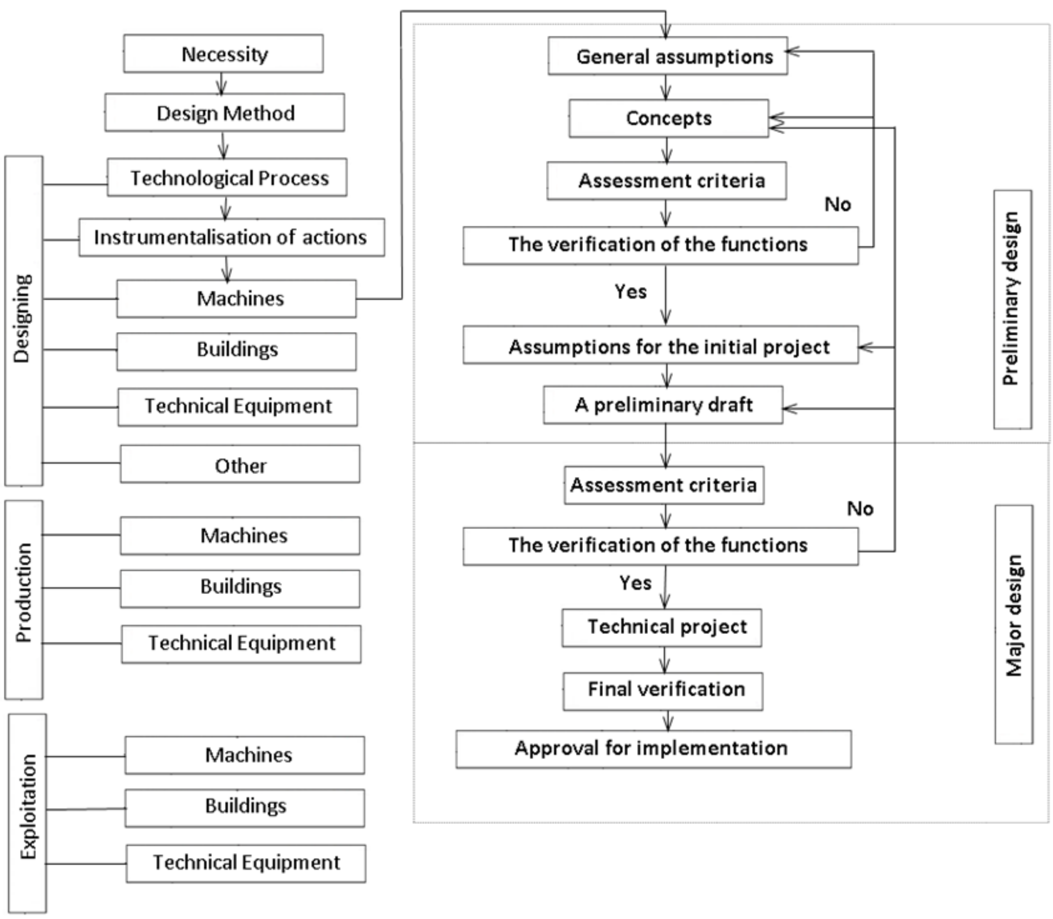

Fig. 1 Relations between stages of engineering and machinery designing

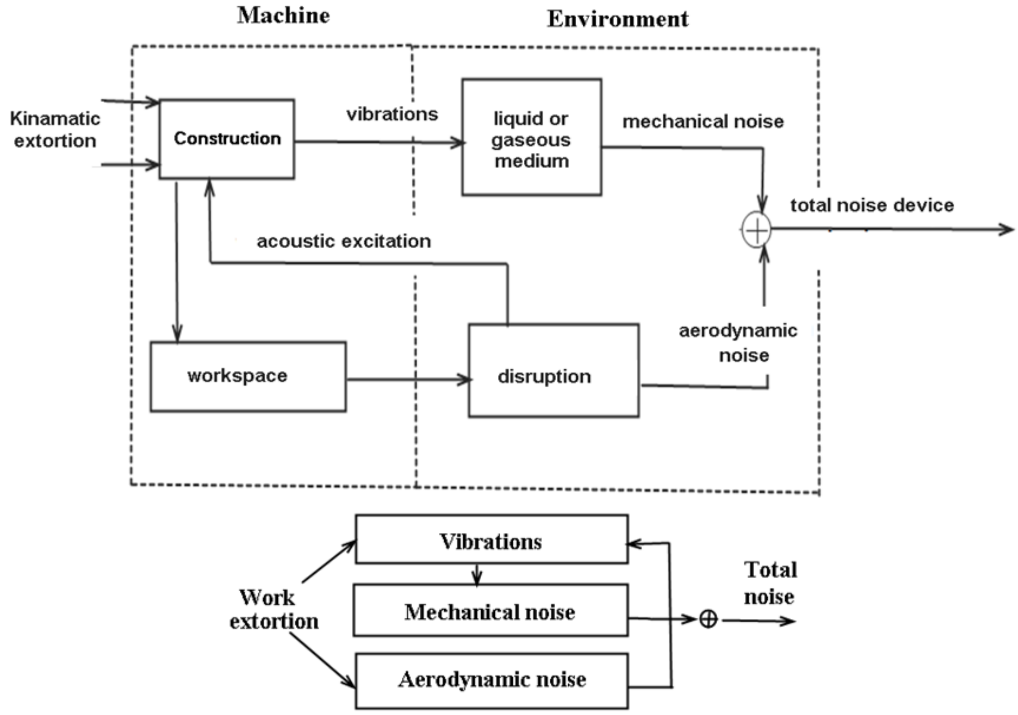

Fig. 2 Relations between stages of engineering and machinery designing

CAUSES OF NOISE GENERATED BY MACHINERY AND EQUIPMENT AS WELL AS METHODS OF REDUCING IT

The term "noise" is understood as all undesired sounds occurring in the human environment. Most often it accompanies people at a workplace or is associated with a widely understood transport. In both cases noise is caused by machinery and technical equipment. Mechanical noise is caused by vibrations of parts of machines and plants. It consists in radiating a part of the vibration energy into the surrounding medium [1].

Vibroacoustic emissions are caused [8] by internal factors that result from the constructional method of implementing the functions of the machine as well as external factors caused by excitations outside the technical object. External causes of vibrations generally have a character of kinematic excitations, so they depend on the positions of the points of support or mounting which change e.g. as a result of vibrations. Internal causes that excite vibrations generally have a character of forces and they result primarily from rotational or reciprocating motion of unbalanced parts as well as from dynamic excitations caused by percussive contact of mating elements (as in the case of gear transmissions).

Due to the mechanism of noise generation by machinery and equipment there can be distinguished mechanical and aerodynamic causes. In practice, noise is generated usually by both these mechanisms and it rarely happens that only one phenomenon is responsible for generating such undesired sound. Diagrams of noise generation by machinery and technical equipment are presented in Fig. 2.

The sound emission L_p to the environment [8] depends on the following factors:

- properties of the sound transmission routes L_{prz},
- sound radiation into the environment L_w,
- values of forces inducing the sound L_s.

This phenomenon can be described by the following general relationship:

$$L_p = L_{prz} + L_W + L_S \qquad (1)$$

An effective reduction of the noise level can be achieved when designing machinery and equipment. Such a reduction consists mainly in:

- limiting or minimizing the emissions of noise by sources,
- limiting the vibroacoustic energy on the routes of its transmission,
- limiting the immission of noise to certain areas of the environment and to humans.

In the case of the last two aforementioned factors, the reduction of the noise emission is associated with redesigning the machine body, changing the method of connection between its individual elements and changing the foundation of the unit (these factors are classified as secondary designing measures). There is also a solution that consists in encasing the machines and equipment that have particularly adverse impact on working conditions, using special cabins (this issue is explained more broadly in [11]). However, the greatest possibilities for reducing the noise are offered by a decrease in the value of forces inducing mechanical vibrations, which constitute the primary source of sounds. A reduction of this factor is considered to be one of basic design measures that allow obtaining a construction with a reduced vibroactivity. A breakdown of project measures according to their importance in construction of machinery and equipment characterized by a reduced emission of noise to the environment is shown in Figure 3.

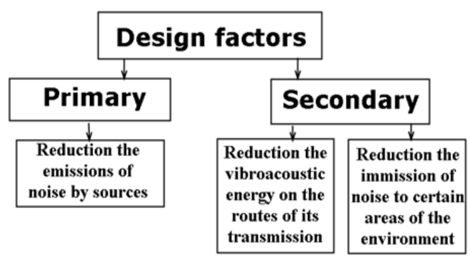

Fig. 3 Breakdown of designing measures in terms of noise emission reduction [2]

THE CONCEPT FOR DESIGNING MACHINES WITH REDUCED VIBROACOUSTIC EMISSIONS

As mentioned in the previous section, the greatest possibilities for reducing emissions of vibrations and noise generated by machinery and equipment can are offered by a limitation of the vibroacoustic energy produced by these units, i.e. a reduction of sources of these emissions. Designing machinery and equipment with reduced noise emissions requires a fundamentally different approach than that used when designing optimized equipment based on other criteria.

The main differences between these two design approaches manifest themselves primarily in:

- defining design criteria, i.e. on the one hand ensuring minimal acoustic or vibroacoustic emissions and on the other hand ensuring for example the greatest possible durability or cost-effectiveness of the product,
- accepting the fact that a certain decrease in the selected measures of durability or strength parameters takes place in the case of constructions with reduced vibroacoustic or acoustic emissions.
- looking for means to compensate the decreases of design parameters mentioned in the paragraph above,
- taking into account the changes in operating conditions (e.g. efficiency or thermal conditions) of equipment with a modified design.

In the proposed concept of designing machinery and equipment, which is consistent with the principle of sustainable development, minimal vibroacoustic emissions were adopted as the main criterion of optimization. The realization of the goal of this concept, i.e. production of a reliable and durable machine characterized by a reduced generation of mechanical vibrations and a reduced noise level as compared with similar solutions was based on the diagram shown in Figure 4.

The initial stage of designing is to determine whether there is a need to make constructional or technological changes in the machine in question. The existence of a need for changes is determined by comparing the sound level values at the workplace required by applicable standards or regulations with the results of measurements at the workplace or – in the case of inability to perform such measurements – with the estimated values of the sound level.

If it is found that the values of the permissible sound level are exceeded, an analysis of causes of the noise should be performed, i.e. main sources of the generated noise should be identified. A possible solution leading to a reduction of the mechanisms responsible for sound emissions should be found on this basis. As a part of the considerations, the solutions alternative in relation to those commonly used should be taken into account. Imposing a criterion of minimizing the vibroacoustic emissions at this stage of the design work may lead to creation of a solution favourable in terms of acoustics, but with worse strength parameters. In accordance with the proposed concept, worsening of strength properties should not cause rejection of the design, but it should be a starting point for further work aimed at creating a machine or device with a satisfactory strength.

The next step in a designing process consistent with the sustainable development should be to assess how the operational properties of the machine have changed as a result of the modifications aimed at improving the acoustic properties. First of all it should be checked whether the thermal conditions and efficiency of the machine allow operating it in the ambient conditions assumed. Such a check can be performed using a simulation on computer computational models. If these properties have changed so much that they prevent normal operation of the machine, the introduction of additional design and process solutions should be considered or operating fluids that enable operation in the changed conditions should be selected.

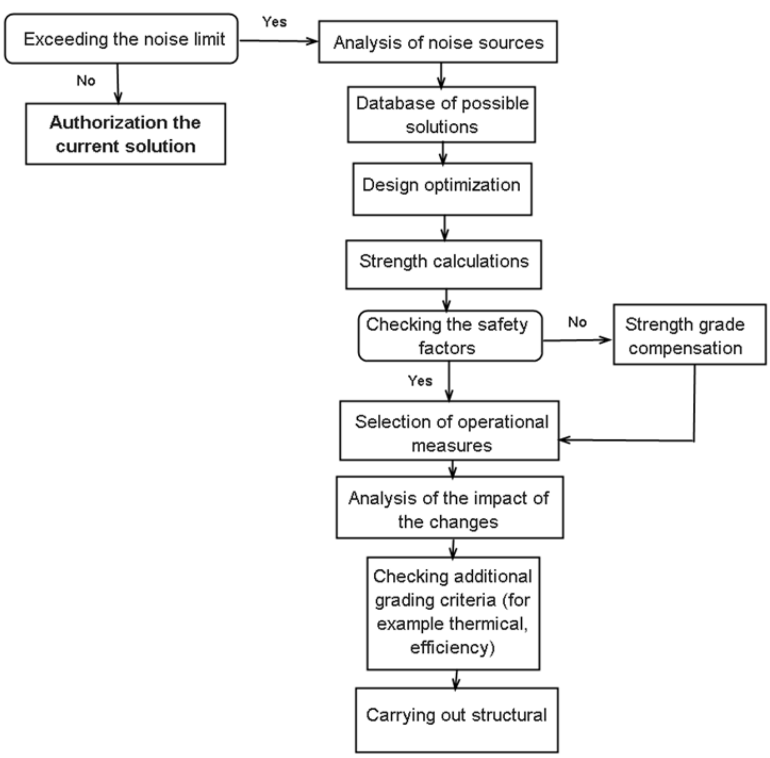

Fig. 4 A concept for machinery and equipment designing in accordance with the sustainable development principle

Final stages of the design work include an overall synthesis of introduced changes which will allow making reliable equipment that at the same time is characterized by reduced vibroacoustic emissions and tests of the developed solution on a test rig. The tests to be performed on the test rig should include verification of the realization of the assumed improvement in vibroacoustic properties, an analysis of the strength conditions through measurements and an evaluation of operating properties.

CASE STUDY

The procedure resulting from the design concept consistent with the sustainable development of the industry (presented in the previous section) was discussed on the example of a cylindrical gear transmission.

Gear transmissions belong to most popular devices entering into the composition of drive systems of machines. In a gear transmission, the rotational motion of one shaft is transmitted to the other one as a result of meshing between the driving wheel and the driven wheel. The main elements of a gear transmission include:

- pairs of gear wheels,
- gear transmission housing,
- shafts supported by rolling or slide bearings,
- sealing.

According to the concept presented in the previous section, the design process should start with an assessment of the possibility of exceeding permissible noise values (as mentioned earlier, the permissible sound level for 8-hour working time is 85 dB (A). Manufacturers usually perform control measurements of noise emitted by gear transmissions operating under a load at a testing station. When designing a new gear transmission, it is sometimes difficult to assess at an early stage whether excessive noise emissions may occur. In order to estimate the expected sound level, the relationships available in the literature concerning this problem can be used. The guidelines prepared by the Association of German Engineers, No. VDI 2159, are used most commonly. An estimation of the expected level of acoustic power emitted by the cylindrical gear transmissions as a function of power is presented in Figure 5. This figure summarizes two characteristics: from 1985 and 1999. A noticeable reduction in the noise level according to the more recent estimation results from an increase in the development level of the technology of building these units. According to the more recent guidelines from 1999, the use of gear transmissions with a power over 100 kW can lead to exceeding the permissible noise levels at the workplace and thus may cause harm to human health.

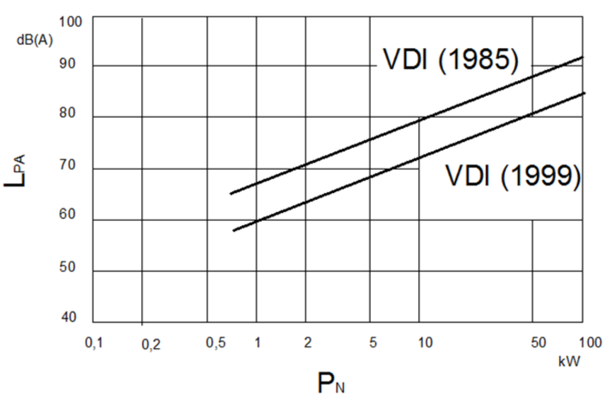

Fig. 3 Estimation of the expected sound power level emitted by cylindrical gears as a function of power, according to the Association of German Engineers, No. VDI 2159

The next step of the designing process is an analysis of causes of noise emission by gear transmissions. The noise is caused primarily by vibrations of transmission components: bearings, housing and gear wheels. This last factor has the greatest impact on the sound level. Vibrations of elements of the unit in question result from external impacts, i.e. from vibrations of machines and motors transmitted to the gear transmission by the linking elements such as shafts and couplings, as well as from internal impacts. In practice it is impossible to avoid external forces affecting gear transmissions. They can only be reduced by properly selected connections of the driving and driven members with the gear transmission. In the case of internal causes there are methods that may significantly reduce values of such forces. They consist primarily in reducing the dynamic forces generated in teeth of gear wheels.

Among many causes of vibrations of gear wheels, the most significant impact on their generation [4] have deviations in workmanship, excitations occurring when teeth move in and out of meshing, as well as mesh stiffness variations. Causes of these vibrations are shown in an illustrative manner in Figure 6. For many years design engineers have made efforts to improve vibroacoustic properties of gear transmissions. The currently used gear transmissions are already very advanced in technology and a further improvement of their acoustic properties requires structural changes in the teeth themselves. Table 1 shows estimated possibilities of reducing the noise by changing selected parameters of gear transmissions and performing an analysis that takes into account the current state of technology. For many years design engineers have made efforts to improve vibroacoustic properties of gear transmissions. The currently used gear transmissions are already very advanced in technology and a further improvement of their acoustic properties requires structural changes in the teeth themselves.

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Table 1 shows estimated possibilities of reducing the noise by changing selected parameters of gear transmissions and performing an analysis that takes into account the current state of technology.

As it results from Table 1, the most effective methods of eliminating the noise sources (i.e. the basic factors) include:

- increasing the gear contact ratio (this reduces mesh stiffness fluctuations),
- applying longitudinal and transverse modifications (this reduces the strokes that occur during teeth meshing),
- increasing the manufacturing precision (this results in decreasing the manufacturing deviations).

Planetary gear trains are currently commonly used due to a number of advantages. Advanced processing technologies are used during the production to ensure a high manufacturing precision (mining companies in Poland require precision class 5). In addition, a longitudinal and transverse modifications of teeth are used more and more frequently. These facts allow stating that the two primary sources of vibrations are eliminated at the gear transmission manufacturing stage.

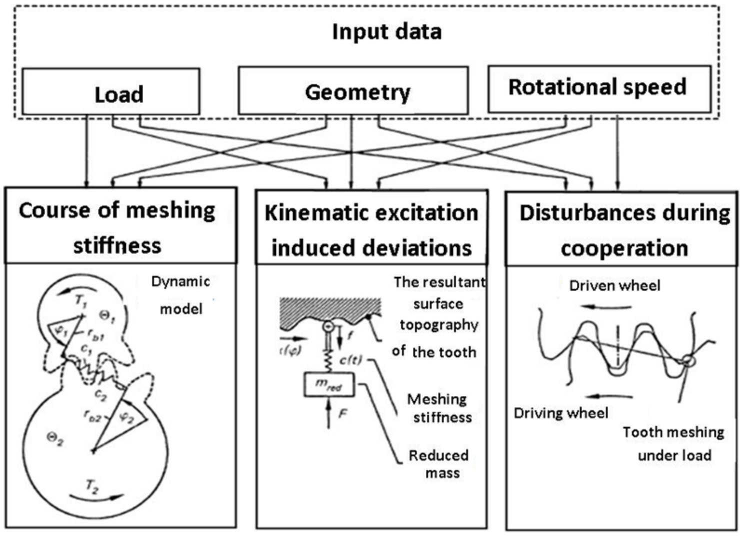

Fig. 6 Causes of vibrations of gears

Table 1
Analysis of the impact of selected parameters of a gear transmission on the reduction of noise

Parameter	Comments
Increase in the gear contact ratio to integer values	Currently, this method brings the best results due to a reduction in stiffness variations, which are the basic cause of vibrations of wheels. The gear contact ratio for a helical gear transmission can be relatively easily increased by increasing the helix angle, but often this method cannot be used for constructional reasons (problems with bearings). In the case of spur teeth, an increase in the contact ratio is associated with significant changes in the teeth parameters, such as an increase in the tooth height or a decrease in the pressure angle.
Transverse modification of the tooth profile	It reduces dynamic excitations caused by teeth moving in and out of the tooth contact. This requires the use of specialized machinery. Most effective for spur teeth.
Longitudinal modification of teeth	It compensates to some extent the errors of non-parallelism of axes and deflections of bodies. This requires the use of specialized machinery.
Increase in the precision of manufacturing the gear wheels	This reduces the impact of manufacturing deviations on vibrations of gear wheels. This requires the use of specialized machinery.
Increase of the damping factor	An increase of this factor can be obtained in the easiest way by the use of non-metallic materials, but this solution leads to a significant deterioration of the strength and operating properties. Another possible measure is to use oils with a higher viscosity, but this will deteriorate the efficiency of gear transmissions. Besides, the effectiveness of this measure is the highest only in the case of resonances.
Lapping	Lapping gives the best results for bevel gears and for non-ground teeth. Currently, most wheels for industrial gear transmissions are produced in a hardened and ground form, for which lapping does not bring any clear benefits.
Reduction of the roughness of teeth	This improves the interoperation of meshing gear wheels. At the moment, most gear wheels are ground.

Source: [based on [4] and own information]

Obviously it is disputable whether the selected design assumptions that provided the basis for determining the extent of the modification correspond with the reality, but in most cases a modification of the tooth profile or direction significantly affects the dynamic excitations that contribute to emissions of unwanted sounds.

For many years there has been a conviction [6, 7, 13] that possibilities of a further reduction of noise emitted by gear transmissions are associated with the use of high values of the gear contact ratio. These values cannot be selected freely – integer values of the gear contact ratio (e.g. 2.0, 3.0) are considered to be especially favourable. Integer values of the gear contact ratio can be obtained by selecting an adequate helix angle (possible only for gears with helical teeth) or by selecting a number of design parameters of teeth, such as tooth height, pressure angle and correction factors. In the second case, design changes concern spur teeth, which are generally used in planetary gear trains. Considering all the circumstances, when designing gears transmissions (especially planetary ones), obtaining a gear contact ratio equal or close to 2.0 can be considered as a criterion for minimal vibroacoustic emissions. This criterion becomes the starting point for the selection of other geometrical parameters of gear teeth (the exact methodology for calculations of these parameters is given in [5, 12]).

The solution obtained based on the above criterion is characterised by very favourable acoustic properties, however, as it might be expected, this resulted in a change of other performance characteristics of gear transmissions. This concerns in particular the seizure resistance of gear wheels, a decrease in the efficiency and an increase in the thermal load. These properties are interrelated due to the fact that as a result of the changes made in the geometry, an increase in the slip speed on gear teeth takes place. As already mentioned in the previous section, a decrease in the strength or operating properties should not provide a basis for rejecting the solution, but only indicates that measures enabling a reduction of adverse factors should be introduced. In the case of gear transmissions there comes to mind a solution consisting in the use of gear oils characterized by an increased seizure resistance and adequate metal conditioners that have very positive impact on lowering the coefficient of friction. This results is lowering the temperature in the friction pair and increasing the seizure resistance.

With respect to bearings of gear transmissions it is possible to reduce their vibrations thanks to an adequate selection of materials, but the best method is to ensure their good technical condition. This can be achieved by vibroacoustic supervision or monitoring conducted by specialized maintenance services.

The last important element of gear transmissions which affects the noise level is the body. This element determines the conditions of the transmission of vibrations caused by gear wheels and bearings inside a gear transmission as well as the radiation of sound generated as a result of the emission of these vibrations to the environment. When constructing the body, a designer has at his disposal a sort of material, from which the body will be made, as well as the shape of elements reinforcing the housing structure (an increase in the number of stiffening elements reduces the sound radiation to the environment). The greatest benefits in terms of vibroacoustic properties are offered by the use of grey cast iron.

SUMMARY

The generation of noise by machinery and equipment is an important problem associated with the safety at work and unfortunately its reduction not always gains a high priority at the design stage. However, the companies that use machines should be aware that maintaining an adequate noise level at workplaces is important from the point of view of the economic result. The factors which affect the result, although difficult to quantify, include a reduction in the productivity of workers, their worse health condition that translates into increased absence, and above all shortening of the permissible working time. Therefore, companies should pay attention to satisfy the requirements resulting from the regulations determining the permissible level of noise emitted by machinery and equipment purchased as a part of investment plans.

The intention of this study was to determine the action plan at the design stage, which would aim at producing a machine characterized by reduced vibroacoustic emissions as compared with similar solutions. The author of the paper is aware of the difficulty of the problem, however obtaining a satisfactory noise level during the operation of machines becomes a requirement in the light of the existing standards and regulations.

The paper presents a designing scheme based on the main criterion of optimization, which is to minimize the vibrations and noise generated by machinery.

This concept takes into account the deterioration of the strength and operational properties of constructions, which should be brought to a satisfactory level by applying additional measures.

The design approach in question was examined on the example of gears, for which it is extremely difficult to achieve a noise reduction due to their highly advanced technology.

The study was carried out as a part of the project “Development of an innovative pro-ecological specialized gear transmission integrated with a diagnostic system” No. POIG.01.04.00-24-094/11.

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