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Application of mechanical and electrical elements in reduction of vibration

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Analysis and modelling

ABSTRACT

Purpose: This work presents methods of reduction of the vibration of mechanical systems by means of passive and active elements as well as examples of implementation of active reduction of vibration by means of electrical elements and mechanical elements in the form of kinematic excitation.

Design/methodology/approach: This work also describes a structural and parametric synthesis, which can be defined as the design of systems meeting specific requirements. These requirements refer to the frequency values of the systems' vibration.

Findings: The examples of implementation of active subsystems presented in this work point out to the fact that one can use mechanical elements as well as electrical elements to reduce mechanical vibration. By applying such elements it is possible to obtain mechanical energy necessary for the active reduction of vibration.

Research limitations/implications: The deliberations presented in this paper are limited to the presentation of possible physical implementation of active elements by means of mechanical and electrical elements. In active subsystems one may also use elements from other environments. In the next phase one should analyse the resultant systems and investigate the interaction between the subsystems and the basic system.

Practical implications: The results represented this work extend the tasks of synthesis to other spheres of science. The practical realization of the reverse task of dynamics introduced in this work can find uses in designing of machines with active and passive elements with the required frequency spectrum.

Originality/value: The presented approach i.e. a non-classical synthetic method applied in designing mechanical systems, one (as early as at the design and construction stage) may verify future systems.

Keywords: Process systems design; Synthesis; Reduction of vibrations

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1. Introduction

Vibration belongs to one of the most common daily-life phenomena. The phenomenon of vibration is understood as periodical movement of a particle or system. Such movement is caused by external factors. Vibration occurs when the system, or part of it, becomes unbalanced i.e. loses its state of equilibrium. The system whose state of equilibrium has been disturbed tends to return to its original state. In case of mechanical systems, this process is caused by elastic or gravitational forces [1,2].

Vibration can be divided into:
- free vibration,
- forced vibration,
- self-excited vibration.

Free vibration is caused by disturbing the system's state of equilibrium when no external forces act on the system. Forced vibration is caused by external forces. Self-excited vibration is vibration of the system sustained by the energy transferred from the source to the system by means of a regulatory mechanism. Self-excited vibration is characterized by the ability to perform unfading periodic movements and to compensate for the loss of energy [1-7].

Vibration is deliberately introduced into some devices and machines in order to use their performance to accomplish special tasks. Most common applications can be found in equipment and machinery used for comminution, densification, purification, milling, crushing, drilling, boring or grinding of materials.

The majority of vibration occurring in devices and machines is harmful and has a disadvantageous effect on their condition. Harmful impact of vibration is caused by the occurrence of increased stresses and the loss of energy, which results in faster wear machinery. Vibration, particularly low-frequency vibration, also has a negative influence on the human organism. For this reason many scientists in various research centres conduct research aimed at the reduction or total elimination of vibration [1,2].

There are many methods of vibration reduction and these can be divided into:

- passive methods,
- semi-active methods,
- active methods.

Passive reduction of vibration consists in application of additional elements in the form of vibration dampers, which aim to dissipate or store energy. In this method of vibration reduction it is the vibration of structure which is used to generate damping forces and not any additional sources of energy. The parameters of passive dampers cannot change in time. Passive reduction of vibration is characterised by strong correlation between efficiency and vibration frequency as well as by sensitivity to the alteration of parameters [1,8,9].

Semi-active methods consist in the application of semi-active eliminators of vibration. They combine some features of the features of passive and active elements. The design of a semi-active subsystem is similar to that of an active subsystem [1].

The difference between active and semi-active subsystems is that the latter are characterised by a small demand for energy. In turn, they differ from passive subsystems by the fact that their parameters may change in time; such changes depending on the current state of the basic system.

A characteristic feature of the method of the active reduction of vibration is the necessity of the presence of additional external sources of energy. The energy supplied from outside prevents undesirable vibration. Active subsystems can reduce vibration of selected parts of machines and devices. The value of their parameters is variable in time and depends on the current state. The design of the active subsystem may include various types of elements: mechanical, pneumatic, hydraulic, electromagnetic or electrodynamic [10-15].

The application of active and semi-active methods enables the elimination of restrictions typical of passive methods. Such methods are more effective but require the use of additional equipment.

2. Synthesis of mechanical systems with selected method

The synthesis presented in this work is a non-classical one. As a result of the synthesis one can obtain the structure and parametres of the system of required properties [1,9,12-17]. The synthesis may also be applied to modify the already existing systems in order to achieve a desired result. The synthesis consists of two basic stages. At the first stage, while designing a new system, it is necessary to define the requirements related to the frequency of free vibration of the system; this being done in order to obtain the structure and parameters of a system composed only of passive elements in the form of inert and elastic elements. At the second stage, it is necessary to select either passive or active reduction of vibration, suitable for the newly obtained system or a system which already exists (Figure 1) [12,13].

In order to obtain the structure and parameters of inert and elastic elements of a dynamic system one applies two basic methods [1]:

- decomposition of a characteristic function into a continued fraction (3),
- decomposition of a characteristic function into simple fractions (4).

Characteristic functions may be functions in the form of mobility (1) or slowness (2):

$$V(s) = H\frac{c_k s^k + c_{k-1}s^{k-2} + \ldots + c_1 s}{d_l s^l + d_{l-1}s^{l-2} + \ldots + d_0} \tag{1}$$

$$U(s) = H\frac{d_l s^l + d_{l-1}s^{l-2} + \ldots + d_0}{c_k s^k + c_{k-1}s^{k-2} + \ldots + c_1 s} \tag{2}$$

where:
k, l - natural numbers,
c, d - real numbers,
H - any positive real number.

$$V(s) = \frac{c_1}{s} + m_1 s + \cfrac{1}{\cfrac{s}{c_2} + \cfrac{1}{m_2 s + \ldots + \cfrac{1}{\cfrac{s}{c_n} + \cfrac{1}{m_n s}}}} \tag{3}$$

$$U(s)\frac{1}{H} = \frac{c_1}{s} + m_1 s + \frac{1}{\frac{s}{c_2} + \frac{1}{m_2 s}} + \ldots + \frac{1}{\frac{s}{c_n} + \frac{1}{m_n s}} \tag{4}$$

where:
c - elastic elements,
m - inertial elements.

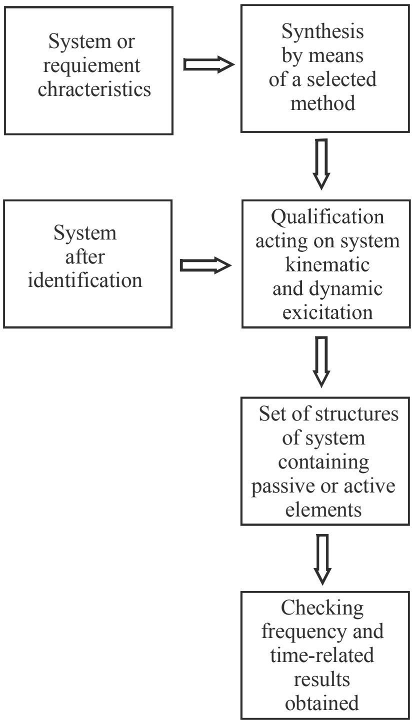

Fig. 1. Idea of synthesis mechanical system

2.1. Passive elements in reductions of vibrations

In order to design a system with the passive reduction of vibration one should follow the diagram presented in Figure 4. Having made the synthesis in the form of decomposition into a continued fraction or simple fractions, one should determine the type and value of external excitation acting on the system [1,8,9].

While choosing the passive reduction of vibration, a design engineer or designer must determine whether passive elements, in the form of viscous dampers, will be proportional to inert elements (as shown in Figure 2, presenting the example of such a system) or to elastic elements (Figure 3).

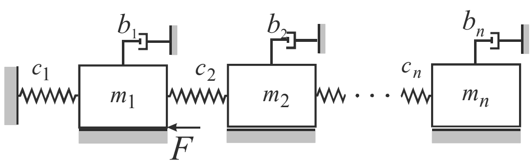

Fig. 2. The model for a discrete mechanical system with passive components proportional to inertial components

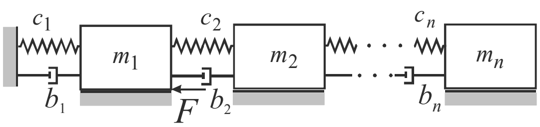

Fig. 3. The model for a discrete mechanical system with passive components proportional to elastic components

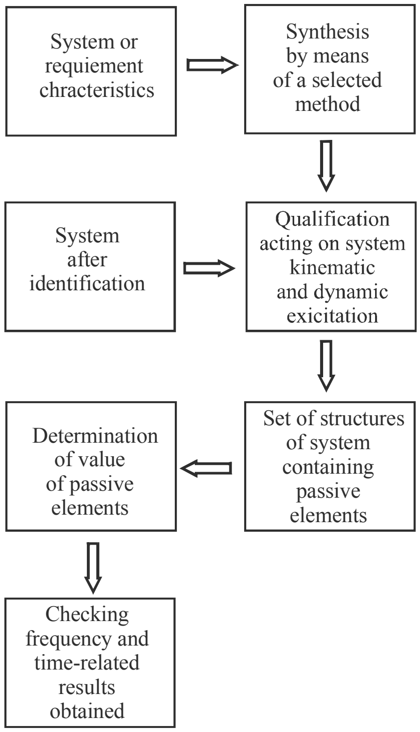

Fig. 4. Idea of synthesis mechanical system with passive elements reducing vibrations

2.2. Active elements in reduction of vibrations

The application of passive methods to reduce vibration has its limitations. These methods prove not effective in case of broad band frequency vibration or low-frequency vibration.

In order to minimise or completely reduce such vibration one should apply other methods e.g. the use of active subsystems.

The synthesis of the systems with the active reduction of vibration is presented in Figure 5 [10-15].

The selection of the active method of vibration reduction makes it possible to reduce vibration of selected parts of machines or devices. The design engineer chooses the structure of the system with an active element or elements.

Solving the matrix set of equations (5), it is possible to obtain of values of individual amplitudes generated by active elements.

$$G = D \cdot A - F \tag{5}$$

where:
G - matrix of excitations generated by active elements,
D - matrix of dynamic stiffness,
A- matrix of amplitudes (approaching zero),
F - matrix of dynamic excitations.

The system with active elements is presented in Figure 6. Active subsystems are located between inert elements, which enables the reduction of vibration in the parts of the system pre-defined by the designer.

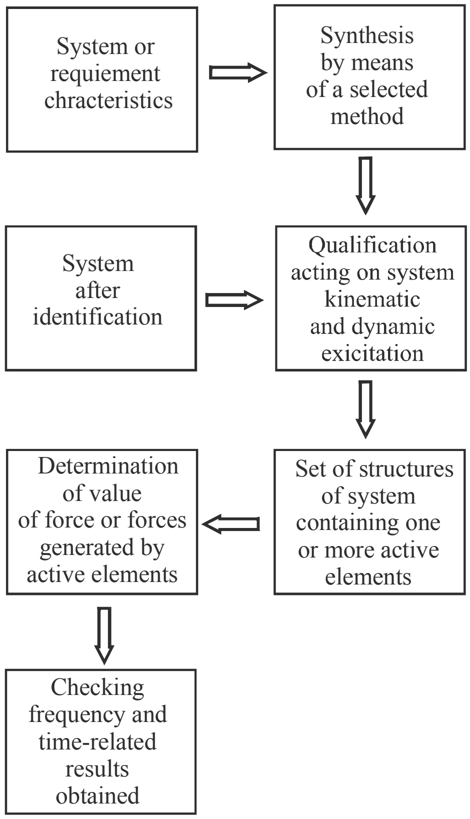

Fig. 5. Idea of synthesis with active elements

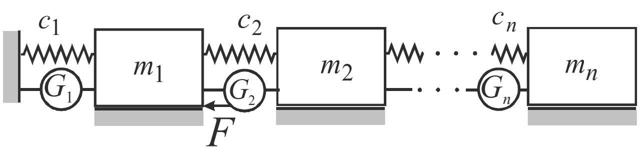

Fig. 6. The model of a discrete mechanical system with active components

2.3. The model of the research with active elements executed by means of kinematic excitations

Physical implementation of an active subsystem proves to be a vital issue as it requires the verification of the influence of interactions between the basic system and the active system. If the influence of the subsystem on the basic system is considerable, one should abandon this solution. Other possibilities include the application of only mechanical elements as an active subsystem. Kinematic excitation meets the aforesaid requirement [18,19].

A characteristic feature of the active method is the possibility of changing the parameters of the subsystem-composing elements in time.

In case of the application of kinematic excitation, the parameter whose value may be changed is shift "*y*". The element whose value does not change is elasticity "*c*".

In order to determine the value of displacement and that of the coefficient of elasticity, it is necessary to apply the dependence below (6):

$$y_i = \frac{K_i}{c_{ii}} \tag{6}$$

where:
K_i - values of kinematic excitations, equivalent to the values of G_i,
y_i - displacement that occurs in the specific kinematic equation,
c_{ii} - values of the elastic components that occurs in the specific kinematic equation.

The synthesis of systems with the active reduction of vibration when active components are mechanical elements is presented in Fig. 7.

Fig. 8 presents a model of the system that incorporates kinematic excitations where the excitation values determined for active vibration damping are implemented.

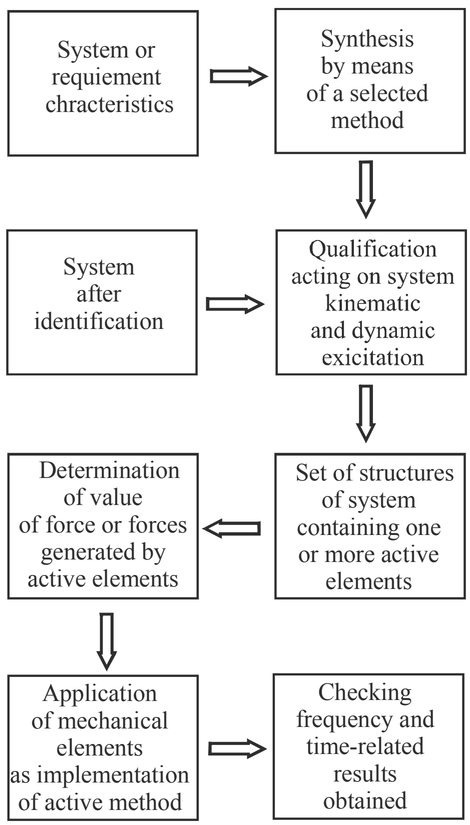

Fig. 7. Idea of synthesis of active mechanical systems by means of kinematic excitations

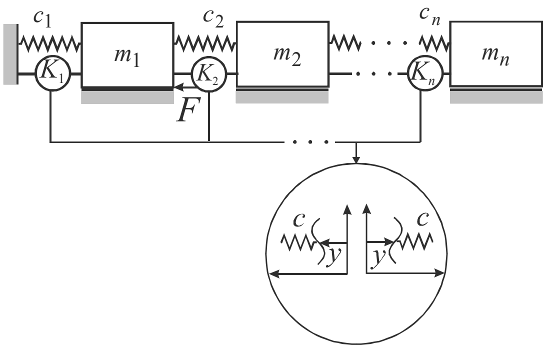

Fig. 8. A model of the system with kinematic excitations

2.4. The model of the research with active elements executed by using electric elements

It was mentioned above that active systems may be composed of elements of various types. This work is limited to the application of mechanical and electrical elements [20-22].

The synthesis of systems with the active reduction of vibration when active components are electrical elements is presented in Figure 9.

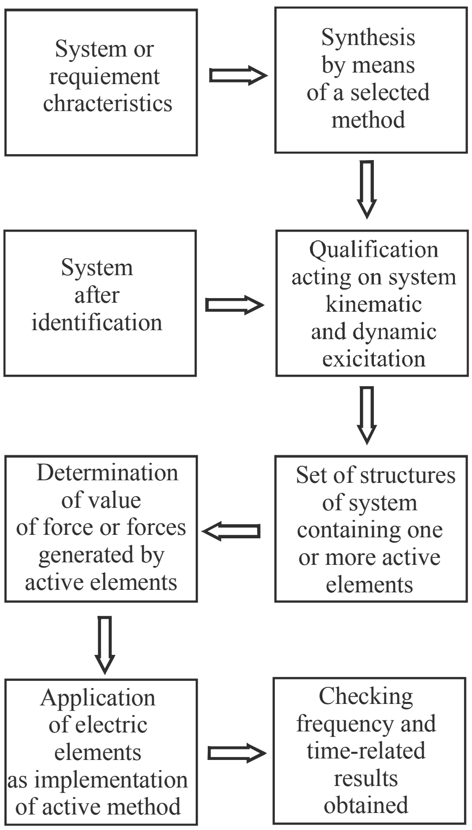

Fig. 9. Idea of synthesis of active electrical elements

Presented below are several possibilities of applying electrical elements. One of the options consists in the application of a coil with moving core (Figure 10). The value of force in the magnetic field is expressed by the following formula (7) [22]:

$$F = BIL \tag{7}$$

where:
F - electrodynamic force,
B - magnetic induction,
I - amperage of the current-carrying wire,
L - length of the current-carrying wire being in the magnetic field.

The value of electrodynamic force is directly proportional to the value of current flowing in the wire and the length of the section of the current-carrying wire in a given magnetic field.

The direction in which electrodynamic force acts is perpendicular to the plane formed by a current-carrying wire and magnetic field induction lines. In order to determine the sense of electrodynamic force one should use the left-hand rule called also the right-handed screw rule.

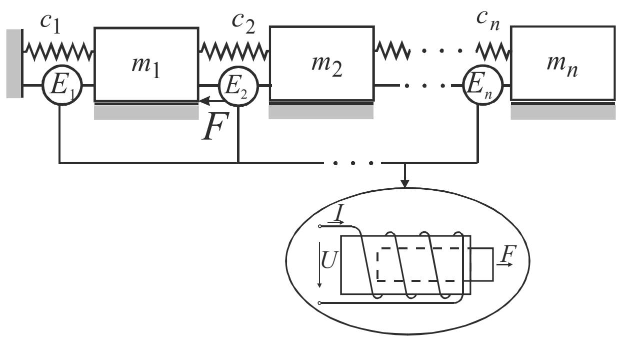

Fig. 10. A model of the system with electric elements - coil with moving core

Another possibility of applying electrical elements in active systems is a relay with a movable plunger [22] as shown in Fig. 11.

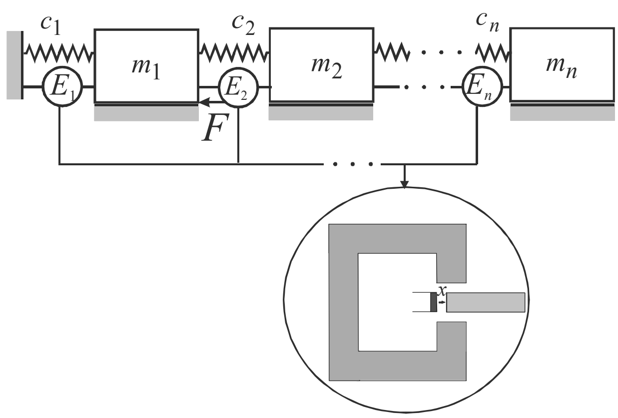

Fig. 11. A model of the system with electric elements - relay with a movable plunger

Another possibility of applying electrical elements in active systems is an electromagnetic relay [22] as shown in Figure 12.

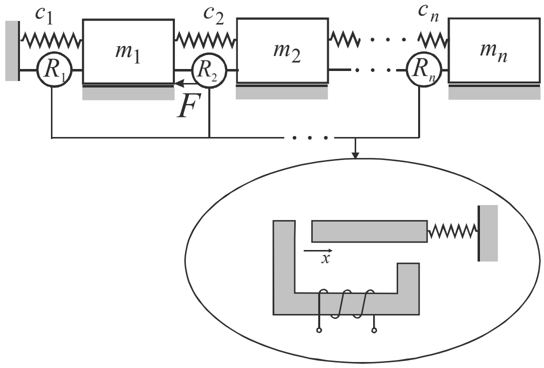

Fig. 12. A model of the system with electric elements - electromagnetic relay

The last solution presented in this work is the application of piezoelectric elements [21,22] (Figure 13).

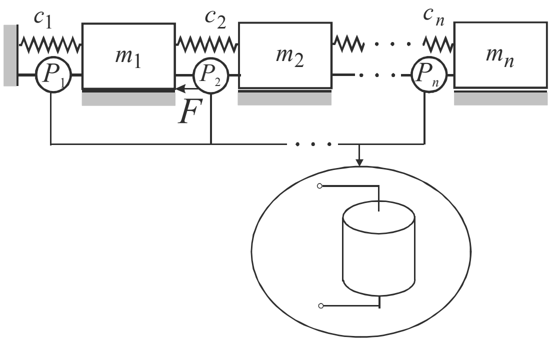

Fig. 13. A model of the system with electric elements - piezoelectric elements

Piezoelectric materials are crystals in which piezoelectric effect can be observed. This effect consists in the occurrence of electric charges on their surface caused by mechanical stresses.

The piezoelectric effect was discovered by the Curie brothers (Peter and Jacob Curie) in 1880, during their research on the influence of mechanical stresses on the properties of piezoelectric materials. On the surface of some crystals (such as tourmaline, quartz and others) they observed electric charges whose value was proportional to applied stress.

Also the research conducted by Gabriel Lippmann in 1881 proved very important. The scientist deduced that there was a possibility of occurrence of the inverse piezoelectric effect consisting in the deformation of crystals under the influence of an electric field.

The inverse piezoelectric effect consists in the change of dimensions of the piezoelectric material caused by the application of an electric field. The deformation occurs due to the shift of ions under the influence of electrostatic forces and is proportional to the applied field. One should remember not to associate it with electrostriction, which is caused by other factors. Electrostriction is a much weaker and more common phenomenon. There is no inverse effect in electrostriction and deformation is proportional to the square value of the applied field.

Piezoelectric materials may include both monocrystals (e.g. quartz) and polycrystals, whose elementary cells have no centre of symmetry. There are also ceramics and organic substances having properties like piezoelectric materials. The characteristic feature of piezoelectric crystals is that they have ionic bonds and their elementary cell has no centre of symmetry. Stress in such crystals causes various types of shifts of "the gravity centre" of the positive and negative charge, which, in turn, leads to the electric polarization of the crystal. The charge which appears on the edges of the crystal is proportional to the deformation.

The way of cutting a piezoelectric element out of the crystal is of great importance as the orientation of the cut-out plate in relation to the crystallographic axes (X, Y, Z) influences the properties of the future element made from this piezoelectric material.

The first practical application of piezoelectric materials goes back to the years of the First World War when they were used in transmitters and receivers of ultrasound wave echo location equipment in order to detect submarines.

Piezoelectric effect occurs almost in all crystalline materials having a non-centrosymmetric crystal structure.

In the natural environment, for instance, it is silicon that is characterized by such properties. However, the most commonly applied are piezoelectric materials produced in an artificial way. The most popular ceramic materials used in the production of piezoelectric materials are lead zirconate titanate, barium titanate and lead titanate.

The bidirectional nature of the effect of piezoelectric elements is presented in Fig.14. The direct effect (Fig. 14a) consists in subjecting the element to mechanical stress in order to generate a charge /voltage. In turn, the application of voltage onto electrodes causes mechanical deformation of piezoelectric material (Fig. 14b).

The phenomenon of conversion of mechanical energy into electric one, occurring in piezoelectric materials, makes it possible to apply the latter in many technological fields e.g. in the reduction or control of mechanical vibration [23].

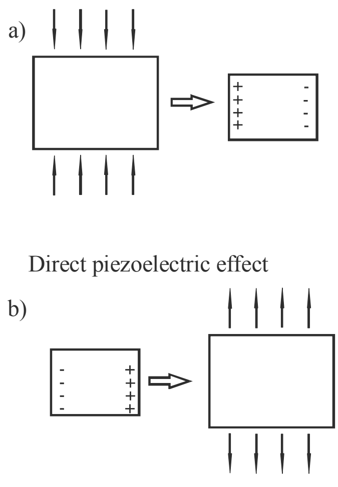

Fig. 14. Direct and inverse piezoelectric effect

3. Conclusions

This work presents a non-classical method of designing discreet vibratory mechanical systems. The designing consists in conducting the structural and parametric synthesis resulting in the development of a system characterised by desired, predefined properties related to the system vibration frequency values. The synthesis described in the present work can be divided into two basic stages. The first one consists in designing a system composed only of elastic and inert elements. At the second stage, a method of vibration reduction is selected for a given system. The approach presented in this work makes it possible to apply measures aimed to eliminate undesired action of equipment and machinery as early as at the design stage.

This work also presents the description and comparison of vibration reduction methods. The most popular methods are passive, active and semi-active.

An important aspect of this work is the presentation of several possibilities of the physical implementation of active subsystems. The application of only mechanical elements in the form of kinematic excitation was shown as the first possibility. In subsequent examples active subsystems consisted of the following electric elements:

- coil with a movable core,
- relay with a movable plunger,
- electromagnetic relay,
- piezoelectric element.

Further research will focus on defining mutual relations between the basic system and the vibration-reducing subsystem. One should investigate how an attached subsystem influences the basic system and, first of all, whether the former changes the initial design assumptions in any manner. These assumptions in question are concerned with the value of vibration frequency.

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