Vibration Control of Mechanical Systems - introduction to the problem*

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Vybračné ovládanie mechanických systémov – úvod do problematiky

Príčiny vibrácií strojov sú rôznorodé a je ich ťažko analyzovať. Ich analýza je veľmi dôležitá, nakoľko vibrácie majú negatívne účinky nielen na životnosť, prevádzkyschopnosť strojov, ale i na obsluhu strojov a životné prostredie. V článku sú charakterizované základné postuláty pasívnych a aktívnych metód pre analýzu, syntézu a návrhu útlmu vibrácií s využitím princípu „riadených" vibrácií. Využitie matematického modelovania mechanického systému a riadenia je predmetom súčasného simulačného výskumu vo svete. Uvedená teória je úspešne aplikovaná pre útlm, redukciu vibrácií strojov, rotorov zariadení, budov, komunikačných prostriedkov.

Key words: methods of vibration reduction, automatic vibration control.

Introduction

In order to counteract negative effects of vibrations properly we should recognize first of all the reasons of the disturbing vibrations rise and expansion. For this purpose, the total analysis of dynamic phenomena of considered machines and devices operation should be carried out. This task is very difficult because of complexity of the machines and devices construction. Machine units are systems composed of many parts with many degrees of freedom, complicated structure and with closed, opened or branched kinematics. They are characterized by holonomic or nonholonomic constraints, elastic elements, elements with variable mass with clearances in kinematics pairs, etc.

There are many sources of mechanical vibrations in machines and devices but their location and identification is very difficult. The reasons of vibrations which disturb normal machines operation are different. Some of them come out from the realization of the technological process. The other result from law-grade work of elements, their abnormal assembly, wear and tear of parts, etc. Beside that some reasons come out from the external influence related to the environment.

The above numerous vibrations sources which take place during machines operation influence their elements. This influence takes the character of periodic, almost periodic or random inputs. The mentioned inputs operate together with other agents as e.g. with static load, compound stress state and variable temperature area. In such conditions resonant states, dynamic critical states and states of unstable vibration motions may arise. Large variable stresses accompanied by vibration phenomena often lead to strain cracks of machine elements and in consequence to their break-down. The vibrations influence machines strength and cause disturbances in the programmable motion of machine elements, generate a noise source and friction increase. They are also the reason of the excessive mechanical energy dissipation, so that simultaneously decrease efficiency, capacity and machines and devices durability. Moreover, the vibrations cause a harmful influence on the environment and machines staff.

The above considerations allow to state that the most important harmful phenomena which accompany machines vibrations are:

- disturbances in normal machines operation,
- decrease of machines and devices durability,
- harmful vibrations influence on the environment,
- noise emission.

According to this the main purposes of the machine vibrations control are:

- most effective machines operation protection,
- minimization of undesirable and harmful effects such as vibrations of machine elements and environment.

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* The article is the first one dedicated to the problem of active methods of mechanical vibrations reduction.

Analysis and synthesis of dynamic processes in the device begins with the mathematical modelling stage. One of the most common method of the modelling is the finite elements method. Using this method the device structure is replaced by a great number of small elements. Next, for each element, coordinates are chosen and matrices of stiffness (K_e), inertia (M_e), load (P_e) and damping (B_e) are created. Beside that, total coordinates are chosen and then their total matrices K, M, P, B are determined. Then, mathematical model of the system takes the form:

$$M\ddot{x} + B\dot{x} + Kx = P \ , \qquad (1)$$

where x is the vector of total coordinates (Kowal, 1996).

Mechanical plants are often characterized by small value of damping so that the elements of matrix B take the same values. If the frequency of input P is equal to one of the plant's natural frequencies, then small input amplitudes cause resonance vibrations of the system. In order to minimize harmful disturbances and reduce vibrations, the following problems should be considered:

- change of P vector coordinates value (i.e. to eliminate or decrease values of input forces),
- choice of appropriate elements of matrices M, K, B (i.e. to increase of natural vibrations frequency).

Method of vibration reduction

During last years there have been attempts of protection of vibration reasons and vibration control. All those tasks are known as the Vibration Control in the English literature (Kowal, 1996). Two main groups of methods may be distinguished here, i.e. passive and active methods.

Having in mind problems formulated at the end of the introduction the following tasks may be considered due to passive methods:

- protection of vibration reasons,
- parametric modifications,
- structural modifications,
- vibration damping.

The protection of vibration reasons consist in elimination of additional energy sources, elimination or decrease input forces and isolation from external disturbances e.g. balancing, decrease of colliding bodies mass, substitution of rolling bearings by slide ones, etc. The parametric modifications lead mainly to changes of mass and stiffness elements. The structural modifications deal with introducing additional constraints to the system or tearing of existing ones (i.e. continuity interruption of vibrator structure via introducing of intermediate elements so called vibroisolators), addition of vibration eliminators. The damping is also important parameter but takes secondary meaning. It refers to mechanical energy dissipation which is exchanged to heat. It causes the decrease of general efficiency of machines and devices. The ideal device performance should run with minimal damping value. In case when the undesirable vibrations cannot be eliminated via constructional or parameters changes the damping should be introduced. This additional damping consist in the use of: constructional materials with appropriate damping value, frictional joints, additional dampers introducing e.g. hydraulic ones.

Discussed above ways of vibration reduction belong to the traditional group of passive methods. Unfortunately their use is restricted because of: small effectiveness in the range of low frequency, sensivity-dependent on exploitation conditions, etc. (Engel et al., 1995; Kowal, 1996). On the other hand these methods allow to dissipate a great deal of vibration energy in the range of sufficiently high frequency (energy dissipation increases with decrease of passive elements stiffness). The passive systems are also not so effective in case of parameters variation of matrix M and K.

Better results may be achieved using active methods which consist in additional energy supply to the system. These methods allow to solute the problem of contradictory requirements such as: efficiency of device operation, low level vibration, dynamic stability and stiffness. The passive methods are characterized by energy dissipation or periodical storage and next its giving up. The above considerations show that traditional methods of vibration control using passive elements are not effective. Such passive vibroisolation (used e. g. to building floors, service platforms for machines and devices, vehicles and driver seats) is not sufficiently effective because their vibrations are related to the range of low frequency. Vibroisolation efficiency (defined as a ratio of variable values in front of and behind vibroisolator) depends on difference of both vibroisolation system and natural frequencies of disturbances. It will get bigger according to the increase of mentioned above difference.

Active methods of vibration control

Active methods lead to structural or parametric modifications of vibration systems using additional energy source (this is why they are called active methods). The active systems may generate local forces related to the variables assigned to other system point source external control signals. Using active methods appropriately controlled external power source can supply or absorb energy due to determined control algorithm. Then the controller consisting of converter of physical value (movement, speed, acceleration, force, pressure etc.), amplifier and actuator (electric, hydraulic, pneumatic etc.) is connected to the device.

The actuator can produce a force that compensates the forces which account for vibrations. It also can change the system parameters in active way. As a result the vibration control problem may be considered as the problem of optimal control for the whole device.

Vibroisolation system as a system of automatic vibration control

The above considerations show that both vibroisolators and vibration eliminators are dedicated to restriction of kinematic parameters of vibroisolation plant (**VP**) or to decrease of dynamic forces transmitted to the plant.

Let consider e.g. problem of plant protection from external inputs caused by foundation movement. Between plant and foundation passive elements (elastic and damping) or active ones (servo-motors) are introduced. They are fed by external energy source. We may introduce here the vibroisolation plant $\boldsymbol{P}_v$, the vibroisolator **V** and ganging between them. The external inputs ***Q***(t) which react on **VP** are created by foundation movements, speeds and accelerations. They are treated as the components of 3-dimenensional (3D) vector of external inputs. The state of **VP** is determined by vector of both generalized coordinates **q**(t) and their derivatives which may be considered as 3D output vector. The dynamic inputs which influence the **VP** are the components of vibroisolator reactions, functions of state variables and input variables ***u*** = ***u***(***q, Q***). If we consider 3D vector of inputs, then the vibroisolation system (**VS**) may be presented in the form of block diagram as in Fig. 1.

Because of full compensation of external inputs is impossible, the problem of vibroisolation may be formulated as a problem of output variables of **VP** sustained in the given range. This way of formulating a problem allows to treat **VS** as system of automatic control. Thus in the nomenclature of vibroisolation theory such notions as input, output, plant etc. are used. As well as in **VS** and in control systems three notions may be introduced: plant, controller, feedback.

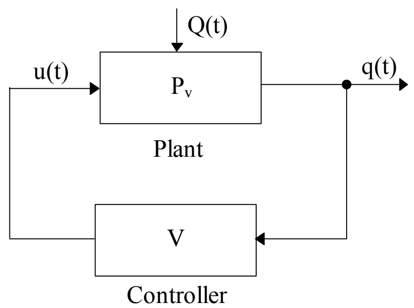

Fig.1. Vibroisolation system - block diagram.

Fig.2., which considers the system of movement vibroisolation with one step of freedom, explains mentioned above motions.

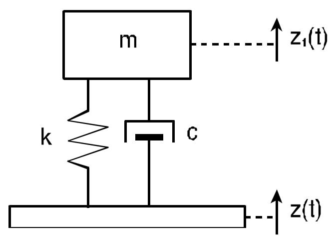

Fig.2. Passive system of movement vibroisolation - physical model.

The equation of this system may be written as:

$$m\ddot{z}_1 + c\cdot\left(\dot{z}_1 - \dot{z}\right) + k\cdot\left(z_1 - z\right) = 0 \qquad (2)$$

and next using Laplace transform:

$$z_1 = \frac{1}{m\cdot s^2}\cdot\left[\left(c\cdot s + k\right)\cdot\left(z - z_1\right)\right] \qquad (3)$$

Then the following block diagram of passive system of movement vibroisolation may be obtained:

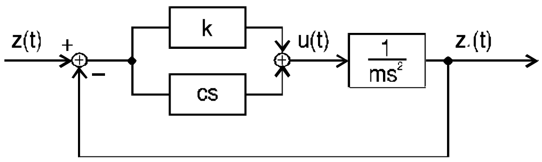

Fig.3. Passive system of movement vibroisolation - block diagram.

Analysis of the system operation allows to state that the **VP** with the mass of m is influenced by the command signal u(t). This signal takes the character of force and we call it as control force marked by F. This force is produced by vibroisolator for which the parameters of both foundation a **VP** are input signals. In general case the main system task is minimization of vibration movements for the plant $z_1 \Rightarrow 0$ (i.e. that the set value of vibration control system w = 0). The control error e(t) is a result of the difference of movement vibration of mass m and foundation ($e(t) = z_1(t) - z(t)) \Rightarrow 0$.

Following (2) the control force may be considered as average waved sum of both proportional forces to the relative movement $\delta = z_1 - z$ and relative speed $\dot{\delta} = \dot{z}_1 - \dot{z}$ (i.e. elasticity and damping forces). This force may be determined from the relationship below:

$$F_s = k\cdot\left(z_1 - z\right) + c\cdot\left(\dot{z}_1 - \dot{z}\right) \qquad (3)$$

The proportional coefficients are: the coefficients of elasticity k and damping c. They also play the role of vibroisolator parameters.

If we assume the criterion of vibroisolation quality (as e.g. minimal acceleration of plant vibration and minimal static deflection) and set input u(t) then the optimal vibroisolator parameters i.e. k and c may be chosen in such a way that the required characteristics of vibration transfer coefficient is obtained. This will be a compromise between the minimal value of T and static deflection limit z_{st}. In such way the earlier thesis that traditional passive systems are not useful in such applications is confirmed because then optimal operation in wide range of frequency and with variable inputs is required.

The vibroisolation problem is presented in more general way in Fig. 4. Then the control force F_s may be produced by vibroisolator with traditional passive elements (the spring and damper) or by hydraulic, pneumatic or electrodynamic servo-motor.

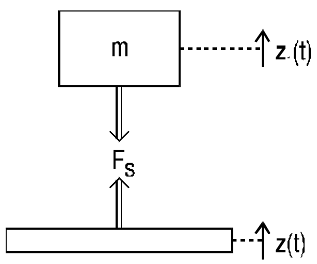

Fig.4. General model of vibroisolation system.

The vibroisolator operation consist in additional dynamic inputs (control forces F_s) generation. They allow to obtain the required parameters of **VP** vibrations (so called vibration field parameters). If such approach is assumed, vibroisolation problem may be considered as the problem of plant vibration control and the generated dynamic inputs as input signals. The above interpretation of **VS** part is useful for the problems of both vibroisolator systems formulation and solutions. It allows to use the methods of control theory to **VS** analysis and synthesis. The passive **VS** shown in Fig. 3 may be interpreted as control plant with PD controller. Its settings are the values of coefficients k and c (stiffness and damping). Because these coefficients take constant values for the spring and damper the controller settings also take same character and are well-chosen only for the considered case.

Classification of controlled systems for vibration reduction

The controlled systems of vibration reduction may be distinguished depending on the way of additional energy source use as follows:

- passive,
- semi-active,
- hybrid.

The active **VS** may be controlled by inputs or by vibratory field parameters. The signal change may take fluent or step character. The mechanical, pneumatic, hydraulic, electromagnetic or electrodynamic elements are used as executive systems. The choice of the kind of system is mostly based on technical and vibration reduction efficiency requirements. The above systems may be classified in more general way as analogue or switching ones. The switching systems may take relay or digital character. The first ones operate only on repetition and negation functions, the second on all logic functions. At present digital systems are widely used because of fast electronic and computational development.

The semi-active systems include passive elements but elastic and damping forces may be changed here. Such system require an external energy source with power of small value. The active part of hybrid systems operates in the range of low frequency and the passive one in higher frequency respectively.

Beside the above classification there is still another one which depends on both the kind of used signals and their processing i.e.:

- compensatory system of vibration reduction,
- adaptive system of vibration reduction.

The first ones are based on filtering and deal with the minimization of disturbance influence (the undesirable vibrations may be considered here as disturbance). The second are characterized by unequaintance of certain parameters due to the controlled process (these parameters take often non-stationary character because of disturbances operation which change the conditions of plant operation in great measure).

This classification is not a univocal one because of the fact that in the compensatory systems the adaptive controllers are used. They often change the parameters in respect to arising disturbance changes. The active methods of mechanical vibrations are theoretically considered but some practical applications also introduced (we shall discuss them in the next papers). The application of active methods of vibration elimination makes possible to overcome the restrictions which take place when passive methods are used. They are practically introduced in motorization industry, at first in control of mechanical vehicles suspensions. They are also applied to reduction of machines vibration level, devices, rotors, installations, power lines, buildings, communications means, etc.

Summary

Beside passive elements of suspension, the active ones (i.e. executive devices) are introduced in active **VS**. They supply the forces due to determined control algorithm in order to achieve the required vibration reduction. Both the active elements and chosen control algorithm application allows to influence the exploitation parameters which are assumed at the designing stage. Such parameters for vibration mechanical systems are: vibration amplitude, frequency range, vibration transfer coefficient and others. The continuous development of computer technique involves the application of special methods which require great power such as: adaptive control, fuzzy control and neural networks. At present many scientific centers all over the world make theoretical and simulation researches at the above algorithms application to vibration control of mechanical systems.

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