Vibration state of technical facilities

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Abstract. Approaches to the management of the vibration state of vibration machines and process flows are considered by introducing additional couplings into the structure of the mechanical system. Based on the structural diagrams, amplitude-frequency characteristics are obtained. The expressions for the minimum amplitude-frequency characteristic are found.

1. Introduction

Vibration processes are of great importance for process flows. On the one hand, vibrations and shocks stimulate the development of problems of vibration protection, vibration isolation, regulation and limitation of dynamic effects in relation to equipment, devices and instrumentation. On the other hand, vibration processes are used in various technologies, which makes it necessary to search and develop methods and means to control the vibration state of various facilities, to develop variants of design and technological solutions to ensure the required range of dynamic properties.

At different times, various aspects of this problem were regarded, related to the refinement of mathematical models, the introduction of new constraints, including the use of external energy sources, the use of automation elements and approaches based on the methods of the theory of automatic control, including direct control using computer technology. From the consideration of individual dynamic phenomena and processes, a definite tendency has emerged towards the study of the vibrational states of facilities, the formation and study of vibrational fields and methods of controlling complex dynamic states, which presupposes the further development of systemic methodological and scientific-methodological viewpoints.

In general, it becomes appropriate to consistently consider and understand the commonality of the problems of dynamics associated with the introduction of a concept of a the vibrational state of a technical facility and using approaches based on the employment of a certain set of basic or typical computational schemes that reflect the dynamic properties of facilities.

Systems analysis assumes consideration of the problems of vibration protection, vibration isolation, damping and vibration stabilization, maintenance of certain forms and levels of vibrations or vibration modes, dynamic state reflecting various aspects of machine dynamics, specific properties of technical facilities and requirements for their operating conditions. Vibration and shock effects are involved into many process flows widely used in practice. For their implementation, they require development of methods and means to create and maintain certain dynamic states and modes. The main thing, in our
opinion, is to define the notion of the vibrational state and to develop the notion associated with it - the notion of the vibrational field, ways and means of changing the properties of mechanical systems considered as a specific task of controlling dynamic properties (or states) of mechanical oscillatory systems in their various applications [1, 2].

There is a close relationship of the vibration state with the concepts of "technical state" and "dynamic state". By linking the vibration state with the concept of “technical state”, it can be argued that the vibration state is a subtype of the technical state. At the same time, the vibrational state can be considered as one of the sides of the dynamic state.

Let us note that the modern theory of vibration protection systems extensively uses the methods of the theory of automatic control. The structural approach to solving problems of analysis and synthesis of oscillatory systems has significant advantages from the standpoint of engineering applications of the theory. It allows one to visually assess the impact of various changes in the structure of the oscillatory system on its dynamics and, in addition, apply developed analytical tools.

High requirements to the dynamic properties of mechanical oscillatory systems are in some cases difficult to satisfy, relying on the usual armory of technical means. Active vibration protection systems, which are essentially special automatic control systems, are more effective.

2. Results and discussion
Active couplings introduce additional complications into the familiar scheme, since they include such elements as converters, amplifiers, etc. If the structural links and the couplings between them in the usual passive vibration protection system are considered natural (basic), then the inclusion of any other links in its structure can be viewed as a process of imposing additional couplings. Ways to improve and change the dynamic properties based on the use of additional inertial elements with motion conversion mechanisms (inertial mechanisms) are considered.

Let us consider two main approaches [3-7].
1) phase shift control in power and kinematic excitation circuits for those situations when it comes to technological excitation of oscillations;
2) management of the dynamic properties of the object based on changes in frequency characteristics.

It is possible to change the vibrational state and to manage the processes of forming the required spectrum of dynamic properties by using additional couplings of active and passive nature used and introducing them into the initial systems.

Let us refine the original standpoints. Any mechanical oscillatory system consisting of a classical set of elements (mass-inertial elements, springs, dampers) can be assigned a dynamically equivalent structural diagram in the form of an automatic control system in which external perturbations are represented as input signals, and the output signals are the parameters of the vibration state. Springs, dampers, and mass-inertial elements will take the form of elementary links - amplifying, integrating and differentiating (Figure 1).

Let us define the corresponding couplings. These include, in accordance with the theory of automatic control, in the first place, direct and reverse ones. In systems with several degrees of freedom, cross-couplings emerge. These relationships make up a conventionally called classic set of relationships. The correspondence of the computational schemes in the form of mechanical oscillatory systems and structural diagrams that are dynamically equivalent to automatic control systems can be seen in Figure 1.

The introduction of additional couplings implies a change in structure. This is achieved by introducing a certain form of parallel branches of links. So, introducing certain links – amplifying and differentiating – in accordance with the laws of transformation of structural schemes, we will see that springs and dampers emerge in a computational scheme – a mechanical oscillatory system – that are interconnected in a certain way. Using the concept of transfer function, it is possible to show the possibility of building a new class of oscillatory mechanical systems that go beyond the classical set. These additional couplings may have transfer functions in the form of fractional rational expressions.
Simplifying the form of the transfer function, you can build a number of computational schemes for mechanical oscillatory systems as they become more complex.

Figure 1. Schemes of the active vibration protection system: a is the schematic computational diagram; b is the equivalent structural diagram; DSV is the force impact sensor; DKV is the kinematic impact sensor; L is the motion conversion mechanism.

The possibility to practically implement these additional relationships requires a separate study. In some cases, additional couplings are implemented by passive means (mechanisms and their individual fragments). In other cases, it is necessary to use more complex links capable of processing information, to introduce forces through the use of external sources of energy.

This approach makes it possible to separate vibration protection systems, in particular, into active and passive ones. It is assumed that the introduction of additional couplings can significantly expand the possibilities of changing the dynamic state of systems both in the form of a vibrational field and through frequency characteristics. The latter are more convenient when using the analytical tools of the theory of automatic control (TAC), so the further presentation will be associated with consideration of the amplitude-frequency characteristics (AFC), transfer functions, transients.

It is shown that in some cases the problem of this introduction of constraints can be reduced to the problem of filtering [7-12]. So, with a kinematic perturbation for the simplest vibration filter, the expression for the amplitude-frequency characteristic is:

$$A(\omega) = \left[ \frac{(c - Lo^2) + k^2o^2}{c - (m + L)o^2 + k^2o^2} \right]^{1/2}$$

where $m$ is the mass of the protected object; $L$ is the reduced mass of the inertial element; $c, k$ are stiffness and damping coefficients; $\omega$ is the frequency.

The research results show that in the superresonance region there is a minimum of expression:

$$A_{\text{min}}(\omega) = \left[ k^2 / (k^2 + ma^2) \right]^{1/2}.$$  

The frequency of the dynamic damping $\omega_d = \sqrt{c / L}$ is independent of the magnitude of the mass of the object (for systems without friction). This property of the mechanical filter is used for auxiliary adjustment (invariance).

Taking into account the possibilities of additional inertial elements, the conditions of invariance for oscillating systems of the following form were justified:

$$d_{11}(p)x_1 + d_{12}(p)x_2 + \ldots + d_{1n}(p)x_n = e_{11}(p)\xi_1 + \ldots + e_{1n}(p)\xi_n$$

$$d_{n1}(p)x_1 + d_{n2}(p)x_2 + \ldots + d_{nn}(p)x_n = e_{n1}(p)\xi_1 + \ldots + e_{nn}(p)\xi_n$$
where \( d_{sj}(p)=a_{sj}p^2+k_{sj}p+c_{sj}; \) \( e_{sj}(p)=m_{sj}p^2+b_{sj}p+r_{sj} \) \((s=1,\ldots,n, j=1,\ldots,n)\) are some polynomials of the operator \( p=\frac{d}{dt}; \) \( x_1, x_2, \ldots, x_n \) are generalized coordinates of the system; \( \xi_1, \xi_2, \ldots, \xi_n \) are kinematic perturbations; \( c_{sj}, r_{sj} \) are stiffnesses; \( k_{sj}, b_{sj} \) are damping coefficients; \( a_{sj}, m_{sj} \) are mass-inertia coefficients. The parameter \( m_{sj} \) reflects the reduced moments of inertia of the motion conversion mechanisms.

Linear oscillatory systems with constant parameters have a number of features that simplify the tasks of analysis and synthesis. When considering a system with lumped parameters in the general case of non-harmonic perturbation, it is possible to implement modes with \( n \) dynamic damping modes, provided the impact is decomposed into the corresponding Fourier series. However, with a change in the frequency of impact, it is necessary to adjust or introduce nonlinear elements. To do that, it is required to consider in detail and take into account the physical features of specific implementations in the class of dynamic damping systems. If it is nonlinearity that we have in mind, then, first of all, attention should be paid to nonlinear forces, which include dry friction forces, centrifugal and gyroscopic ones; among the specially introduced nonlinearities, we would like to note stops or restrictions, sensitivity thresholds and stagnation zones.

Free and forced oscillations are considered taking into account the forces of dry friction in the screw mechanism of motion conversion in comparison with the results of numerical studies using a computer.

3. Conclusion
The experience gained in the practice of solving problems of vibration protection shows that the nonlinearity of the characteristics of the system elements plays a significant role, which implies a preliminary thorough formation of the type and structure of the initial so-called basic models. The nonlinear properties of elastic elements are considered. The behavioral features of systems with “soft” and “hard” frequency characteristics are determined. A similar approach is being developed in terms of taking into account the forces of dry friction accompanying the work of the elements of a movable joint formed in a screw pair of a motion conversion mechanism; the features of the implementation, shape and stability of the dynamic damping modes are shown.

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