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DYNAMICS OF VERTICAL ROTOR SYSTEMS

ANNOTATION

of the dissertation for the degree of
Philosophy Doctor (PhD) in the specialty
6D060300 – "Mechanics"

Relevance of the research topic. Today there are numerous works on the study of the nonlinear dynamics of rotor systems. But despite the wide distribution of such systems, their dynamics has not been sufficiently studied due to the difficulties associated with the need to take into account the combined action of factors such as the effect of a liquid upon partial filling, external non-conservative forces, linear and angular imbalances.

In the design of rotary machines, one of the most important mechanical components described by nonlinear models, which determines the performance and reliability of the system, are elastic supports, in our case, rolling bearings act as elastic supports. Ignoring the nonlinear properties of bearings degrades the results of both qualitative and quantitative analyzes of rotor systems. This is due to the fact that in the analysis of linear rotor systems with rolling bearings, an approximate assessment of the stiffness and damping properties of bearings is most often used, when, in reality, the stiffness of the bearing significantly depends on the load, i.e. on the operating mode of the rotor system, on the geometry and size of the bearing clearances, on the size of the fit of the inner and outer rings in the bearing.

In a large variety of rotary machines, a significant part is occupied by rotary systems with cavities containing liquid (shafts of liquid-cooled turbomachines, liquid gyroscopes, centrifuges, separators, etc.). Rotors with cavities partially filled with liquid are non-conservative systems. The reason for the non-conservatism of the system and the occurrence of self-oscillations in it is the liquid that partially fills the rotor cavity. The influence of the liquid reaction force on the movement of the system is in many respects similar to the behavior of the internal friction force, that is, it converts the energy of rotation of the shaft into the energy of its oscillations behind the critical speed of the rotor, that is, it contributes to the emergence of instability. An analysis of the experimental work shows that under certain conditions, the liquid in the rotor cavity is the main source of the occurrence of unstable modes of motion of the system. The physical reason for this is the violation of the state of equilibrium between the centrifugal acceleration of liquid particles and the pressure gradient acting in the opposite direction.

When designing and evaluating the vibration characteristics of rotary machines, it is necessary to take into account the vibrations of the body, i.e. consider the dynamic system "rotor-fluid-foundation" as a whole. In many theoretical and practical works on the dynamics of rotor systems containing a liquid, only oscillations of a rotor with a liquid are considered, and the foundation is considered

stationary. This assumption leads to significant errors in assessing the dynamic and kinematic characteristics of the rotor system as a whole. Experimental studies of such dynamic systems as rotor systems show the importance of taking into account the vibration of the foundation and the need to develop measures to reduce them.

It investigates the dynamics of a rotor with a cavity, partially filled with liquid, installed vertically on an elastic foundation, rotating on rolling bearings. In connection with the increased requirements for the accuracy of rotation and an increase in the rotational speed of the rotors, it becomes necessary to take into account the elastic properties of rolling bearings. The most significant factor influencing the dynamics of the rotor here is assumed to be nonlinear stiffness properties of a rolling bearing, when, in particular, radial compliance arises due to deformations of the rolling elements on the raceways at the contact points.

New trends in centrifugal technology have led to the emergence of various designs of centrifuges, some of which are difficult to assess quantitatively and qualitatively using known methods. There are many scientific works, patents and copyright certificates on this topic, where methods of mechanical separation of solids from liquids by centrifugation are proposed.

In this work, we investigate the spatial motion of a particle and the time of its sedimentation in a vertical centrifuge, for a complete assessment of the process of separating solid particles from a liquid, it is taken into account that the angular velocity of rotation of the rotor, glasses and the angle of their inclination are variable quantities depending on time, which also complicates the search. general solution of differential equations of particles and mechanical system. Based on several previously published works and publications, an analytical research and evaluation methodology has been developed that is used to describe the separation and sedimentation processes for a rotary plant used for slurry treatment.

Purpose of the work: development of generalized dynamic models of nonlinear rotor systems, taking into account the interrelated vibrations of the “rotor-fluid-foundation” system, as well as the study of the process of separation of solid particles in vertical rotor systems. The following tasks are solved in the work:

– creation and research of a generalized dynamic model of the “rotor-liquid-foundation” system, which allows to study the dynamics of interconnected movements of vertical rotors with a liquid in the presence of nonlinearity and the foundation of the installation;

– development of an analytical technique for calculating the amplitudes of natural nonlinear oscillations and critical frequencies of vertical rotor systems with cavities partially filled with liquid;

– development of an analytical technique for calculating the amplitudes of forced vibrations and resonant frequencies of vertical rotor systems with cavities partially filled with liquid;

– development of a methodology for calculating the main characteristics of the separation process of solid particles in vertical rotor systems.

Research methods:

– basic fundamental laws of theoretical mechanics and mechanics of continuous media;

– methods of the theory of linear and nonlinear oscillations;

– classical high-precision numerical methods for solving nonlinear differential equations.

Scientific novelty of the work. This paper presents a comprehensive solution for a rotor system with a cavity partially filled with liquid, installed on an elastic foundation, rotating in rolling bearings with a nonlinear characteristic. With the help of Jacobi elliptic functions, solutions of nonlinear rotor systems characterized by the Duffing equation are found, natural and forced oscillations of the system are investigated. The frequencies of natural, forced and self-oscillations of nonlinear systems “Rotor - liquid – foundation” are determined. A generalized dynamic model of the “Rotor-liquid-foundation” system has been developed, which makes it possible to study the interrelated vibrations of vertical rotors with a liquid, taking into account the movement of the foundation and the nonlinearity of the supports. For the first time, an analytical technique has been developed for calculating the amplitudes, critical and resonant frequencies of natural and forced nonlinear oscillations of vertical rotor systems, the cavities of which are partially filled with liquid. For the first time, a method was developed for calculating the main characteristics of the separation process of solid particles in vertical rotor systems.

Scientific provisions for the defense:

– generalized dynamic and mathematical model of the "rotor-liquid-foundation" system, which allows to study the dynamics of interconnected movements of vertical rotors with liquid in the presence of nonlinearity and the foundation of the installation;

– analytical method for calculating the amplitudes of natural and forced vibrations, critical and resonant frequencies of vertical rotor systems with cavities partially filled with liquid in the presence of nonlinearity;

– methodology for calculating the main characteristics of the separation process of solid particles in vertical rotor systems.

Reliability and validity of scientific provisions, conclusions and results of dissertation work. When constructing a dynamic model of the "solid-liquid" system, the Lagrange equations of the second kind and the Euler hydrodynamic equation are used. The non-linear characteristic of rolling bearings is modeled in accordance with the Hertzian contact theory. To find solutions to nonlinear differential equations of motion of a rigid body, the method of complex amplitudes, the method of harmonic balance and harmonic linearization (for equations of Duffing type), etc. are used. To determine the amplitude of forced and natural vibrations, subharmonic and ultraharmonic (or superharmonic) vibrations of the rotor and foundation, methods of the theory of nonlinear vibrations, the theory of higher algebra are used.

Theoretical and practical significance of the research. The results of the work are the scientific basis for improving research in the nonlinear dynamics of vertical rotor systems with a cavity partially filled with liquid and make it possible to carry out pre-design computational experiments with the lowest cost of funds,

give qualitative and quantitative characteristics and reduce the design time for new vertical rotor machines, improve their quality and reliability. The practical significance of the presented work is aimed at studying the effect of nonlinearity on the production process of rotary devices, as well as studying the dynamics of continuous vertical centrifuges used in the purification of oil from other components, the separation of valuable and valuable elements from heavy oil, paraffin from light carbohydrates, thanks to which it is possible to solve many issues, such as increasing the fluidity of oil through pipes, increasing the service life of equipment and pipelines of an oil refinery, improving the ecological state of the regions, assistance in solving social issues.

The relationship of this work with other research works. This work was carried out within the framework of the project of the program of grant funding for applied research in the field of Energy and Mechanical engineering "Design and study of the dynamics of rotary machines for the separation of multiphase liquid media, taking into account the nonlinearity of supports and the action of a high-frequency electromagnetic field" (2020-2022, AP08856167).

Approbation of work. The main results of the work were reported at Department of Mechanics Al-Farabi Kazakh National University under the guidance of Professor A.B. Kydyrbekuly, Mathematics Research Center at Keele University (United Kingdom) under the direction of Professor J.Kaplunov in 2019, Ocean and Mechanical Engineering Department in the Florida Atlantic University (Boca Raton, USA) under the guidance of Professor I. Elishakoff in 2020 on scientific seminars, as well as at following scientific and practical conferences: International Conference on "Modern Achievements of Science and Education" (Paris, France, 2013), 1st International Conference on Mathematical Methods & Computational Techniques in Science & Engineering (Athens, Greece, 2014), XII International conference on the Theory of Machines and Mechanisms (Liberec, Czech Republic, 2016), "Priority tasks and strategy of technical sciences" (Togliatti, Russia, 2017), "Actual problems of computer science, mechanics and robotics. Digital technologies in mechanical engineering" (Almaty, Kazakhstan, 2018), XIII International conference on the Theory of Machines and Mechanisms (Liberec, Czech Republic, 2021) and at the second international symposium "Mechanics of the Future" dedicated to the 90th anniversary of Academician U. A. Dzholdasbekov (Almaty, Kazakhstan, 2021).

Publications. The main scientific results of the dissertation are reflected in 12 published works, including 3 articles in scientific journals included in the list of recommended by the Committee for Control in Education and Science of Ministry of Education and Science RK for the publication of the main results of scientific activity; 4 articles in periodical foreign scientific journals and proceedings of international conferences indexed by the Scopus database, including 2 articles with a non-zero impact factor; 6 articles in the proceedings of foreign and domestic scientific conferences and 1 patent.

Personal contribution of the author. The main research results presented in the thesis were obtained by the author independently.

The structure and scope of the dissertation work. The dissertation work consists of an introduction, three sections, a conclusion, a 105 references. The total volume of the thesis is 121 pages, including 51 figures and 3 tables.

The main content of the dissertation. The introduction highlights such issues as the relevance of the topic of dissertation research, the main purpose of the work, object, subject and research methods, scientific novelty, scientific and practical significance of the dissertation work.

In the first section, the current state of the problem under study is described and a review of works and literature in the field of nonlinear oscillations of a rigid body, the cavity of which is partially filled with liquid, is given. In addition, a dynamic model of the rotor was built, the cavity of which is partially filled with liquid, taking into account the nonlinearity of elastic supports installed on a movable foundation, and an analysis of nonlinear natural and forced oscillations of the "rotor-liquid-foundation" system was carried out.

In the second section, a dynamic model of a rotor installed on a movable foundation is built, taking into account the nonlinearity of elastic supports, methods based on the method of Jacobi elliptic functions are proposed, which allow to determine with high accuracy the amplitudes and frequencies of natural and forced nonlinear oscillations of the "rotor-foundation" system, and a comparative analysis by well-known classical methods.

In the third section, an analysis of the separation and sedimentation of solid particles in multiphase media with a low concentration of a centrifuge separator for crude oil purification, which is one of the applied examples of the considered rotary system in production, is carried out; important results are obtained.

In the conclusion, the main results and conclusions obtained in the dissertation work are presented.