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Methodology for modeling and determining the frequency response trace of robotic composite structures

***Abstract**. The methodology of modeling and determining the natural frequencies of oscillations of a robotic structure made of composite material including motors, bearings, gears, and ratio changers is considered. The vibration forms of a multi-stage bench for semi-natural modeling from composite material determined using the finite element method are presented. The developed methods allow the study of complex robotic systems of homogeneous and composite materials.*

Streszczenie.** Rozważana jest metodologia modelowania i określania naturalnych częstotliwości drgań konstrukcji robotycznej wykonanej z materiału kompozytowego, w tym silników, łożysk, kół zębatych i zmieniaczy przełożeń. Opracowane metody pozwalają na badanie złożonych systemów robotycznych z materiałów jednorodnych i kompozytowych. **Metoda modelowania i określania częstotliwości drgań kompozytowych konstrukcji robotyki

Keywords: composite materials, robotic systems, stands, finite element method, natural frequencies.
Słowa kluczowe: materiały kompozytowe, systemy robotyczne, stojaki, metoda elementów skończonych, częstotliwości naturalne.

Introduction

Robotic stands are widely used in mechanical engineering, instrument making, shipbuilding, etc. At the same time, methods for calculating the natural frequencies of oscillations of these structures and scientific works are not enough. The study and determination of the natural frequencies of vibration of structures having moving parts is very important for the performance of these mechanisms. The movement of the channels of such structures is reduced to a high-speed movement of the channels, which leads to a significant loading of the robotic system by inertial forces. Dynamic loads significantly affect the operability of these structures, since the range of variation of the move frequencies of moving parts has a wide range of variation and the first frequencies of natural vibrations must have high values, which is achieved by a significant tightening of the structure and this leads to an increase in the weight of moving parts and, as a consequence, to an increase in inertial loads. Therefore, when designing robotic structures, it is necessary to achieve optimal stiffness or reduce the inertial characteristics of moving parts. The highest specific strength is possessed by modern composite materials, which allow varying the stiffness characteristics of the material depending on the location of the warp and weft in the multilayer composite structure.

Recent years have been characterized by intensive development and use of structures made of structural materials. Features of the processing technology of composite materials to create ones with a given orientation of properties are the following: high specific characteristics of stiffness and strength distinguish composites in the family of structural materials [1, 2, 3].

At the same time, one of the factors determining the operability of structures is the strength and stability of its dynamic parameters. Exceeding permissible tensile strengths and catastrophic changes in structural elements lead, as a rule, to depletion of the bearing capacity of structures.

Recently, much attention has been paid to the behavior of structures under dynamic effects [4, 5]. With dynamics of loading, we can significantly reduce the weight of the structure and increase their technical and economic indicators.

The desire to maximize the advantages of composite materials compared with other structural ones and metals requires the improvement of research methods.

A comprehensive study of the bearing capacity of structures made of composite materials is a complex scientific and technical task, require the implementation of a large amount of theoretical and experimental research in the process of development and manufacture [5, 6, 7]. One of the methods that determine the solution to this problem is to improve research methods by creating algorithms and programs and adapting existing developments that allow, within the framework of a single methodological approach, detailed analysis of structures made of composite materials.

Theoretical Basis

We consider the modeling procedure of a robotic system using the example of a multi-stage dynamic stand for semi-natural modeling (stand). The stand under consideration has three degrees of freedom, allowing simulating the movement of the tested product in six degrees of freedom. The spatial movement of the test product is provided by the directional fork rotating the product around the vertical axis, the pitch channel rotating the product around the horizontal axis of the drawing plane and the roll channel allowing the product to rotate around the axis perpendicular to the plane of the drawing, that is, around the axis of the pitch ring shown in the Figure 1. Now we are going to consider the methodology of the location of the basis of the multilayer composite material in the design of the stand and determine the natural frequencies of vibration there. The use of composite material with high specific strength has not yet been used in the manufacture of stands. At the same time, composite material is an underestimated material in the development of stands and it is necessary to consider its use during the manufacture. The specific strength of the composite material is 1.5 times higher than the materials currently used in the manufacture of stands. The main disadvantage is its low stiffness in a direction that does not coincide with the basis of the composite. At the same time, it is multilayer; therefore, by changing the direction of the base of the composite in a multilayer structure, sufficient structural rigidity can be achieved.

Solving the problems of determining the natural frequencies of oscillations of these complex structures as the stand under consideration is a difficult task. The solution of the problem by the analytical method is not possible, therefore, the most suitable for solving this problem is the numerical method. It allows not only obtaining the eigenvalues and eigenvectors characterizing the natural frequencies and vibration modes of these structures [8, 9].

The problem is solved by the finite element method by the most common numerical method, which allows solving a wide class of problems, including structures made of composite materials [10, 11].

The stand has gears, bearings, and ratio changers in its design, which are inadequately approximated by finite elements [12]. Therefore, the gears were replaced by a system of rods in terms of stiffness equal to the rigidity [13]. A similar procedure was used to model bearings and gearboxes [14].

The stand was also approximated by three-layer composite shells with external bearing layers and a filler between the bearing layers [3, 6]. The filler made of a light material, such as foam, perceives only shear stresses and prevents the convergence of bearing layers. The characteristics of the multilayer composite material were determined based on the specified characteristics of its composite layers. In the arrangement of the layers of the composite material the location of its base is important. The base of the composite should be located along the paths of maximum stresses to obtain the most rigid structure of the composite. To identify the paths of maximum stresses as a first approximation, in this work, at the first stage, we calculated a test bench made of a homogeneous material and determined the paths of maximum stresses [15].

At the second stage, the base made of composite material was located along the obtained trajectories of maximum stresses, and the bench was already counted from the composite. Since the composite material has weak shear characteristics, the location of the base was adjusted in accordance with the results of the second calculation to obtain the optimal location of the multilayer composite structure. Thus, the optimal design of the stand was modeled from a composite material and the frequency characteristics of the stand were determined.

Methods

At the first stage, the stand is modeled by double-curvature shells, three-layer shells, and rods [16, 17]. The second stage is devoted to the analytical determination of the stiffness characteristics of ratio changers, bearings, and gears in accordance with the developed programs [18, 19]. Then we model, for example, sliding bearing, using the bar structure of the corresponding bearing stiffness.

Next, we establish the geometric and physico-mechanical characteristics of the corresponding elements of the stand. The next stage is devoted to the approximation of the stand by finite elements [20].

The procedure for determining the natural frequencies of the oscillations of the stand was as follows: equation of motion of a structure based on the Lagrange equations in a finite element formulation is the following [4]:

$$[M]\{\ddot{q}\} + [K]\{q\} = \{Q\}. \quad (1)$$

Here $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{Q\}$ is the vector of external forces, $[q]$ is the generalized movement, and dot over letter means time derivative.

We define the solutions of equation (1) in the following form: $q = C_1 sin(\omega t + \varphi) + C_1 cos(\omega t + \varphi)$, where ω, t, φ is the frequency, time and phase shift, and equating the vector of external forces to zero. We obtain an equation for determining the natural vibrations of the structure:

$$([M]\{\omega^2\} + [K])\{q\} = \{0\}.$$

The determination of the natural frequencies and vibrational modes of the structure is reduced to the determination of the eigenvalues and eigenvectors of the matrix $[M]^{-1}[K]$.

An important factor in determining the natural frequencies of vibration by the finite element method is the convergence or reliability of the calculation results. It was determined by reducing the size of the finite element mesh. In this study, the number of elements was 132100. With the number of finite partition elements 150211, the results differed by no more than 3%.

When modeling structures with moving parts, it is important to avoid the intersection of them, which is unacceptable. Modern computer-aided design systems related to "heavy" ones have kinematic modules that allow simulating the movement of robotic systems, avoiding the collision and intersection of moving systems of the considered structures. In this study, the movement of a multi-stage dynamic stand was simulated, which eliminates the collision and intersection of moving structural elements at the design stage.

Results

The determination of natural vibration frequencies of structures containing such elements as bearings, gears, ratio changers, complex surfaces of double curvature, and multilayer composite materials is a difficult task for analytical solutions, therefore, this problem is solved mainly numerically using modern computer-aided design systems. One of the most suitable numerical methods for solving these problems is the finite element method. But in this case, the approximation and accounting of bearings, gears, and ratio changers is a difficult task. A detailed approximation of these elements leads to an unjustified increase in the number of finite elements.

Therefore, to solve this problem, it is necessary to use additional approaches. In modern computer-aided design systems, such as, for example, ANSYS or Solid Works, bearing is approximated in the form of a system located in the plane, while bearing at its own vibration frequencies operates in three directions, and its spatial stiffness must be taken into account. The method of accounting for such structural elements is described above. The determination of the natural vibration frequencies of dynamic stands is carried out in order to prevent resonance phenomena that occur, as it is known, when the forced and natural vibration frequencies coincide.

Fig. 1 shows the approximation of the stand by finite elements and first oscillation frequency of the stand made of composite material. There is front and top view.

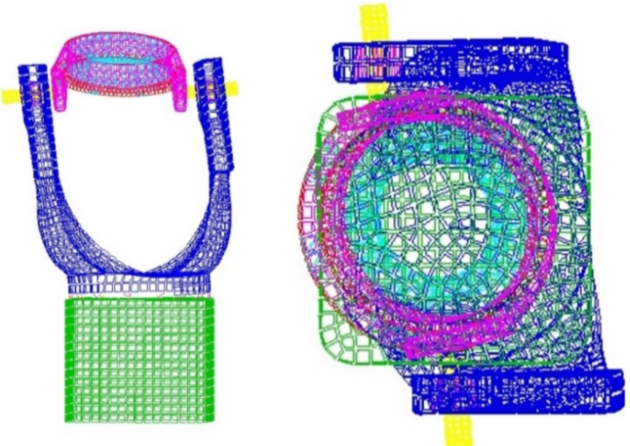

Fig.1. Approximation of the stand by finite elements. First oscillation frequency of the stand. Front and top view

As it can be seen from the Figure 1, the connection of the base with the course fork of the stand is performed using a rod system for stiffness corresponding to the ring gear located at this place. Similarly, the pitch and roll ring of the stand is located on the bearing assembly replaced in the model shown in the Figure 1 by a rod system for the rigidity of the corresponding bearing assembly. In addition, in the stands, to create more effort on the modules of the heel, pitch and heel rings, ratio changers are used, the stiffness of which is taken into account in the system under consideration with the simulation of the core system according to the stiffness of the corresponding one of the ratio changer.

There is the developed in State Scientific Research Institute of Aviation Systems (GosNIIAS) three-layer dynamic stand for semi-natural modelling in the Figure 2

Fig. 2. Three-layer dynamic stand for semi-natural modelling (GosNIIAS)

There is the tangage channel drawing in the Figure 3.

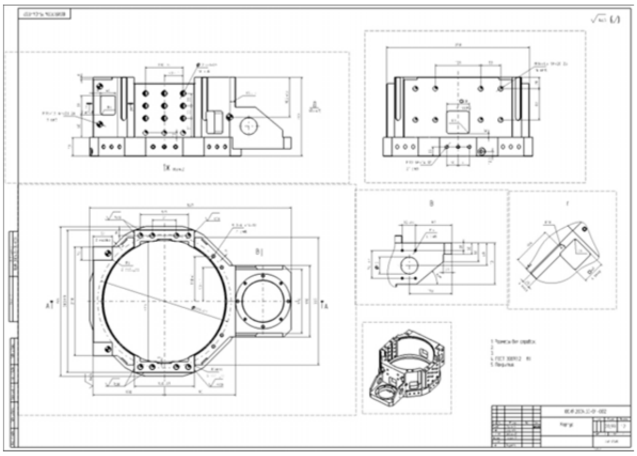

Fig. 3. Tangage channel drawing

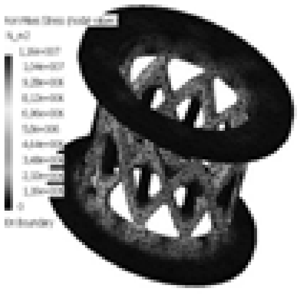

Fig. 4. Stress-strain state of the roll channel

Figure 4 shows the result of calculating the stress-strain state of the roll channel under the operational loads.

Conclusions

Stands for semi-natural modeling are designed to simulate flight characteristics in ground conditions and allow manipulating the device under study in six degrees of freedom.

Modeling a structure containing double-curvature shell structures, three-layer structures, which are load-bearing layers filled with polystyrene or other lightweight material located between them, which prevents the approaching layers from coming together and mainly perceives shear stresses is a difficult task. To solve these problems, it is necessary to know the design capabilities of automated systems. In addition, the presence in the design of such elements bearings, gears, ratio changers, etc. requires the development of a methodology for taking into account such details when determining the frequency characteristics of the complex structures.

A technique has been developed for modeling and approximating structures made of multilayer composite material as applied to stands with bearings, gears, and ratio changers. A methodology has been developed for modeling and approximating structures from a multilayer composite material as applied to robotic stands with bearings, gears, and ratio changers. A technique has been developed for placing the base of the composite material along the lines of maximum stresses to create maximum structural rigidity. Also, the procedure for calculating the natural vibration frequencies and for modeling the stand from a multilayer composite material has been developed. In addition, using the developed model of the stand in the kinematic module of the automatic design system and kinematic analysis of the behavior of the robotic stand during their movement was performed. The study avoids the intersection of parts of the stand during movement and their collision. The methodology implemented in the work allows studying complex structures containing bearings, gears, and ratio changers in dynamics, to determine the natural vibration frequencies that are important for studying of these structures.

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