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doi:10.15199/48.2021.08.12

Modeling and analysis of the stress-strain state of robotic systems

Abstract. *The paper considers the methodology for modeling and analyzing the performance of a robotic system: multi-stage semi-natural simulation stand designed to simulate the flight characteristics of guidance systems in ground conditions. The results of the calculation showed that the use of a composite material gives advantages over the traditionally used materials for the manufacture of such stands: magnesium alloys, due to the high specific strength of the composite material.*

Streszczenie. *W artykule rozważono metodykę modelowania i analizy działania systemu robotycznego: wieloetapowe półnaturalne stanowisko symulacyjne przeznaczone do symulacji charakterystyk lotu systemów naprowadzania w warunkach naziemnych. Wyniki obliczeń wykazały, że zastosowanie materiału kompozytowego daje przewagę nad tradycyjnie stosowanymi materiałami do produkcji takich stojaków: stopami magnezu, ze względu na wysoką wytrzymałość właściwą materiału kompozytowego. (**Modelowanie i analiza stanu naprężenie-odkształcenie systemów robotycznych**)*

Keywords: composite materials, complex designs, gearboxes, bearings, gear rings, finite element method, stress-strain state.
Słowa kluczowe: materiały kompozytowe, złożone konstrukcje, przekładnie, łożyska, pierścienie zębate, .

Introduction

Until now, composite materials, which are more and more widely used in aviation and provide significant advantages over traditional materials, have not been used in the design and production of multi-stage dynamic stands, moreover, static analysis and analysis of stands made of composite materials under the action of loads and various arrangements of the layers of the composite. Experience shows that composite materials, due to their high physical and mechanical properties, can improve the technical characteristics of the products being developed [1, 2].

Theoretical Basis

As applied to multi-stage dynamic stands, the composite material will reduce the inertial characteristics of the stand, which are one of the main parameters affecting the efficiency of its operation. In this regard, study, design and calculation of multi-stage dynamic stands made of composite materials are an important and relevant topic.

The object of development (research) is the development of methods for the design and analysis of multi-stage dynamic stands for semi-natural modeling from composite materials on the basis of the developed methodology of modeling, design, static calculation and analysis of stands [3]. The developed methodology and algorithms, consisting in the given sequence of modeling on high-level computer-aided design (CAD) systems, static calculation and analysis, as well as taking into account the influence of the location of the material on the strength characteristics of multi-stage dynamic stands of semi-natural modeling, will allow solving the following problems:

- to model a stand made of composite materials on high-level CAD systems;
- to investigate the stress-strain state of stands made of composite materials;
- to determine the frequency characteristics of the stand;
- to take into account the influence of the arrangement of layers of composite material on the strength and stiffness characteristics of the stand;
- to investigate the kinematic behavior of the stand.

Modeling, design and analysis of the stand behavior were carried out using computer-aided three-dimensional interactive application (CATIA) CAD and its kinematic module [4, 5].

Methods

We consider design problems and methods for solving them. The complexities of designing the structure of a multi-stage dynamic stand lie in the presence in the structure of shells of double curvature with edges described by various curves, as well as in the conjugation of such shell elements with adjoining or adjacent shell elements, which also have complex shapes. In addition, the use of composite materials further complicates the design of a multi-stage dynamic stand. This is due to the need to consider the issues of conjugation of homogeneous and composite materials, the optimal arrangement of composite layers in terms of strength and stiffness characteristics and the technology of manufacturing products from composite materials. In connection with the less rigid modular characteristics of the composite material, it is also necessary to provide for the filling of the free space of the shell elements with a cellular (honeycomb) or foam structure in order to obtain a three-layer shell having higher stiffness characteristics as compared to a hollow shell [6, 7].

Thanks to the wide capabilities of CATIA CAD, which has one of the most advanced design programs for complex surfaces, it is possible to accurately align complex shells using the smoothing procedure for polynomials describing complex spatial curves and surfaces.

The second problem arising in the design of a dynamic stand is a preliminary assessment of the operability and analysis of the behavior of the stand. The kinematic CATIA CAD allows evaluating at the design stage the spatial movement of all channels of the stand and gearboxes and eliminating possible mutual intersection of channel parts during movement [8]. The kinematic module simulates the spatial motion of the stand, and the law of motion of each channel is set independently of each other using a variety of curves or using analytical equations. In this case, the laws of motion must be consistent. The coordination of the laws of motion is verified experimentally [9].

The third stage of design consists in approximating the stand structure by finite elements and conducting a study on static loads and determining the frequency characteristics of the stand. These studies in this work are carried out using the computational module CATIA, the finite element method. The calculation module CATIA has an extensive library of finite elements, including layered finite elements that allow specifying an arbitrary number of layers with different physical and mechanical characteristics and a different angular position of the composite material base. At the same time, three-layer shells, i. e. shells with rigid bearing upper and lower layers and material with the characteristics of foam or other lightweight aggregate between them, which mainly serves as an obstacle to the approach of the outer layers and the perception of shear stresses, are investigated according to different laws [10, 11].

When studying a three-layer shell structure, it is necessary to take into account the compression of the filler, the nature of the distribution of shear characteristics over the thickness. Therefore, the problem arises of specifying the characteristics of the composite material corresponding to the actual behavior of the three-layer material under the action of loads [12, 13].

The design of three-layer shells and plates, of which the structure of a composite dynamic stand consists, includes the following procedures [7, 10]:

- determination of the reduced stiffness, strength and mass characteristics of the filler;
- determination of the stress-strain state of the plate or shell and testing it for strength;
- calculation of local stability of structural elements (plates and shells) and verification of the fulfillment of the conditions for maintaining the bearing capacity in case of loss of stability;
- satisfying the criterion of bond strength between the filler and bearing layers;
- determination of the thickness of the bearing layers.

The design of three-layer structures includes many variable parameters, therefore, we present the proven rules [7] that allow to reduce the number of variable parameters:

- reinforced filler and base of the bearing layers should, if possible, be positioned in proportion to the effective stresses;
- size and shape of the cell of the discrete filler should be located in such a way that the local buckling of the cell corresponds to the plastic region of the carrier layer. This allows maintaining the shape of the surface of the structure. This condition is met when the ratio of the cell size to the thickness of the carrier layer is not more than 25;
- relative stiffness of the filler and base layer must be equal.

The most suitable for modeling the stand structure is a multilayer shell three-four-angle finite element (Fig. 1), which has six degrees of freedom at each node.

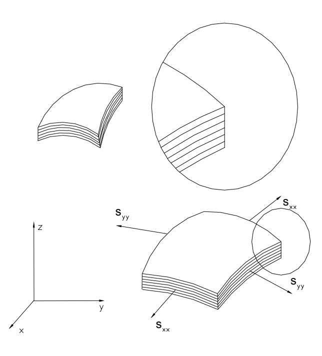

Fig.1. Multilayer three-four-angle shell finite element

The considered finite element takes into account bending and membrane deformations, the material is anisototropic with characteristics specified in the plane of the element by layers and accepting concentrated, distributed, mass and temperature loads.

As a result of calculations, the components of the stress-strain state of the stand are determined in the middle surface by layers and on the boundary surfaces of the shell under the action of static operating loads [14, 15].

The weakest link in the discrediting of the stand is the modeling of ball bearings. Accounting for their interaction with the structure is a difficult task [16]. Geometrically identical modeling of ball bearings leads to an unjustified increase in the number of equations, the solution error of which negates the efforts for accurate modeling, therefore, to take into account ball bearings, assumptions were made that allow to take into account the mechanism of interaction of the ball bearing with the structure with sufficient reliability [17, 18].

The assumptions boil down to the following:

- ball was replaced by a rod element with hinged support at the ends, which largely corresponds to the behavior of the ball in the bearing;
- rigidity of the rod system simulating a ball bearing was taken equal to the rigidity of the ball bearing.

For simplicity of calculations, the gearboxes included in the stand were calculated separately using the developed program, and then the elastic compliance of the gearboxes was taken into account when calculating the structure.

The supporting-rotary mechanism of the stand was modeled by a combination of the above-described finite elements. The total number of elements was 3170 finite elements, including bar elements, bearing support.

The accuracy of the results obtained was checked by the convergence of the results depending on the number of elements in the partition. The results of the stress-strain state when dividing into 5006 finite elements and the adopted scheme differed by an acceptable error for the accepted type of calculations ~ 3%.

The accuracy of the program was checked by solving test problems and comparing the results obtained with known analytical solutions. The discrepancy between the results was observed in the third decimal place [19].

The solution to the problems of determining the dynamic characteristics of the stand can be obtained from the Lagrange equation:

$$\frac{d}{dt}\,\frac{\partial\ T}{\partial\ \{\dot{q}\}}+\frac{\partial\ U}{\partial\ \{q\}}=\{Q\} \tag{1}$$

where $\{\dot{q}\}$is the generalized velocity, $\{q\}$ is the generalized displacement, $T=[m]\times\{\dot{q}\}\times dA$ is the kinetic energy, $U=\langle\sigma\rangle\times\{\varepsilon\}\times dA$ is the potential energy, $Q=\langle p\rangle\times\{u\}\times dA$ is the vector of external forces, $[m]$ is the matrix of mass characteristics of the material, $\langle\sigma\rangle$is the stress vector, $\{\varepsilon\}$ is the vector of deformations, $\langle p\rangle$is the external forces, $\{u\}$is the vector of displacements, dA is the elementary volume, through $\langle\,\rangle$ and $\{\,\}$ are designated, respectively, the vector row and vector column, dot above the letter means differentiation with respect to time t.

We take into account the following dependencies:

$$\begin{aligned}&[\sigma]=[E]\times\{\varepsilon\},\quad \{\varepsilon\}=[S]\times\{u\},\\&\{u\}=[L]\times\{q\},\quad \{\dot{u}\}=[L]\times\{\dot{q}\},\end{aligned} \tag{2}$$

where $[E]$ is the matrix of the mechanical characteristics of the material, $[S]$ is the matrix of the relation between deformations and displacements, $[L]$is the matrix of the transition from displacements $\{u\}$ to generalized displacements $\{q\}$. For a composite material, the stress-strain ratio can be written in the following form:

$$\left\{\frac{N}{M}\right\}=\begin{bmatrix}A & B\\ B & D\end{bmatrix}\rightleftarrows\left\{\frac{\varepsilon}{\kappa}\right\}\text{ or }\{\sigma\}=[E_1]\times\{\varepsilon\}. \tag{3}$$

Here it is indicated: $\begin{Bmatrix} N \\ M \end{Bmatrix}$ are the membrane forces and bending moments, $[A]$, $[B]$, $[D]$ are the submatrices of characteristics of a composite material having the same structure. In particular, $[A]$ is the submatrix of the connection between membrane forces and deformations, are full matrix of 6 by 6 size.

Integrating the components of equation (1) over generalized velocities and displacements, we bring equation (1) to the form (4):

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

Here $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{Q\}$ is the vector of external forces.

The equation for determining the stress-strain state of the structure will be obtained from equation (4) equating to zero the first term of the equation:

(5) $$[K] \times \{q\} = \{Q\}.$$

The fourth stage of design is to carry out calculations, research and analysis of the results. The stress-strain state of the stand was determined under emergency loads applied at the locations of the locking devices. As a result of the study, a complete picture of the stress-strain state of the stand was obtained. The applied procedure makes it possible to design stands of various configurations, dividing only variable elements into finite elements.

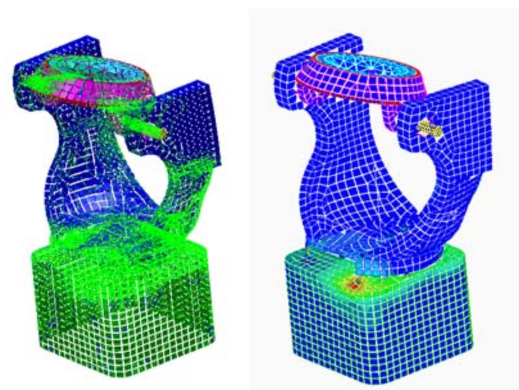

Fig. 2. Distribution of displacements and stresses in the stand when a load is applied to locking device

The Fig. 2 shows the distribution of displacements and stresses in the shells of the stand when a dynamic load is applied to the stopper located in the middle of the right branch of the yoke. The dynamic load arises when the pitch ring hits the locking device, which serves as a limiter for the movement of the bench pitch channel. In the calculations, the dynamic load was converted to static load in accordance with the d'Alembert principle. The grid shows the finite element approximation of the test bench.

Fig. 3. Three-degree semi-natural modeling stand

Fig. 3 shows a semi-natural modeling stand that simulates flight performance in ground conditions.

Conclusions

The obtained results of the natural vibrations of the stand are in good agreement with the available experimental data in terms of qualitative and quantitative indicators (within 15-20%).

In addition, modeling, calculation and kinematic analysis of the gearbox were carried out. The calculation of the stiffness and determination of the natural frequency of the gearbox were carried out on the basis of the program, developed in the EXCEL spreadsheet field. The calculations are in good agreement (within 15%) with the available experimental data.

The performance of the gearbox was tested using CATIA CAD kinematic module.

To conduct research on a multi-stage dynamic stand made of a composite material, one-layer three-four-carbon shell finite elements were replaced with multilayer finite elements (Fig. 1).

The procedure of replacing one finite element with a similar one in terms of geometric parameters in the CATIA CAD calculation module is automated and does not pose any particular problems.

The conducted studies of multi-stage dynamic stands of semi-natural modeling showed that the developed methodology and algorithms for design, modeling, calculation and analysis make it possible to design stand, investigate its stress-strain state and determine frequency characteristics. Moreover, the calculation error is comparable to the experimental results.

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