Computer modeling of robotic systems made of composite materials, analysis of the stress-strain state under dynamic influences

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Abstract. In the present study, a robotic system is considered: a multi-stage semi-natural simulation stand. The stand is designed to simulate the flight characteristics of aircraft instruments in laboratory conditions. The use of such stands can significantly reduce the cost of developing and testing aircraft instruments and contains all the attributes of robotic systems, which allows the developed method of computer modeling and analysis of stands to be applied in the field of robotic systems. The problem is solved by the finite element method. As a result of the study, a technique has been developed for approximating parts that carry out movements: gear rims, bearings, gearboxes, motors in the finite element method. Comparison with the available experimental studies showed the effectiveness of the developed methodology. As the stand material, a composite material is used, which has a high specific strength, which makes it possible to change the physical and mechanical characteristics depending on the location of the composite base in the layers of the multilayer composite structure. A technique has been developed for arranging the base layers in a multilayer composite to obtain maximum strength and rigidity of the stand, which is one of the main factors in the efficiency of the stand. The analysis of the behavior and stress-strain state of the bench under dynamic impact has been carried out.

1 Introduction

Robotic systems are now becoming more widespread in many areas of science and technology due to the development of computer vision, artificial intelligence, which allows analyzing the existing state and carrying out the necessary transformations [1-5]. In the near future, this will make it possible to replace a person, especially in harmful and dangerous industries and situations. Therefore, a comprehensive analysis of such systems, including the study and analysis of systems during operation, is an important and relevant topic. Computer simulation of robotic systems containing moving elements and moving parts: bearings, gears, gearboxes, servo drives, etc. is a complex task that requires a large amount of theoretical and experimental research in the design and manufacturing process [6-9]. Additional difficulties are imposed when considering the dynamic impact on such structures. The solution of such problems is mainly carried out by numerical methods using computer technology and modern

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computer-aided design systems [10,11]. If computer modeling of the design of robotic systems in computer-aided design systems is debugged and does not present any particular difficulties, the modeling of mechanisms that carry out movements is not sufficiently studied and mathematical identification in the finite element method requires further research.

2 Materials and methods

2.1 Resolving equation

To solve the problems of mechanics of a solid deformed body under dynamic loading, a geometrically nonlinear equation is used [12–16]. In this case, the nonlinear terms are determined by the displacements obtained at the previous loading steps

$$[M]\{\ddot{q}\}+[K]\{q\} = \{Q\} - [N_{nl}]$$

Here it is denoted: [M] - mass matrix, [K] - stiffness matrix, $[N_{nl}]$ - geometrically nonlinear term, q - vector of generalized displacements, {Q} - vector of external forces, $\{\ddot{q}\}$ - generalized accelerations.

2.2 Stress-strain relationship

To determine potential energy of deformation of the system and to find the stiffness matrix, it is necessary to find the relationship between stresses and strains. When using a multilayer composite material, it is necessary to determine the influence of the location of the warp of the composite material in the layers of the multilayer composite material on the parameters of the stress-strain coupling matrix. To do this, we consider the plane-stressed state of an orthotropic material, to which the multilayer composite material belongs. The relationship between stresses and strains, when the coordinate axes coincide with the material orthotropic axes, has the form.

$$\{\sigma\} = [E]\{\varepsilon\}, \tag{1}$$

here

$$[E] = \begin{Bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{Bmatrix},$$

$$\{\varepsilon\}^T = \{\varepsilon_s,\ \varepsilon_\theta,\ \varepsilon_{s\theta}\}, \qquad \{\sigma\}^T = \{\sigma_s,\ \sigma_\theta,\ \sigma_{s\theta}\}$$

$$Q_{11} = E_s/(1-\ v_{s\theta}v_{\theta s}), Q_{12} = v_{s\theta}E_s/(1-\ v_{s\theta}v_{\theta s}), Q_{21} = v_{\theta s}E_s/(1-\ v_{s\theta}v_{\theta s}),$$
$$Q_{22} = E_\theta/(1-\ v_{s\theta}v_{\theta s}), Q_{66} = G_{66}$$

When the coordinate axes are rotated through the angle θ, the stress-strain relation matrix takes the form

$$[\bar{E}] = \begin{Bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{21} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{61} & \bar{Q}_{62} & \bar{Q}_{66} \end{Bmatrix}, \tag{2}$$

here

$$\bar{Q}_{11} = c^4Q_{11} - s^4Q_{22} + 2(Q_{12} + 2Q_{66})s^2c^2,$$
$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})s^2c^2 + (s^2+c^2)Q_{22},$$
$$\bar{Q}_{16} = (c^2Q_{11} - s^2Q_{12} + (Q_{12} + 2Q_{66})(s^2-c^2))sc, \tag{3}$$
$$\bar{Q}_{22} = s^4Q_{11} - c^4Q_{22} + 2(Q_{12} + 2Q_{66})s^2c^2,$$
$$\bar{Q}_{26} = (s^2Q_{11} - c^2Q_{12} - (Q_{12} + 2Q_{66})(s^2-c^2))sc,$$
$$\bar{Q}_{66} = (Q_{11} - 2Q_{12} + Q_{22})s^2c^2 + (s^2-c^2)Q_{66},$$

$$s = \sin\theta\,, c = \cos\theta.$$

The deformation of a layer located at a distance z from the median deformation plane can be written as

$$\{\varepsilon\} = \{\varepsilon^o\} + z\{\chi^o\},$$

where $\{\varepsilon^o\}$ - deformations, $\{\chi^o\}$ - curvature, the index "o" means that the deformations belong to the middle surface.

Substituting these relations into equations (1) we obtain

$$\{\sigma\} = [\bar{Q}]\{\varepsilon^o\} + z[\bar{Q}]\{\chi^o\}$$

Normal forces N and moments M can be determined from the relations

$$\{N\} = \int_{-h/2}^{h/2}\{\sigma\}dz,\ \ \{N\}^T = (N_s,\ \ N_\theta,\ \ N_{s\theta}),$$
$$\{M\} = \int_{-h/2}^{h/2}\{\sigma\}zdz,\ \ \{M\}^T = (M_s,\ \ M_\theta,\ \ M_{s\theta}), \tag{4}$$

From equation (4) we get

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = [E]\begin{Bmatrix} \varepsilon^o \\ \chi^o \end{Bmatrix},\quad [E] = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix}, \tag{5}$$

$$[A] = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ A_{61} & A_{62} & A_{66} \end{bmatrix},\quad [B] = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{21} & B_{22} & B_{26} \\ B_{61} & B_{62} & B_{66} \end{bmatrix},\quad [D] = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{61} & D_{62} & D_{66} \end{bmatrix}.$$

$$\{A_{ij},\ B_{ij},\ D_{ij}\} = \int_{-h/2}^{h/2} Q_{ij}(1, z, z^2)\,dz\,, (i, j = 1,2,3) \tag{6}$$

In this study, we consider a multilayer composite material with constant values of the layer parameters. Then from equation (6) we obtain the relations

$$A_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}(h_k - h_{k-1}),\ \ i, j = 1,2,6,$$
$$B_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}({h^2}_k - {h^2}_{k-1}),\ \ i, j = 1,2,6, \tag{7}$$
$$D_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}({h^3}_k - {h^3}_{k-1}),\ \ i, j = 1,2,6,$$

Here it is indicated: A_{ij}, B_{ij}, D_{ij} - membrane, flexural-membrane and flexural stiffnesses.

Figure 1 show equations (7) used in the notation.

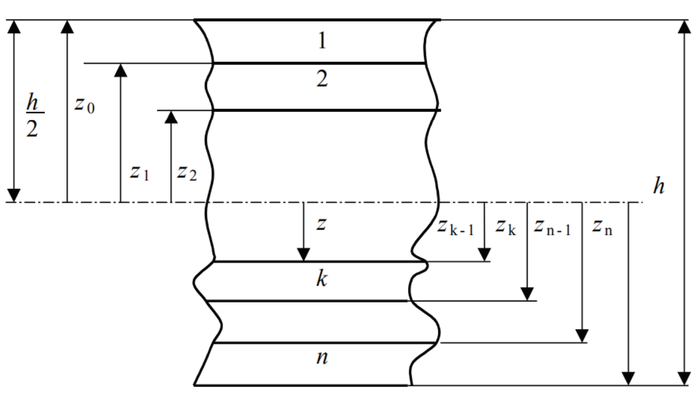

Fig. 1. Multilayer composite material.

2.3 Three-layer shells

The rigidity of parts in robotic systems is of great importance, because the more rigid the robotic structure, the more accurate positioning is provided. Therefore, to increase the rigidity of the elements of robotic systems with a low weight of structural elements in robotic systems, in this study, three-layer shell structures are used, consisting of high-strength multilayer composite materials of the outer layers between which having a foam layer that prevents the bearing layers from approaching and perceives mainly the shear stresses of the three-layer shell. Mathematically, this is provided by supplementing the stiffness matrix with a shear stiffness matrix.

$$\begin{Bmatrix}\sigma_4\\ \sigma_5\end{Bmatrix}^{(k)}=\begin{Bmatrix}\bar{Q}_{44} & 0\\ 0 & \bar{Q}_{55}\end{Bmatrix}\begin{Bmatrix}\bar{\varepsilon}_4\\ \bar{\varepsilon}_5\end{Bmatrix}^{(k)},$$

where $\bar{Q}_{44}=G_{13},\ \bar{Q}_{55}=G_{23},\ G_{13},G_{23}$ are shear moduli.

To determine the displacement parameters and the angle of rotation of the filler normal, in this study, a linear dependence on the displacements and rotation angles of the carrier layers of a three-layer shell structure is used

$$v_2=(\bar{v}_1+\bar{v}_3)/2,\qquad \varphi_2=(\bar{v}_1-\bar{v}_3)/t$$
$$\bar{v}_1=v_1-t_1e_{13}/2,\ \bar{v}_3=v_3+t_3e_{23}/2.$$

Here it is indicated: t is the distance of the three-layer shell between the neutral layers of the carrier layers, t_1, t_3 are the thicknesses of the carrier layers, t_2 is the thickness of the filler layer.

For a filler layer located at a distance z from the neutral plane of the filler, the displacements and the rotation angle of the filler can be written as

$$v_2(z)=v_1+z\varphi_2$$
$$=0.5(v_1-t_1e_{13}/2+v_3+t_3e_{23}/2)$$
$$+\ z(v_1-t_1e_{13}/2-v_3-t_3e_{23}/2)/t_2,$$
$$u_2(z)=u_1+z\varphi_2=0.5(u_1-t_1e_{13}/2+u_3+t_3e_{23}/2)+\ z(u-t_1e_{13}/2-u_3-t_3e_{23}/2)/t_2,$$
$$w_2(z)=w_2+z(w_3-w_1)/t_2.$$

These ratios can be applied to an arbitrary number of layers of sandwich material.

2.4 Methodology for maximizing structural rigidity

The strength and stiffness characteristics of a multilayer composite material depend on the location of the warp of the composite in the layers of the multilayer structure [17, 18]. Since the maximum strength of the layer is provided when the base is located along the line of action of the load, it is necessary to position the base of the layers of the composite material along the lines of action of maximum tensile or compressive stresses, i.e. along the lines of action of maximum loads. In the case of complex structures containing surfaces of double curvature, as with the considered design of a multi-degree bench for semi-natural modeling, the basis of the composite material should be placed along the trajectories of maximum stresses. At the same time, it is necessary that part of the layers of the multilayer composite should be placed at an angle to the trajectories of maximum stresses to ensure the perception of shear stresses acting in the structure. Optimization of the arrangement of layers is achieved by existing experience in the design and manufacture of composite structures, as well as experiments. In the present study, a technique for ensuring maximum rigidity of a composite material structure is proposed, which consists in the following:

• We model a structure from a homogeneous material

• We carry out the calculation for the existing operational loads
• We determine the trajectory of the action of maximum stresses
• We place the composite material along the trajectories of maximum stresses obtained from the solution of the problem for a homogeneous material
• We determine the trajectories of maximum stresses for a structure made of composite material
• We adjust the location of the composite base from the solution of the problem for a structure made of composite material
• We make sure that the basis of the composite material coincides with the trajectories of maximum stresses and carry out the final calculation.
• At the same time, we evaluate the strength by shear stresses in order to provide a sufficient number of layers perceiving shear stresses.

2.5 Method for determining the rigidity of gearboxes, bearing supports and gear rims

Robotic systems have parts in their design that ensure the movement of channels. These include bearings, ring gears, gears, gearboxes, servos, motors. Identifying such details in the finite element method is a difficult task. This study proposes a method for identifying such parts by replacing them with rod systems identical in rigidity to the replaced parts. The authors have developed a program for calculating the stiffness of bearings, gear rims, gears, gearboxes, servo drives, motors and which ensure the rigidity of the this elements with rod systems of identical rigidity. Comparison of the proposed method with the available experimental data showed the validity of the proposed method.

2.6 Modeling and approximation

The stand considered in the work contains all elements of robotic systems: moving elements, bearings, gears, gearboxes, etc. Therefore, the methods considered in this study are applicable to robotic systems. A multi-stage dynamic stand of simulation consists of a base connected by a toothed rim to the forward fork, on bearing supports in the forward fork there is a pitch channel, in which the roll channel is located, connected by a gear to the pitch. This design allows you to simulate the movement of the tested product in six degrees of freedom and simulate the flight characteristics of the product in the laboratory. The bench is a complex structure with parts that ensure the movement of the bench channels.

In the computer-aided design system, the bench was simulated and was approximated by finite elements [19-23]. Figure 2 shows the bench model approximated by finite elements.

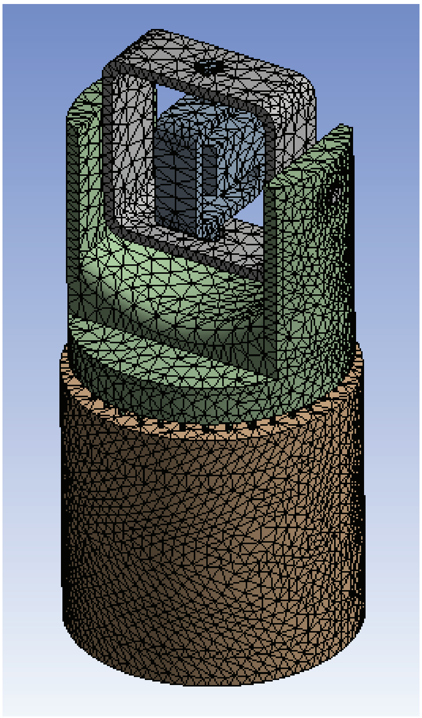

Fig. 2. Finite element approximation of the stand.

2.7 Solution method

Calculation a complex stress-strain state of a test bench under dynamic influences made of composite material consists of several stages

- Simulation of a stand from a homogeneous material in computer-aided design systems.
- Approximation of the stand by finite elements
- Calculation and analysis of the stress-strain state of the stand on the action of static loads. Solving the problem for static loads is reduced to solving the system of equations [24]

$$[K]\{q\} = \{Q\},$$

Here $[K]$ is the stiffness matrix, $\{Q\}$ is the vector of external forces, $\{q\}$ is the generalized displacement.

- Determination of the maximum size of finite elements necessary to obtain an acceptable exact solution, i.e. convergence of results. The convergence of the results is carried out according to the following method:

  - the stand is divided into finite elements,
  - the stand is calculated for static loads,
  - the results obtained are analyzed,

- calculation of the stand with the number of finite elements increased by 1.5 times is carried out,

- the results obtained are compared with the previous result, and if the results differ by no more than 3%, it is considered that the previous split is sufficient to obtain acceptable results. If the difference in the results is more than 3%, then the procedure is continued until the difference is no more than 3%.

- To calculate the stand from a composite material, it is necessary to assign the characteristics of the composite material to the finite elements

- To simulate a stand made of a composite material of maximum rigidity, it is necessary to determine the trajectories of maximum stresses according to the method described in section 2.4 of this work.

- Calculate the stand for dynamic loads.

To analyze the complex stress-strain state of a stand made of composite material for dynamic effects
Calculation and analysis of a stand made of composite material for dynamic effects is carried out on the basis of equations (1) and consists of the following steps:

- To solve the problems of dynamic loading of structures, it is necessary to set the initial perturbation of the structure, i.e. assign minor displacements to nodal structural elements. For example, the displacement of nodes from the solution of the problem of the static loading multiplied by 10^{-8}. In this case, the shape of the initial perturbation does not affect the final results.
- Resolving equations for nonlinear problems contain geometrically or physically nonlinear terms. Solving such problems is a difficult task. Therefore, to solve problems of this kind, the nonlinear terms are transferred to the right-hand sides of equations (1) and are determined from the displacements obtained at the previous loading steps. The first step is to solve a linear problem. To improve the convergence of the results, when calculating the nonlinear terms, extrapolation is applied over several previous loading steps.
- When solving dynamic problems, for the convergence of results, special attention should be paid to the loading step. Comparing the obtained results and the results of the previous loading step. If the results differ by more than 3-4%, it is necessary to reduce the loading step by half. The initial loading step depends on the problem being solved. For a rapidly increasing or instantaneous increase in load, as a rule, the initial loading step is 10^{-7} seconds.

3 Results

As a result of the study:
• a technique for modeling a simulation bench has been developed;
• methodology for determining the maximum rigidity of a stand made of composite material;
• methodology for determining the physical and mechanical characteristics of a multilayer composite material;

• methodology for taking into account the details of the stand, ensuring the movement of the channels of the stand;
• a technique for approximating the bench by finite elements to obtain acceptably accurate results;
• a stand model was obtained from a composite material of maximum rigidity;
• methodology for solving problems of dynamic impact on structures;
• calculation of the stand made of composite material under dynamic influences was carried out;
• An analysis of the complex stress-strain state of a stand made of composite material under dynamic influences was carried out;

The results of calculation of the stress-strain state of the stand under dynamic influences are shown in Figure 3. The maximum stress of the complex stress-strain state was 89,13 MPa.

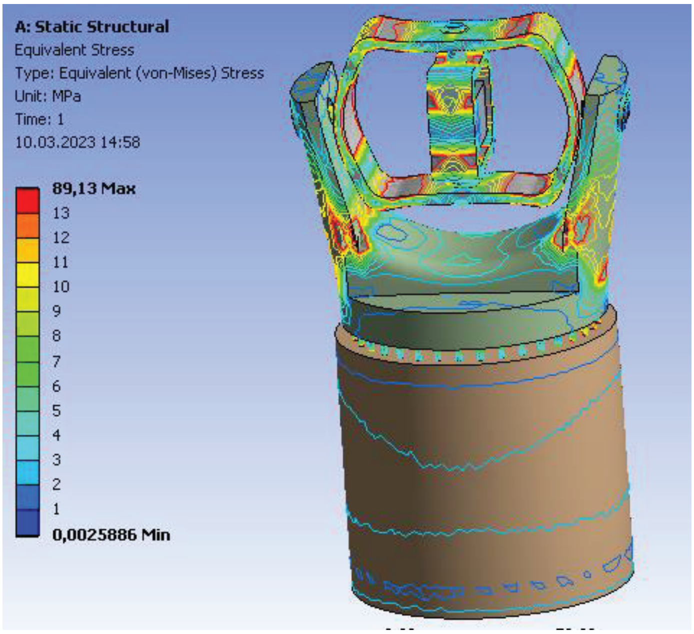

Fig. 3. Isolines of a complex stress-strain state of a dynamic bench of semi-natural modeling from a composite material under a dynamic inertial load.

4 Conclusions

Simulation of a stand made of composite material and analysis of a complex stress-strain state under dynamic impact have been carried out. HIL simulation stands in Russia are made of magnesium alloys, at the same time; the composite material has higher specific strength characteristics, so the use of composite material in robotic structures has broad prospects. The stand of semi-natural modeling has all the attributes of robotic systems, therefore the applied calculation and analysis method of the stand is applicable for the study of robotic systems that are widely used in various fields of science and technology.

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References

1. V. Frolov, E. I. Vorobyov, Mechanics of industrial robots: Textbook for universities (Higher School, Moscow, 1988)
2. V. E. Berbyuk, Dynamics and optimization of robotic systems (Naukova Dumka, Kiev, 1989)
3. M. Z. Kolovsky, A.V. Sloushch, The basics of industrial robot dynamics (Nauka, Moscow, 1988)
4. F. L. Chernousko, N.N. Bolotnik, V.G. Gradetsky, Manipulation robots: dynamics, control, automation (Nauka, Moscow, 1989)
5. B. A. Jonker, Intern. J. Robot. Research **9(**4) (1990)
6. R. D. Beizelman, B.V. Tsypkin, L.Ya. Perel, Rolling bearings (Mashinostroenie, Moscow, 1975)
7. F. S. Dmitriev, Design of gearboxes for precision instruments (Mashinostroenie, Leningrad, 1971)
8. D. Turcic, A. Midha, ASME J. Dynamic Systems, Measurements and Control **106** (1984)
9. I. Hoopert, J. Tribol. **136** (2014)
10. K. Z. Khairnasov, V.D. Yudaev, V.N. Favorin, Proceed. II All-Union Symp. "Stab. Mech. Defor. Solid Body Kalinin (1986)
11. K. Z. Khairnasov, V.B. Yudaev, V.N. Favorin, Proceed. Intern. Conf. Fract. Mech. China, Beijing (1987)
12. I. F. Obraztsov, A.S. Volmir, K.Z. Khairnasov, Report Academy Sci. USSR **266**(6) (1982)
13. D. Striklin, D. Navaratna, T. Pian, Rocket technol. Astronaut. **4**(6) (1986)
14. D. Stricklin, W. Heisler, W. Riesemann, Rocket technol. Astronaut. **11**(3) (1978)
15. D. Striklin et al. Rocket technol. Astronaut. **6**(4) (1971)
16. D. Striklin et al. Rocket technol. Astronaut. **6**(12) (1968)
17. V.V. Vasiliev, Composite materials (Handbook, 1990)
18. J. Lyubina, Handbook of composite materials. books 1 and book 2 (Mashinostroenie, Moscow, 1988)
19. O. C. Zienkiewicz, R.L. Taylor, J.Z. Zhu, Finite element method: its basis and fundamental (Butterworth-Heinemann, Oxford, 2013)
20. S. Moaveni, Finite Element Analysis Theory and Application with ANSYS (Pearson Education, London, 2015)
21. I. Koutromanos, Applied Fundamentals of Finite Element Analysis Linear Finite Element Analysis (John Wiley & Sons, New York 2018)
22. K. J. Bathe, Finite element procedures (Pearson education Inc., New York, 2006)
23. W. Sunada, and S. Dubowsky, J. Mech. Design **103** (1981)
24. K. Z. Khairnasov Bulletin of the Peoples' Friendship University of Russia. Series: Eng. Research, **1** (2002)