

SUBSTANTIATING A METHOD FOR COMPUTER ANALYSIS OF THE STRESS-STRAIN STATE OF THE TUBBING ERECTOR MANIPULATOR MECHANISM

Purpose. To develop and substantiate a method for computer analysis of the stress-strain state that occurs in the tubing erector manipulator mechanism with several degrees of freedom, using modern computing complexes based on the finite-element method.

Methodology. The research uses software complexes, with the help of which a calculation-theoretical apparatus has been created, which is intended for calculating dynamic and static loads that occur in the elements of the tubing erector manipulator mechanism. The results of modeling the stress-strain state in the parts and nodes of this mechanism, obtained using the SolidWorks Motion and SolidWorks Simulation programs, have been compared. The errors in these results have been estimated.

Findings. The effectiveness of the proposed analysis method, based on the combination of SolidWorks applications, in particular, SolidWorks Motion and SolidWorks Simulation, has been proven on the example of modeling the most complex design of the UT62 tubing erector mechanism.

Originality. For the first time, a method for computer analysis of the stress-strain state that occurs in the tubing erector manipulator mechanism of the UT62 type has been developed and substantiated. The essence of the method is that initially, using the SolidWorks Motion application, the laws of motion of the motors are set. The tubing erecting process itself is divided into discrete moments of time with the selection of parts in which the stress fields are calculated and with the determination of the maximum equivalent stress, using the Simulation Setup tool. The change in these stresses during the erecting cycle is analyzed, and if it is necessary to refine the data, the discrete time step of the mechanism motion is reduced. Specific information about the stress-strain state of the part is obtained in the SolidWorks Simulation application, using data imported from the SolidWorks Motion program about gravitational and inertial forces that occur in the tubing erector mechanism.

Practical value. The proposed method can be used for modeling the motion of mechanisms of different complexity, in particular, in the design of domestic tubing erectors.

Keywords: *SOLIDWORKS, SOLIDWORKS MOTION, SOLIDWORKS SIMULATION, tubing erector manipulator, mechanical mates, equivalent stresses*

Introduction. Literature review. Ukrainian scientists are actively working to improve domestic technology, produce innovative ideas, and generate new directions of fundamental and applied research.

The scientific school of mining mechanical engineers at Dnipro University of Technology is actively working in the applied industry, developing new scientific directions. Thus, the works conducted under the guidance of Professors K. Ziborov [1, 2], S. Fedoryachenko [3, 4] substantiate rational parameters of transport functioning. Professor S. Felonenko in [5] studied the exploitation of improved mining dump trucks.

In the field of machine mechanics, the studies by Professors K. Zabolotnyi [6, 7], V. Samus [8, 9], S. Ilyin [10, 11], and I. Belmas [12, 13] are widely known.

Scientific works on the creation of safe equipment for the preparatory working advance belong to M. Polushyna [14] and T. Moskaleva [15, 16].

Unsolved aspects of the problem. In connection with the development of research performed using modern software complexes, there is a need to develop methods for conducting a computational experiment that would ensure the effective use and modernization of technological machines. Today, scientific research concerns the improvement of the tubing erector designs [17, 18]. As the results of this issue study have

shown, the known designs of tubing erectors have increased metal consumption and drive power. This is because at present there is no scientifically based methodology for determining the rational parameters of such machines.

The scientific idea of the proposed work is the creation of a method for computer analysis of the stress-strain state in mechanisms using a combination of modern approaches based on finite element actions. The idea has been realized through the introduction of a number of computing complexes.

For tunneling, where the tubings and blocks are set in the soils developed by the blasting method, lever-type tubing erectors are used. The drilling machine digs blastholes in the face for laying explosives, which is conducted from the retractable platforms of the tubing erector. When blasting, the tubing erector is driven away from the face to protect the equipment from flying rock pieces. The caved rock is removed using a rock-loading machine. Then, the installation of cast-iron tubing segments or reinforced concrete blocks begins in the mined-out space. The segments are fed to the tubing erector on a trolley. Its executive body is lowered to the segment and connects it with a gripping device. Further, each segment is set alternately to the left and right, starting with the lower tray one. In order to assemble all structural elements, the segment erector manipulator must have several degrees of mobility, which ensures that the fastening element is moved in the radial direction of the tunnel working cross-section, and in the cir-

cular and longitudinal directions up to the tunnel axis. Last, in the tunnel space, the upper key segment with wedge-shaped faces is erected, on which the erector presses to expand the processing ring, after which the segments are connected to each other using bolts.

The purpose of this research is to substantiate a method for computer analysis of the stress-strain state of the manipulator mechanism in the process of erecting, as well as its verification.

To develop and substantiate a computer model, the structure and operation of the studied equipment is examined. Fig. 1, *a* presents a scheme of the UT62 tubbing erector design and Fig. 1, *b* shows the design of its manipulator mechanism.

The computer model of the mechanism, created using the SOLIDWORKS program tools, has rotational kinematic pairs that connect the crank 2 (Lever arm), the crank rod 4 (Shoulder) and the control link 5 (Section) with the hoisting device 6. The latter performs the function of assembling the Pin 5 tubbings in the mine working tunnel. The crank 2 (Lever arm) with counter-weight 3 is set on the drive shaft of the hydraulic motor 1 (Support). Two power hydraulic cylinders 8 (Engine) control the links 4 (Shoulder) and 5 (Section) (Fig. 1, *b*).

The rotational kinematic pairs of the manipulator mechanism have the form of one-bladed and two-bladed lugs connected by a finger.

To connect the parts into a composite structure, use the Mate command. Select the Mechanical Mates connection type and set the Hinge command. Then the Mechanical properties (Analysis) tab appears, where special connection zones for further work in SolidWorks Motion and SolidWorks Simulation applications are marked. In particular, Mate location and Load Bearing Faces. These are sections of elements to which a load is applied from the interaction of the connected parts. Here, it is necessary to indicate which faces or planes are required in the future, by doing this in the windows for the selection of Concentric Selections and Coincident Selections. Then, in the Analysis tab, it is necessary to indicate the place of application of interaction forces and the bearing faces.

After the model is transferred to work in the SolidWorks Motion application, all connections are converted to elementary ones (rotational and translational) and the extra, that is, the matching ones, are automatically removed.

The task to develop a method for computer analysis of the stress-strain state in the tubbing erector manipulator mechanism having been set, the following parameters are provided for its testing: UT62 type tubbing erector; tunnel diameter – 9.5 m; lining type – tubbings, blocks; the weight of tubbing or block is no more than 10 kN.

Description of modeling algorithms. First approach. Firstly, the forces are determined that occur in the parts and nodes of the mechanism during the operation of the tubbing erector manipulator, taking into account the gravitational and inertial forces, using the SolidWorks Motion software application. Next, the parameters of the stress-strain state in the parts of the tubbing erector manipulator are calculated by issuing com-

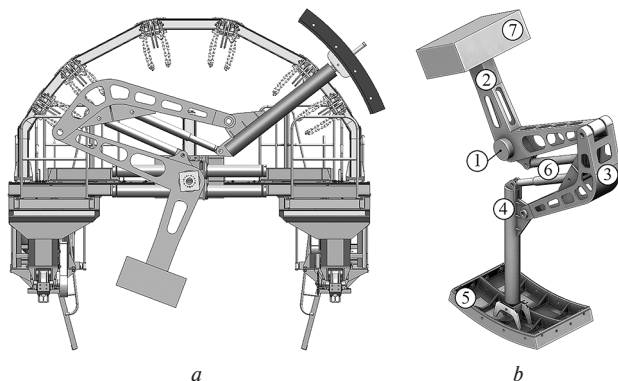


Fig. 1. Tubbing erector manipulator design

mands built into the specified application, that is, Calculate Simulation Results, Simulation Plot.

Among the SolidWorks Motion program tools, LinearMotor1, LinearMotor2 and RotaryMotor1 are selected. To control them, the Displacement command is issued. The movement of tubbings for a certain time must occur along a given trajectory with a specified velocity and acceleration, and the direction of this movement – from the loading place to erecting place. To do this, a mathematical model has been developed that describes the trajectory of the tubbing movement. In the model, the tubbing movement is divided into several stages, for each of which a certain number of points (frames) is determined. The number of each frame corresponds to the coordinates of characteristic motion points in the mechanism at a certain moment in time. As a result, three matrices have been formulated containing the coordinate values of the axes of the manipulator hydraulic cylinders hinges, which correspond to the discrete time moment. Then, the program calculates the displacement of all three motors in discrete time during the tubbing erecting cycle. The data obtained after performing cubic interpolation (Interpolation type – Cubic Spline) is imported into the SolidWorks Motion application.

After the motion analysis using the Simulation Setup command, those parts of the mechanism are determined for which it is necessary to calculate the stress-strain state with an indication of the time moment (Fig. 2).

Then, using the Calculate Simulation Results command, the corresponding research is performed by the Simulation command with the determination of the maximum values of the equivalent stresses (Table), using which, a graph is constructed of their dependences on the manipulator operation time (Fig. 3)

If the need arises, then the value of the motion time step is reduced, and the determination of the stress-strain state values is detailed. In the studied case of erecting the tubbing, the maximum equivalent stress is reached when $t = 19.5$ s (Fig. 4). The Figure shows the stress distribution field and indicates the maximum of them. It should be noted that the indicated time corresponds to the moment of transition from rotational motion of the tubbing to the translational radial motion.

The advantage of the described approach is in the possibility of determining the inertial loads arising during the manipulator movement and in the fact that the calculation time is short due to the use of a “coarse” finite-element mesh.

The disadvantage of the approach is that, using the Simulation Setup command, it is impossible to control the size of the computational mesh elements. This affects the accuracy of the calculation results.

Second approach. The parameters are determined of the stress-strain state arising in the tubbing erector mechanism parts using the SolidWorks Simulation application, taking into account only gravitational forces. In this case, it is necessary to consistently calculate the stresses in parts and nodes that occur under the action of static load in all positions of the manipulator when erecting the tubbing. The dynamic load is calculated approximately, taking into account the coefficient of dynamics.

When modeling, it is necessary to take into account that the Mechanical Mates function, provided in the SolidWorks program and accepted by the SolidWorks Motion application as a boundary condition, when working with the SolidWorks Simulation program is not supported; for example, it concerns the Hinge connection. Therefore, it is necessary to create connectors of the Pin Connector type with a retaining ring that prevents axial displacement of the mechanism element using the Connections/Connectors tool.

When analyzing the stress-strain state of the parts, it is necessary to use a finite-element mesh, which takes into account the model shape curvature (Curvature based mesh command) and provides the maximum size of each element (Maximum element size) being 20 mm.

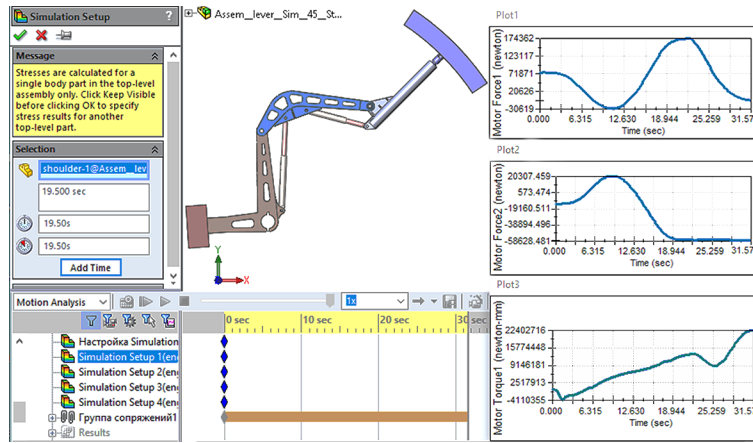


Fig. 2. General view of the window for setting the Simulation Setup command

The results of the determination of the maximum values of the equivalent stresses depending on the manipulator operation time

No.	Time, s	Stress, MPa	No.	Time, s	Stress, MPa
1	0	63.67	11	23	125.30
2	5	49.51	12	24	120.89
3	10	59.37	13	25	118.00
4	15	103.32	14	26	117.90
5	18	125.43	15	27	117.58
6	19	126.64	16	28	117.52
7	19.5	126.73	17	29	117.79
8	20	126.41	18	30	117.83
9	21	125.39	19	31	117.58
10	22	125.00	20	31.57	117.58

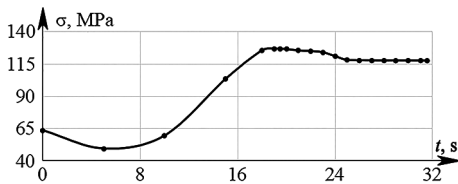


Fig. 3. Dependency graph of the maximum equivalent stresses in the manipulator elements on discrete time

The equivalent stress field determined after performing the static calculation is shown in Fig. 5. As the calculation analysis shows, the maximum stress is 153 MPa and it is observed in the rod of the first hydraulic cylinder.

Therefore, the advantages of the second approach include the short duration of equivalent stress calculation, the ability to change the computational mesh size (thereby providing probing, output of results both for nodes and elements), which affects the accuracy of the state analysis results.

The disadvantage of the method is that the inertial load is approximated by the coefficient of dynamics. In addition, the maximum equivalent stress is observed in a different place, in contrast to the first approach result, indicating a qualitatively incorrect result.

Third approach. It provides for a preliminary calculation using the SolidWorks Motion program of gravitational and inertial forces arising in the tubbing erector mechanism, and then importing the results into the SolidWorks Simulation ap-

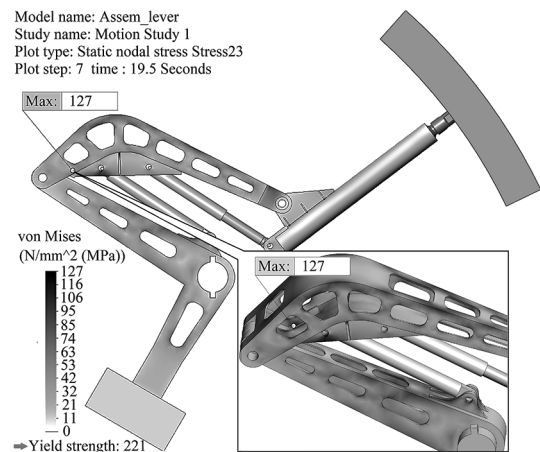


Fig. 4. Curve of the stress-strain state in the tubbing erector manipulator

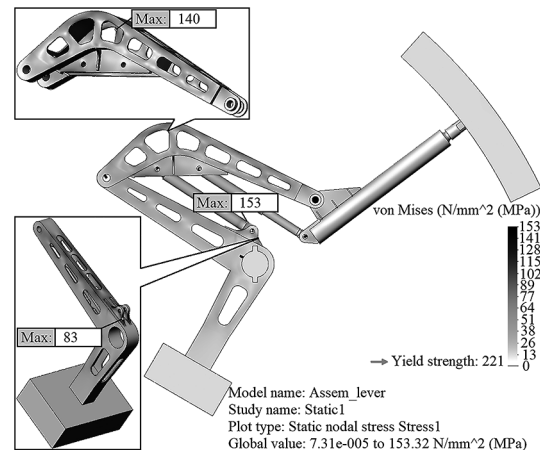


Fig. 5. Curve of the stress-strain state in the tubbing erector manipulator

plication. Next, the stress-strain state in the manipulator mechanism parts is determined. To do this, in the application to the assembly unit located in the added SolidWorks Simulation module, the Import Motion Loads command is issued from the menu. In the opened window, the parts should be selected and indicated that are subject to "static research" using the SolidWorks Simulation program, as well as enter the frame number at which the maximum stress is expected to be reached.

Further, a tab with its name, for example, CM1-ALT-Frame-489, where 489 is the frame number, appears in the

opened window of the studied part. The SolidWorks Simulation research property command includes the Use inertial relief function, which adds an “inertia” attribute to the part motion, thereby restricting its movement as a solid body.

The SolidWorks Simulation research tree in the External Loads folder contains the following branches: ALT Centrifugal – centrifugal forces, ALT Gravity – gravitational forces. The value of the mentioned forces is transferred to the program from the SolidWorks Motion application. For example, in our case, the remote Load Direct transfer branches, such as ALT RemoteLoads 1 and ALT RemoteLoads 3 will be additionally created, arising in the Hinge1 and Hinge4, which connect the Lever arm part with the Support and Engine1 korpus parts.

The Import Motion Loads command with a part of the connected parts works incorrectly. It should be noted that the Import Motion Loads tool correctly sets only those remote loads that occur in the two-bladed lugs of hinges, that is, the load in the one-bladed lugs must be specified manually. For example, this applies to the Hinge2 one-bladed lug connecting the Lever arm crank to the Shoulder crank rod.

Therefore, when calculating the stress fields in the Lever arm and Section parts, it is necessary, first, to find the projections of remote loads in the hinges connecting the Shoulder part with the Lever arm and Section parts on the coordinate axis, as well as the projections of related parts, by determining the remote loads that they experience. In this case, it should be taken into account that all parts constantly rotate relative to each other.

To determine the projections, the location of the manipulator parts, which corresponds to the time moment of 19.5 s, is modeled. Further, coordinate systems parallel to the original coordinates are introduced into the models of the Lever arm and Section parts, in particular, into the holes of one-bladed lugs. Then, in the assembly unit, the Shoulder part model is edited and coordinate systems at those points are constructed, whose axes will be oriented on the Top and Right planes of the Lever arm and Section parts in the same way as the axes of the two coordinate systems previously introduced into these parts (Fig. 6).

Next, in the Simulation context menu, the Import Motion Loads command is issued. In the opened window we check if the name Motion Study matches the calculation performed by the SolidWorks Motion application. Then, from the list of Available assembly components, we then transfer the names of the Lever arm, Shoulder and Section parts to the Selected Component window, enable the Single frame study button and indicate the Frame no – 499, closest to the time of 19.5 s.

After that, the tabs of research by the SolidWorks Simulation program with the name CM1-ALT-Frame-499 will appear on the images of the selected parts.

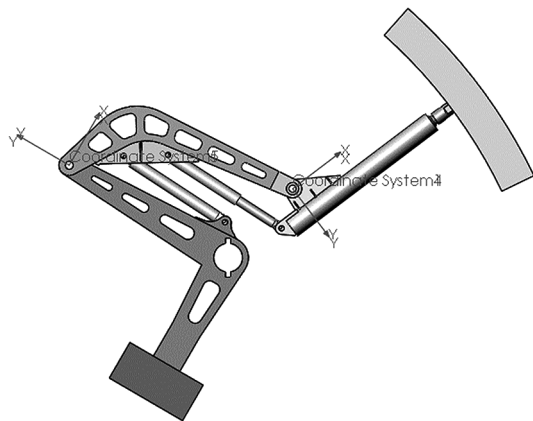


Fig. 6. Coordinate system construction in the model of manipulator parts for determining the projection of remote loads in the hinges

Using the SolidWorks Motion application, loads such as inertial forces and gravity forces are added to the Shoulder part. A peculiarity of the conducted research is that the Shoulder part does not have fasteners. In this case, to compensate for imbalances, the Use inertial relief research property is used. Then we perform a static stress calculation.

As the result shows, the maximum stress is 134 MPa and it occurs in the ribs of the lugs and in the holes for fastening the first hydraulic cylinder (Fig. 7). For comparison, the research with the use of the first approach (Fig. 4) has confirmed a result of 127 MPa, which is 5 % less than in the third approach. The maximum stress localization in both calculations is the same, namely, it occurs in the lug near the location of the first hydraulic cylinder.

A static stress analysis is performed in the Shoulder part using a Curvature based mesh (with programmed curvature in it) with a maximum element size of 20 mm. As a consequence, the maximum equivalent stress is 141 MPa (Fig. 8), and the maximum stress localization is the same as before.

To construct projections of the force acting on the Shoulder part from the side of the Lever arm part, it is necessary to issue the commands List Result Force, Remote load interface force in the Result folder. In the property manager, we select the Coordinate System4, as well as the faces of the two-bladed lug model. We have the following result: 10.35 kN along the x-axis, and 178.58 kN along the y-axis. Similarly, in the lug connecting the Shoulder and Section parts, the projection of forces along the x-axis is 11.17 kN, and along the y-axis is 77.55 kN.

After that, we proceed to a similar tab called CM1-ALT-Frame-499, which contains the Lever arm part model. Here we issue the Remote Loads/Mass command and set the projections of forces constructed above with the opposite sign in relation to those acting from the side of the Lever arm part onto the Shoulder part. We perform a static research. The stress fields are shown in Fig. 9, a. As can be seen, the maximum stresses occur in the lug near the first hydraulic cylinder and reach a value of 92 MPa. In the static research performed in the first approach, the maximum stresses were 83 MPa, and they occurred in the same lug.

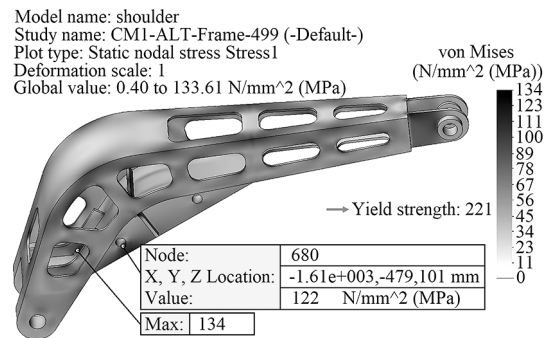


Fig. 7. Curve of the stress-strain state in the Shoulder part

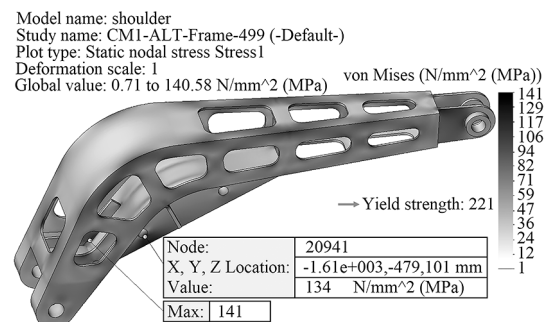
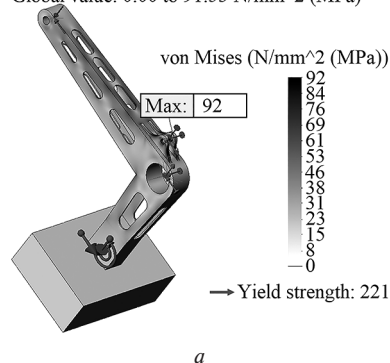


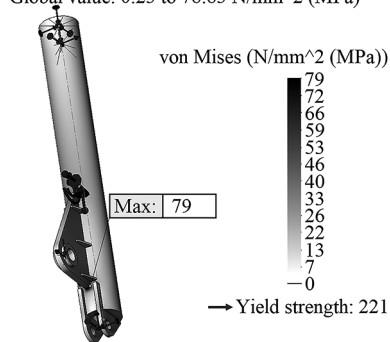
Fig. 8. Result of studying the Shoulder part using the computational Curvature based mesh

Model name: lever arm
 Study name: CM1-ALT-Frame-499 (-Default-)
 Plot type: Static nodal stress Stress1
 Deformation scale: 1
 Global value: 0.00 to 91.53 N/mm² (MPa)



a

Model name: section
 Study name: CM1-ALT-Frame-499 (-Default-)
 Plot type: Static nodal stress Stress1
 Deformation scale: 1
 Global value: 0.23 to 78.83 N/mm² (MPa)



b

Fig. 9. Curves of the stress-strain state in the Lever arm and Section parts

Similarly, the stress-strain state parameters are calculated in the Section part. As can be seen from the parameter value distribution, the part is exposed to acting bending stresses, the maximum value of which is 79 MPa (Fig. 9, b), and it occurs in the lug near the second hydraulic cylinder.

Therefore, it can be concluded that the research during the third approach provides for additional constructions, which significantly increases the duration of determining the stress-strain state parameters.

At the same time, due to the possibility of correcting the finite-element mesh, the accuracy of calculating equivalent stresses has been increased by 10–15 %.

Conclusions. Based on the research results of the stress-strain state arising in the manipulator mechanism when erecting tubbings, which is performed using the SolidWorks, SolidWorks Motion, SolidWorks Simulation programs and their combination, the following characteristics have been revealed:

1. When determining the stresses arising during the operation of the tubing erector manipulator in the parts and nodes of its mechanism, taking into account the gravitational forces and inertial forces (using the SolidWorks Motion software application), followed by the calculation of the stress-strain state in each of these parts by using the commands available in the application, the value of the equivalent stresses has been underestimated by 10–15 % of the real one. This is due to the use of a high-size finite-element mesh for calculations and the impossibility of correcting it, since access to the Simulation application settings is denied in the SolidWorks Motion program interface.

2. Determination of mechanical stresses arising in the erecting tubing mechanism parts, directly using the SolidWorks Simulation program, taking into account only gravita-

tional forces, and the dynamic load calculated using a coefficient of dynamics, gives qualitatively and quantitatively incorrect pattern of the stress-strain state. This is conditioned by the fact that in such an approach, the increase in the weight of parts is taken into account during the calculations. In real processes, inertial forces during the manipulator mechanism operation act in different directions, reaching significant values during transient operation modes.

3. When transferring force information from a SolidWorks Motion application to a SolidWorks Simulation application, there are some problems. For example, the Import Motion Loads command cannot work correctly with all parts; in particular, some of the mated parts are not included in the list of components available for modeling. In addition, when using this command, remote loads, such as those occurring in one-bladed hinge lugs, may not always be displayed. This leads to modeling of unbalanced external loads in the studied part and to an erroneous result in determining the stress-strain state. As a way out of the situation, the remote loads must be modeled manually, which significantly increases the calculation time.

4. A method for computer analysis of the stress-strain state that occurs in the tubing erector manipulator mechanism is proposed. The essence of the method is that the SolidWorks Motion program pre-sets the laws of motion of the motors so that the tubing moves along a given trajectory. Then, using the Simulation Setup tool, the erecting process is divided into discrete time moments and the parts are selected, relative to the movement of which the stress fields are calculated and the maximum equivalent stress is determined using the Calculate Simulation Results command. Then, the changes in these fields are analyzed during the erecting cycle, if necessary, reducing the discrete time step. For a refined solution of the stress-strain state in the SolidWorks Simulation application, the Import Motion Loads command is available, for the execution of which the part name and the frame number are specified, relative to which the refined calculation of equivalent stresses is performed.

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Обґрунтування методу комп'ютерного аналізу напружено-деформованого стану механізму маніпулятора тьюбінгоукладача

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Мета. Використовуючи сучасні обчислювальні комплекси, що базуються на методі застосування скінченних елементів, розробити та обґрунтувати метод комп'ютерного аналізу напружено-деформованого стану, який виникає в механізмі маніпулятора тьюбінгоукладача, котрий має декілька ступенів вільності.

Методика. У дослідженні застосовані програмні комплекси, за допомогою яких був створений розрахунково-теоретичний апарат, призначений для обчислення динамічних і статичних навантажень, що виникають в елементах механізму маніпулятора тьюбінгоукладача. Зіставлені результати моделювання напружено-деформованого стану в деталях і вузлах цього механізму, отримані із застосуванням програм SolidWorks Motion і SolidWorks Simulation. Були оцінені похибки в таких результатах.

Результати. На прикладі моделювання найбільш складної конструкції механізму тьюбінгоукладача марки УТ62 доведена ефективність запропонованого методу аналізу, що базується на застосуванні комбінації додатків програм SolidWorks, зокрема SolidWorks Motion і SolidWorks Simulation.

Наукова новизна. Уперше був розроблений та обґрунтований метод комп'ютерного аналізу напружено-деформованого стану, що виникає в механізмі маніпулятора тьюбінгоукладача типу УТ62. Суть методу полягає в тому, що спочатку, скориставшись додатком SolidWorks Motion, задають закони руху двигунів. Сам процес укладання тьюбінгів був розбитий на дискретні моменти часу з вибором деталей, в яких розраховують поля напружень, та із визначенням максимального еквівалентного напруження, здійнявши при цьому інструмент Simulation Setup. Аналізується зміна цих напружень протягом циклу укладання, за потреби уточнення даних зменшується дискретний часовий крок руху механізму. Конкретну інформацію про напружено-деформований стан деталі отримують у додатку SolidWorks Simulation, використовуючи імпортовані із програми SolidWorks Motion дані про гравітаційні сили й сили інерції, що виникають у механізмі укладача.

Практична значимість. Запропонований метод можна використовувати для моделювання руху механізмів різної складності, зокрема у проектуванні вітчизняних тьюбінгоукладачів.

Ключові слова: SOLIDWORKS, SOLIDWORKS MOTION, SOLIDWORKS SIMULATION, маніпулятор тьюбінгоукладача, механічні спряження, еквівалентні напруження

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