

Synthesis of a mechanism for clamping a drilling robot's cargo

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Abstract. Robotics is developing rather intensively in Russian oil and gas industry today. Robotic drilling systems provide cost reduction and increase of work safety. Drilling robots' gripping devices are designed for gripping, transporting, mounting, rotating massive cylindrical bodies. The analysis of the Russian adopted classification of gripper devices for industrial robots has shown that the existing schemes of mechanisms do not allow to realize a number of specific requirements to the gripper devices of drilling robots: a wide range of grip diameters and providing the possibility of rotation of the gripped body. The paper is devoted to geometrical synthesis of a gripper mechanism for a drilling robot. In the work the scheme of gripper mechanism is offered which provides the possibility of gripping and rotating massive cylindrical bodies of a wide range of diameters. An analytical and kinematic models of such a mechanism are developed. The analytical model of the mechanism includes a set of mathematical dependences describing the motion of all the links. We have developed the Mathcad program, by means of which we have determined the optimal parameters of the links of the mechanism in order to achieve the widest range of capture diameters.

1 Introduction

Robotic solutions in the oil and gas industry are spreading rapidly. Drilling robotics increases the efficiency of drilling operations and has a significant positive impact on occupational health and safety [5, 10-11]. A recognized leader in drilling robotics is the Norwegian research company Robotic Drilling Systems [18], which introduced four versions of high-precision autonomous robots as part of a single production complex.

In the process of designing the assemblies and parts of robotic systems there are solved the problems of optimal location of drives and mechanisms in the body of the gripper device, taking into account the restrictions on dimensions and weight characteristics of a particular anthropomorphic robot model. The use of computer-aided solid-state models of the machine greatly extends the capabilities of obtaining the optimal result on the overall dimensions and weight characteristics of the whole machine.

In [24] the authors demonstrate the process of CAD-model optimization using the results of CAE modeling and MathCad calculations as an integrated approach. MathCad was used for calculations based on data obtained from CAD-model dimensions in Creo

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environment. The simulation result is covered by feedback for the optimization procedures in MathCad.

An effective approach in design based on CAD-CAE systems integration is stated by the authors of papers [9, 14], which present the results of structural design optimization using an open integrated tool environment that allows engineers to efficiently search in a CAD solid model the design of a mechanism with optimal kinematic and dynamic parameters. The authors demonstrate the application of such an environment, in which the design parameterization is performed, which supports the variation of design parameters in solid-state models of the product, based on which the optimization of the target parameter, implemented in the engineering software tools, is performed. In works [12-13, 15-17] the authors also show the effectiveness of designing designs of various objects and processes based on parameterization and subsequent design optimization by one or more target parameters.

It is noted in [6] that in recent decades the urgent need for stronger and lighter product designs, along with dramatic improvements in computing power, has led to the introduction of simulation into traditional product development. Simulation allows designers to create virtual prototypes that can accelerate the design phase and thus overall product development time. A new way of simulation-based design (SBD) is presented. He includes several simulation and optimization methods.

A number of authors [8, 15, 26] cite the results of their research in the field of parametric modeling and parameter selection for turbine and engine casings, parts. They applied the second-order response surface method (RSM) to build an approximate model instead of numerical simulation in the optimization process to reduce optimization time, the «numerical twisting method» to design and manufacture impellers and blades, Creo Parametric software to construct a 3D model of a connecting rod, which was imported into ANSYS software to perform finite-element analysis and optimization

The design of soft grippers is a growing area of research because of their great capabilities in automation. One of the challenges in robot design is the ability to grasp a wider range of objects with variable stiffness, shape and size with a single gripper. Thus, a model of an ideal design of a soft robotic gripper with variable stiffness is presented in [29]. Its distinctive features lie in the methods used for modeling gripper mechanisms and in the variable stiffness characteristics of the soft gripper. Multi-purpose functions such as gripper displacement and force transfer coefficient are taken into account in the simulation and the functions of the mechanism are controlled by the MDF (multiple degrees of freedom) matrix. The exact stiffness required for gripping an object is then selected using an adaptive optimization method. The developed ABBIRB-1410 robot gripper type can improve the work cycle in industrial applications and perform object gripping with the required reliability and speed.

The authors of [27] have developed a new MATLAB tool package for simulation of robots with grippers. Kinematic analysis, simulation of arm movements, and gripper device are performed. The tool library contains various parameters, such as finger sizes, joint angles, etc., that are used for kinematics of various soft grippers.

An adaptive gripper design is demonstrated in [22]. Reducing the magnitude of contact strains is key in many practical applications to reduce potential damage due to excessive contact pressure. The gripper is constructed using a new accurately simulate method to the interaction between a compliant gripper and a deformable object. The main advantage of this method over existing conventional approaches such as finite element analysis (FEA) is its computational efficiency, which allows it to be used in optimization algorithms.

In [3] the idea of designing and analyzing new gripper manipulators with configurable platforms is put forward. First, a GPM-type synthesis is performed and a new class of reconfigurable manipulators with remotely controlled grippers is constructed. Then, based

on the kinematic model, the motion system and the parameters of the manipulator reconfiguration are analyzed. Additionally, a gripper position analysis is performed to evaluate the workspace and identify motion characteristics. Numerical examples and simulation results are obtained to demonstrate the presented methodology.

A study [23] presents the result of designing a new three-fingered gripper controlled by a four-link mechanism. The optimal mechanism provides a trajectory that approximates the arc of a lattice circle. Thus, the independently controlled three fingers of the prototype either surround or squeeze the object with one degree of freedom for each finger. Thus, the gripper provides a force closure when gripping a load. The change in force acting on the gripping element along the trajectory was presented in comparison with calculations for 32 static cases of gripping cylindrical objects. A regression analysis between the calculated values and the measured data showed a high pre-trustworthiness of the model. The mechanism provided a contact force in the range of 155-215 N along the trajectory.

In [30], a gripping device was proposed that should be adaptable to objects of different shapes and sizes. Therefore, a gripper with one degree of freedom (DOF) and a six-arm mechanism was developed. A design method based on proportional coefficients has been proposed in which the constraints are complex and the gripping mechanism has many structural parameters. The efficiency of the design can be improved by decreasing the target path according to the proportional coefficients. A hexagonal mechanism with one DOF, satisfying the finite constraints, has several modes of operation with a single actuator. Based on this, the elastic element is added as part of the mechanism rather than outside of it, and a mechanical model of the rigid-flex coupling is created to analyze the effect of the elastic element on force additivity.

In [1], a design of a new gripper, which can be used in various automation processes, including "pick-and-place" operations, was developed. This project is mainly designed for educational and research purposes, especially for students studying mechatronics and robotics. The grip consists of four fingers that move simultaneously, allowing the grip to open and close. It is a one degree of freedom (DOF) system. One finger is driven by an electric motor through a four-link mechanism. The motion is transmitted from the lead finger to the other three fingers through a slide-and-crank mechanism. The results of the research for determining its geometrical and kinematic models are presented and verified with the help of the CAD-model of the gripper. Given some given dimensional constraints, acceptable functional sizes and singular configurations are determined. The finger profile is designed for gripping objects of different shapes. A prototype is developed and tested to verify the design.

A new gripping mechanism with redundant 2-DOF constraints of the parallel wrist with a large range of motion without singularity is presented in [25]. This mechanism produces a two-coordinate pure rolling motion on a sphere. The mechanism is compact, light, stiff and fast. Using a geometric approach, compact parametric closed inverse and forward kinematic models of the mechanism and Jacobian matrices are obtained and it is shown that the mechanism has no singularities in the entire range of motion. It is shown that a large working space of rotation and displacement can be obtained with the right choice of design parameters. The correctness of the obtained models of inverse and forward kinematics is verified by comparing them with the results obtained with the help of the MSC Adams software. In the CAD, the analysis of contact interference is performed and the practical workspace of the proposed mechanism is obtained.

The authors of [7] discuss grippers made of soft materials that are well suited for flexible production due to their property of adapting to the shapes of workpieces. Unfortunately, the lifting capacity of such grippers is low, which prevents their wide industrial application. In this work, the possibility of using grippers to move and assemble heavy loads is investigated. After structural FEM simulations and physical experiments, the

authors state that the simulations are so reliable that computer-aided design of the gripping process becomes feasible without any preliminary experiments.

In [19], based on the developed design set of gripper elements for mechatronic parallel grippers and the characteristics of the motion objects as well as certain gripping points, a new method is described that allows one to automatically configure gripper elements with built-in sensors for several workpieces sizes. The requirements for the gripping elements are presented as a set of parametric functions, according to which the overall structure of the gripper device is broken down into modules according to technical and functional aspects. The gripping points with sufficient contact area with the workpieces are defined, which is the basis for the design of the entire gripper mechanism.

The paper [4] discusses the design and implementation of a high-speed electromechanical robotic gripper for gripping and manipulating objects. Unlike existing solutions, this gripper is able to manipulate objects, providing high productivity in complex industrial feeding and packaging operations. The motivation for the development of the gripper was the industry's need to manipulate products with complex geometries.

The analysis of the adopted in Russia classification of gripper devices for industrial robots showed that the existing schemes of mechanisms do not allow to realize a number of specific requirements to the gripper devices of drilling robots: cargo weight up to 1500 kg, a wide range of gripper diameters and providing the possibility of rotation of the gripped body.

2 Materials and methods

2.1 Geometrical synthesis of the gripper mechanism

The aim of the work is geometrical synthesis of a new clamping mechanism of a drilling robot, which has a number of specific requirements, ensuring its use as a part of the gripping device of a drilling robot. The research tasks are to develop a scheme of the mechanism, its mathematical and kinematic models, which are used to determine the optimum combination of parameters ensuring the largest diameter of the gripper and the load clamping force.

The gripping device of the drilling robot is designed for gripping, trans-orting, mounting, rotating massive cylindrical bodies - cargo (drill pipes, tools for well construction and maintenance). Input data are:

Cargo diameter range (mm) $D_{\min} \dots D_{\max}$

Cargo-carrying capacity of the gripper (kg) P ;

Method of changing of gripper - automatic;

Clamping scheme - four-point;

Maximum acceleration during transportation of cargo (m/s^2) a_{\max} ;

Speed of cargo rotation (min^{-1}) $n_{\min} \dots n_{\max}$.

According to the classification of gripping devices (GD) of industrial robots adopted in Russia, the designed device:

According to the principle of operation - clamping device;

By the character of object positioning - centering GD with an additional attachment for rotating the gripping object;

By the number of working positions - a single-position GD;

By the type of control - adaptive positioning GD;

By the nature of attachment to the robot arm - a GD suitable for automatic changeover

A diagram of the gripping mechanism is shown in the figure (see Fig. 1). Cylindrical cargo 8 with a diameter D_z (in the range from D_{\min} to D_{\max}) in the clamping device is based

on the conditions of 4-point contact using two fixed rollers 7 and two movable rollers 6, which make clamping movements. The figure shows the left part of the mechanism in which point *E* lies on rotation axis of the movable roller. The second part of the mechanism is symmetrical to the first with respect to the axis of the slide 1.

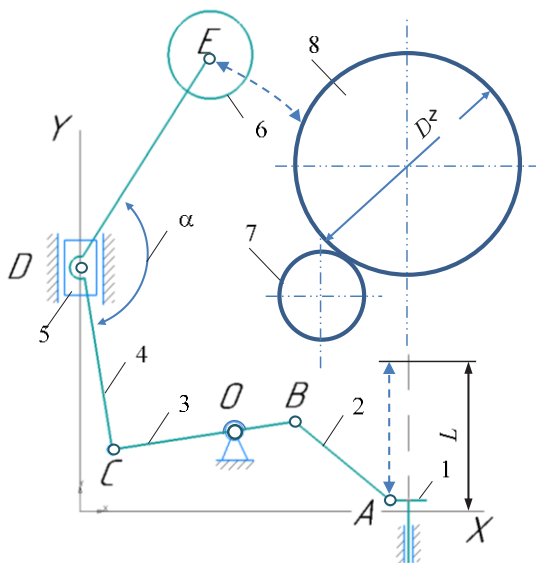


Fig. 1. Schematic of the drilling robot gripper mechanism. Compiled by the authors.

Here is a description of how the mechanism works. The source of motion of the slide 1 moves by the length *L* in the forward and reverse direction. The rod 2 performs a complex rotational and reciprocating movement due to the hinge connections with the point of the ram *A* and the point *B* of the rocker 3. The rocker 3 rotates relative to the stationary stand *O* and at point *C* is connected by a hinge to the clamping rod 4, which at point *D* is hinged to the slide 5 moving along the *Y* axis. The arms of crank 4 are rotated by angle α at point *D*. In this setting, the range of gripped diameters will depend on the length of the trajectory of movement of point *E*.

Structural analysis of the mechanism. Determine the number of links, types and classes of kinematic pairs of the mechanism. For a planar mechanism, the degree of mobility of the mechanism *W* is determined by the formula:

$$W = 3 \cdot n - 2 \cdot p_5 - 1 \cdot p_4, \tag{1}$$

where *n* is the number of moving links; *p*₅, *p*₄ are the number of kinematic pairs of the 5th and 4th classes respectively.

$$W = 3 \cdot 5 - 2 \cdot 7 - 0 = 1.$$

To find such a variant, which ensures the efficiency of the mechanism at the largest range of diameters of gripped objects, a mathematical model of the movement of points of elements of the mechanism was developed

The source of motion of the links of the mechanism is the rectilinear movement of point *A* at distance *L*. Divide the segment *L* into *N* equal segments. Introduce the index variable *i* = 0...*N*. Then the coordinates of point *A* for each *i*-th position are determined by the formula

$$X_A(i) = X_A = const, \quad Y_A(i) = L \cdot i / N. \tag{2}$$

The motion of rod 2 is described by two equations: the rotation of point B around point O; the movement of point A, which belongs to the ram and has co-ordinates from (1). The system of equations for determining the motion of point B is as follows:

$$\begin{cases} (X_B(i) - X_A(i))^2 + (Y_B(i) - Y_A(i))^2 = |AB|^2 \\ (X_B(i) - X_O)^2 + (Y_B(i) - Y_O)^2 = |OB|^2 \end{cases} \quad (3)$$

Point C belongs to the rocker 3 and functionally corresponds to the motion of point B rotated by 180 degrees with respect to point O. The coordinates of point C are determined by the formula

$$\begin{aligned} X_C(i) &= X_O + |CO| \cos \left(\arctg \left(\frac{Y_O - Y_B(i)}{X_O - X_B(i)} \right) + \pi \right) \\ Y_C(i) &= Y_O + |CO| \sin \left(\arctg \left(\frac{Y_O - Y_B(i)}{X_O - X_B(i)} \right) + \pi \right) \end{aligned} \quad (4)$$

Point D is the center of rotation of point C and simultaneously moves only along the Y axis ($X_D(i) = 0$). Therefore, solve the equation to determine $Y_D(i)$:

$$(X_D(i) - X_C(i))^2 + (Y_D(i) - Y_C(i))^2 = |DC|^2 \quad (5)$$

The end point E of the mechanism is rotated around the point D with respect to the point C by an angle defined by the formula

$$\varphi(i) = \arctg \left(\frac{Y_D(i) - Y_C(i)}{X_C(i)} \right) - \alpha + \frac{\pi}{2} \quad (6)$$

Then the coordinates of motion of point E are determined by the formula

$$\begin{aligned} X_E(i) &= X_D(i) + |ED| \sin(\varphi(i)) \\ Y_E(i) &= Y_D(i) + |ED| \cos(\varphi(i)) \end{aligned} \quad (7)$$

The presented mathematical model of point motion is used for multivariant designing of gripper mechanism parameters. The criteria for selecting the variants were the absence of point E deviation in the opposite direction when the stroke length L increases and the possible large difference $Y_E(0) - Y_E(N)$, which provides the maximum range of clamped diameters.

2.2 Gripping force

A feature of the gripper is the wide range of clamping cylindrical surfaces of drill pipes, tools and other attachments used on the drill rig. The clamping force at any diameter of the cylindrical surface must provide a firm grip. For each diameter a different pattern of roller contact points will correspond to the cargo. Consequently, to ensure the necessary clamping

force of the cargo it is necessary to determine the drive parameters for different diameters of the clamped surface (see Fig. 2).

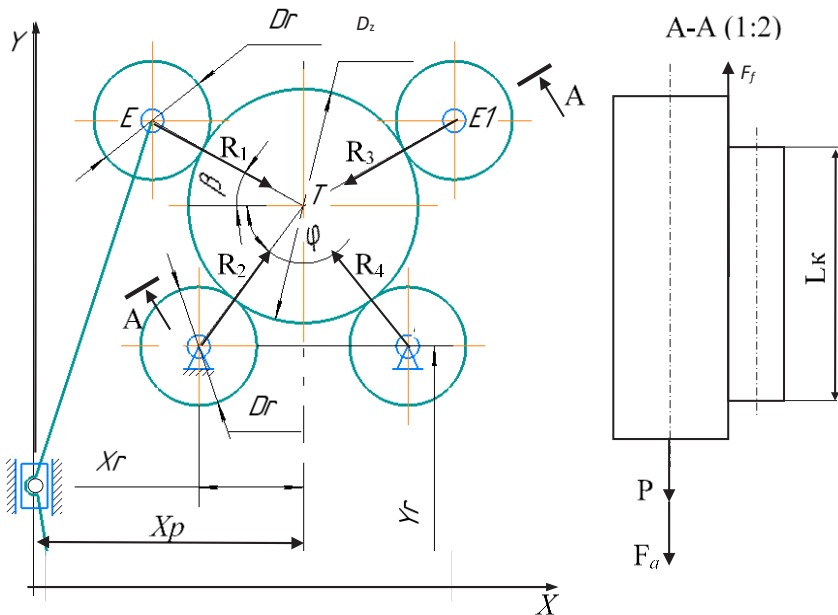


Fig. 2. Schematic of the clamping forces in the gripper. Compiled by the authors.

The rollers of length L_k under the action of the clamping forces $R_1 \dots R_4$ come into contact with the workpiece and by the friction force F_f keep it from falling or turning, caused by the action of the gravity force of the cargo P and the inertial force F_a , arising from the movement of the workpiece with acceleration a . The length of the rollers must be selected to ensure that the contact stresses on the cargo material are acceptable.

For a mechanism whose links move at low speeds when the masses and moments of inertia of the links of the mechanism are unknown (at the stages preceding the conceptual design) we apply a static form of force calculation of the mechanism.

We take the most heavily loaded version of the gripper with the cargo, in which the weight of the cargo is directed vertically downwards (see Fig. 2). In this case, the gripper holds the workpiece only due to the friction forces between the rollers and the cylindrical surface of the cargo. The maximum gravity force P_{max} , taking into account the inertial force resulting from the accelerated movement of the cargo vertically upwards, and the safety coefficient K_z :

$$P_{max} = (P + F_a)K_z = (P + a \cdot P/g) K_z. \tag{8}$$

The frictional force required to hold the cargo is distributed over the four contact lines. Therefore, the force R_1 to be generated by a single gripper is determined by the formula:

$$R_1 = \frac{P_{max}}{4\mu}, \tag{9}$$

where μ is the coefficient of friction on the contact surfaces of the roller and the cargo.

According to the scheme of the mechanism (see Fig. 2), when clamping different

diameters, the center of the circle of the cargo moves along the Y -axis. In this case, the angle of the clamping force vector R_1 changes within certain limits, which can lead to spontaneous unclamping of the gripper mechanism when changing the layout of the load.

The diameter of the clamp D_z and its corresponding coordinate of the center of the circle of the load Y_l is determined from the system of equations:

$$\begin{cases} X_r^2 + (Y_l - Y_r)^2 = \left(\frac{D_z + D_r}{2}\right)^2 \\ (X_{Ej} - X_r)^2 + (Y_{Ej} - Y_l)^2 = \left(\frac{D_z + D_r}{2}\right)^2 \end{cases}, \quad (10)$$

where D_r is the diameter of the roller; X_r, Y_r are the coordinates of the stationary roller; X_{Ej}, Y_{Ej} are the coordinates of the endpoint E for the j -th position.

Tilt angle for the j -th position of the roller

$$\beta_j = \arctg\left(\frac{Y_{Ej} - Y_l}{X_r - X_{Ej}}\right). \quad (11)$$

Determine for the known angle β_j the vertical and horizontal projection component of the required clamping force by the formulas:

$$R_{xx} = R_1 \cos(\beta) \quad R_{yy} = R_1 \sin(\beta) \quad (12)$$

When the weight P_{\max} is horizontal and the gripping rollers are positioned at the bottom, the two vertical components of the clamping force $2R_{yy}$ counteract the maximum weight of the workpiece P_{\max} . Therefore, it is necessary to check the condition $2R_{yy} > P_{\max}$ to ensure that the gripping mechanism will hold the load securely in the horizontal position.

3 Results

By formulas (2) - (7) the program Mathcad is made, the text of which is shown in the figure (see Fig. 3).

With the help of CAD-system the kinematic model of the mechanism presented in

Fig. 4 was made, by means of which the efficiency of the mechanism with the calculated parameters: length of all links, coordinates of point O , angle of rocker, length of pusher stroke L was confirmed. Also the range of clamped load diameters from $D_{\min}=100$ mm to $D_{\max}=305$ mm was determined.

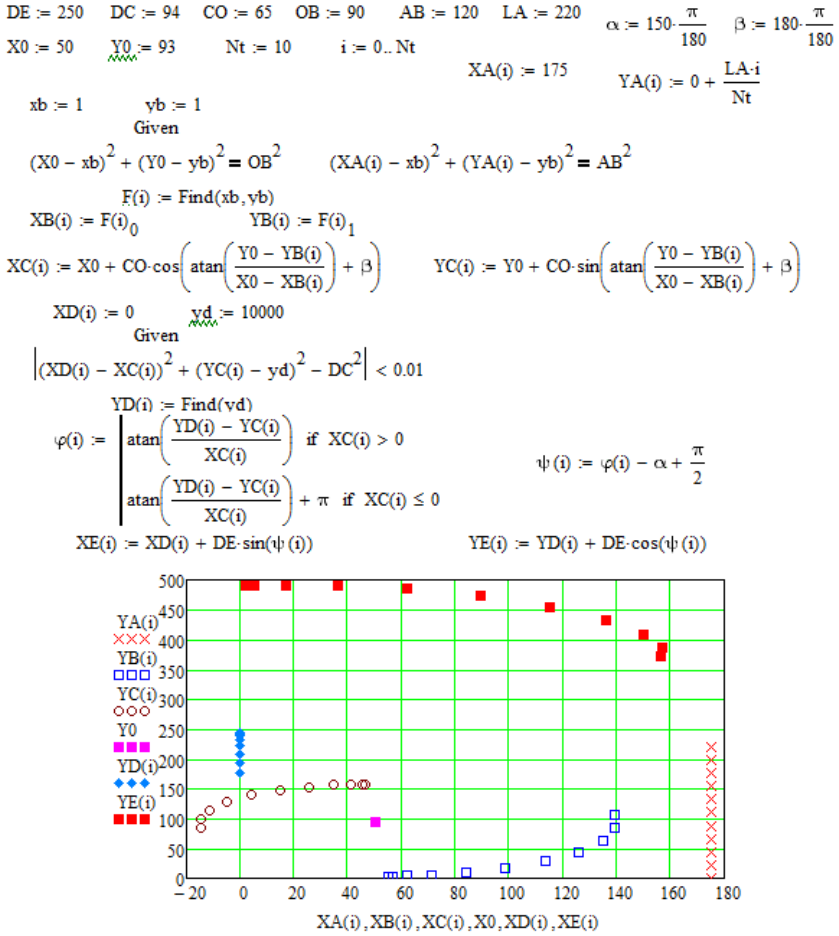


Fig. 3. Mathcad program for calculating the trajectory of the gripper mechanism points. Compiled by the authors.

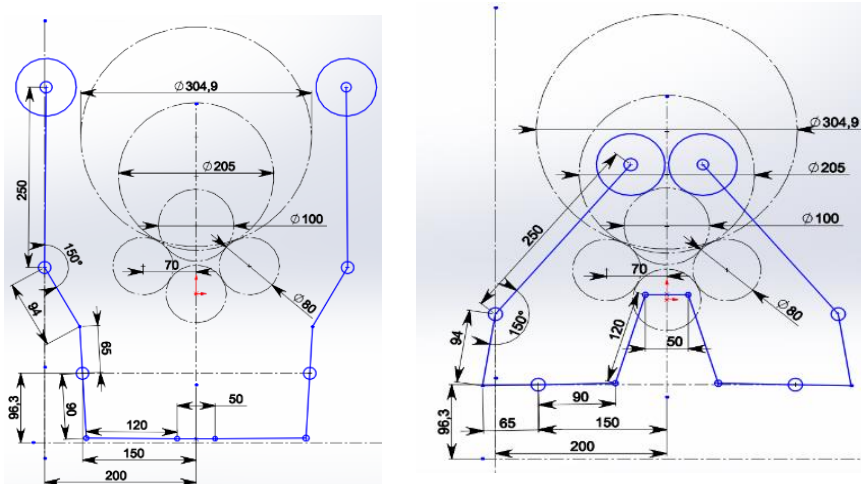


Fig. 4. Kinematic model of a clamping mechanism. Compiled by the authors.

Maximum force of gravity of the cargo P_{max} by formula (8) at $P=1500$ kg, $a=5$ m/s², $K_z=1.5$

$$P_{max}=(1500+5 \cdot 1500/9.81) 1.5 = 33968 \text{ N.}$$

Force R_1 by formula (9):

$$R_1=33968/4/0.35 = 24263 \text{ N}$$

Calculations according to formulas (10) - (12) are shown in Fig. 5.

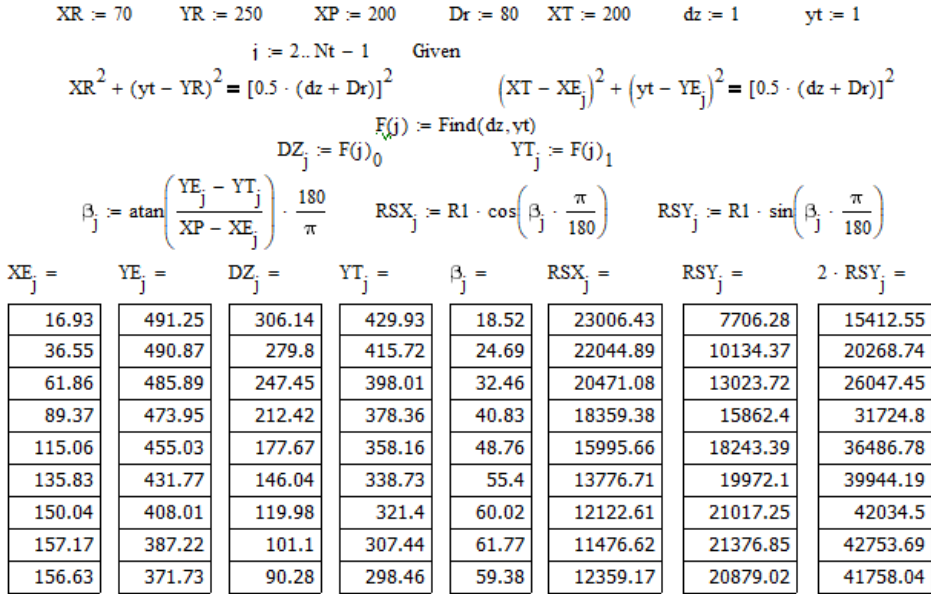


Fig. 5. Calculation of coordinates of cargo circle centers Y_i for clamp diameters D_z , the angle of inclination of the clamping force and its projection components. Compiled by the authors.

According to the results of calculations in Fig. 5 in the case of horizontal position of the load the condition $2R_{sy} > R_1$ is satisfied only at the range of load clamps from 90 to 247 mm.

Based on the above methodology, we consider an example of designing a mechanism for manipulating a cargo of 1500 kg, with an acceleration of 5 m/s². When the cargo is in a strictly vertical position, the gripper mechanism must generate a clamping force $R_1=24263$ N on a single roller. The calculation shows that in the range of clamping diameters of 90 ... 305 mm the angle of inclination of the clamping force increases approximately three times, from 18 to 60 degrees. Consequently, to maintain a given clamping force R_1 at different clamping diameters the projection components of this force change and have a significant impact on the links of the mechanism and on the conditions of holding the workpiece. Fig. 6 shows that for clamping diameters above 250 mm the conditions for reliable holding the load in the horizontal position are no longer met.

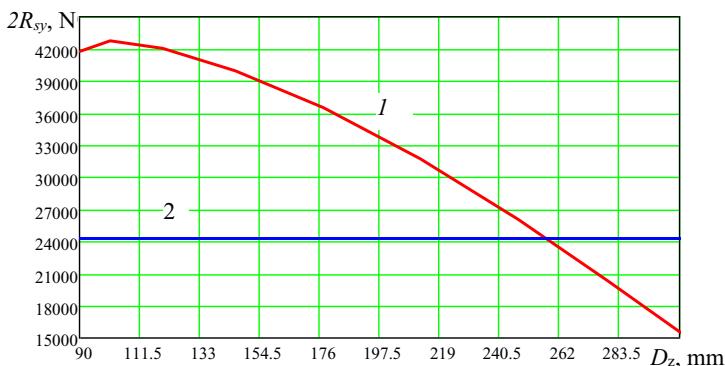


Fig. 6. Dependence of the doubled value of the horizontal component of the clamping force (1) on the diameter of the load. (2) - required clamping force R_1 . Compiled by the authors.

The test of the clamping force at the horizontal position of the load has shown that at diameters from 90 to 250 mm the load will be held reliably under the influence of its weight in the gripping links of the mechanism. However, for diameters over 250 mm the load holding condition is violated. Obviously, this is a constructive property of mechanisms of this type.

4 Discussion

By analogy with researchers in works [9, 14, 24] the sketch of gripper of the drilling work, constructed on the basis of mathematical model of movement of points of the mechanism in MathCad and kinematic model in CAD - system are presented. Using MathCad mathematical model the main parameters of links of the gripping mechanism have been determined according to the criterion of maximum range of gripped diameters. A kinematic model of the gripping mechanism confirmed the effectiveness of the mechanism and allowed to determine the range of clamped diameters.

Researches in the field of industrial robots also cannot do without wide application of CAD-CAE systems and understanding of features of force interactions at gripping of cargoes. Especially it is actual at development of new mechanisms of gripper devices. In [28], the behavioral effects of interaction between a man and a robotic gripper were studied, for which the parameters of the gripping force and the kinematic data of the gripper mechanism gears being designed were compared. Our work focuses on finding optimal combinations of kinematics and gripping force factors

In the studies [21], the situation was similar. We present gripping mechanisms with three and four degrees of freedom of the output link (DOF) to develop robot grippers that can perform twisting and rolling of loads. The kinematics of the gripper mechanisms are investigated. Measures to facilitate device miniaturization and advanced design concepts are discussed. We propose a methodology for finding the kinematic parameters of the mechanism to find the largest range of gripper diameters

The results obtained in the presented study are confirmed by the authors of [20], which discusses the application of an additional degree of freedom to create the possibility of rotating the load in the gripper device. The advantages of the proposed idea are to save the cost of a gripper drive and to reduce the weight of an industrial robot. Several variants of a kinematically redundant manipulating platform with five degrees of freedom are presented, as well as conceptual mechanical constructions for realization of gripper element motions.

In our work, the mechanism is also investigated when the diameter of the clamped load changes

5 Conclusion

In the article the design procedure of the gripper mechanism of a drilling robot is presented, in accordance with which the scheme of the mechanism, which provides four-point location and gripping of loads of different diameters, is developed. To find such a combination of mechanism parameters that would provide the maximal range of cargo gripping, a mathematical model of movement of mechanism links was created. Through the selection of a large number of variants we were able to determine the optimal combination of parameters of the mechanism. The kinematic model of the mechanism made it possible to check the operability of the mechanism and to determine the range of the captured loads.

The proposed methodology also includes estimation of necessary clamping force, which should be created by the mechanism when moving roller contacts the surface of the load to keep it reliably in vertical and horizontal position. This example shows that increasing the diameter of the clamp results in a significant change in the ratio of the two projections of the required clamping force. Therefore, for this type of mechanism it is necessary to consider this fact and check the conditions for reliable load holding in the vertical and horizontal position.

The gripper drive has to provide a different magnitude of tractive force for each clamping diameter. When performing a force calculation of the mechanism for a given clamping force, the parameters of the traction drive of the mechanism should be selected according to the highest required force on the drive slide. The obtained results can be used for creating and improving designs of gripper devices for drilling robots. In the future, our work can be used to create a series of standard sizes of gripper mechanisms for drilling robots with different load lifting capacity and range of gripping diameters.

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