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Simulation of the structural and force parameters of a robotic platform using co-simulation

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Abstract

The paper presents the methodology and results of modeling the operation of the parallel mechanism - a 6-DOF robotic platform of the Stewart-Gough type. MSC Adams and Matlab software packages were used as modeling tools, as well as a general-purpose, high-level object-oriented programming language, Python. The digital layout, which has the properties of a parameterized simulation model, is built in the MSC Adams software package. The Python programming language is used as an alternative to the Adams View internal command language for creating and iteratively modifying modeling objects in Adams. Mutual integration of Matlab Simulink and Adams View provides the implementation of joint simulation and allows to perform kinematic, dynamic and force analysis of the mechanism, taking into account its design features through the use of a virtual prototype. Simulink provides the ability to import of physical and mechanical parameters of a solid model from Adams. The proposed implementation of the Python-Adams interface in the form of special procedures and functions automates the execution of a computational experiment and allows solving the problem of optimizing structural elements and finding the optimal geometric design of the platform in accordance with the selected optimality criteria. This is implemented through conducting a series of experiments consisting in sequential multiple changes in geometric parameters, followed by simulation model and analysis of the results in order to find design options that meet the specified criteria. The technique was tested on the example of one of the design versions of the platform when moving along several characteristic types of a given trajectory. The results of a computational experiment are presented and an analysis of the force characteristics during movement along a given trajectory is carried out.

Keywords: design optimization, parallel manipulators, virtual prototype, simulation modeling, kinematic characteristics, Stewart-Gough platform.

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1. Introduction

Mechanisms of parallel kinematics have recently become quite widespread, first of all, these are parallel robotic mobility platform (RMP) used in tool positioning systems in mechanical engineering and medicine, in simulators of aircraft and military equipment, for orienting telescopes and antennas. A feature of these mechanisms are parallel kinematic links that transmit movement from a fixed base to a movable end-effector. The prospects for the use of such mechanisms are determined by a wide range of possibilities for solving operational problems: testing high-tech equipment and its individual components; use as moving bases in simulators to control equipment (cars, aircraft, specialized equipment); creation of specialized devices for holding various devices and actuators in a given position during movement. The use of mechanisms with a parallel structure is quite effectively implemented in simulators that simulate the processes of controlling mobile technical equipment, where 6-degree positioning systems are implemented as the main drive devices. The widespread application of parallel RMP is due to design features that provide a number of operational advantages: simplicity of the mechanism elements and their assembly, high structural rigidity, low weight and low metal consumption with comparable rigidity, high load capacity, increased accuracy of movement and positioning, good dynamic characteristics , high speeds and accelerations, the possibility of simple scaling of the device circuit. Parallel mechanisms also have disadvantages: a relatively small workspace , the presence of special positions in which there is a loss of controllability, a nonlinear dependence of kinematics and dynamics on the point of the workspace , the complexity of the control system, the possibility of interference of supports. Efficient implementation of technical problems in the use of parallel RMP in various fields has served as an impetus for many studies aimed at maintaining the advantages while reducing the disadvantages of these mechanisms [1]-[19]. The following main tasks solved by researchers in this field can be distinguished:

- elaboration and optimization of the structural layout, determination of the possibilities and conditions for the use of a certain standard size for various operational tasks when designing new designs [1]-[4];
- determination of the possibilities of using a certain standard size of the platform in accordance with the boundary values of the parameters of its drive links for working out the given geometric parameters of the trajectory, for example, the maximum allowable movements of the executive body in given directions [5];
- development and study of the laws of motion control in drive links (electric cylinders) in accordance with a given trajectory of movement of the final link (the inverse problem of kinematics) [6]-[11];
- testing of the control system in order to check the required trajectories of movement of the end-effector (actuator or moved object), determination of positioning accuracy [12];
- kinematic, dynamic and force analysis of the mechanism, development of algorithms for determining the set of achievable positions of the platform during the formation of its workspace [13]-[19].

To solve these scientific problems, researchers use mathematical models and various analytical methods, physical models and laboratory stands, as well as applied software tools that open up wide possibilities for studying and modeling the kinematic and dynamic parameters of mechanisms. This work is a continuation of this direction, and it is proposed to use Adams View - Matlab Simulink co-simulation as a modeling tool using the Python-Adams interface.

Co-simulation has now become a powerful tool for the design of engineering systems. Co-Simulation uses a set of specialized software packages and allows designers to explore various aspects of a system, as well as automatically estimating the parameters of a much larger number of design options compared to manual trial and error. Co-simulation is an effective method for solving multiphysics problems.

Dynamic analysis of the co-simulation environment provides a visual output of the functional parameters of the system under study in real time and allows to check its performance on a virtual prototype. When developing a control system, this reduces the need for hardware prototyping and subsequent testing of the control algorithm. Co-simulation saves time and allows to modify structural elements before fabrication.

One of the topical problems, within the framework of which co-simulation can be used, is the study of the kinematics and motion dynamics of parallel manipulators. This is due to the fact that due to the design features, namely the presence of parallel kinematic links, the disadvantage of these mechanisms is the possibility of interference (crossing) of individual kinematic chains and, as a result, the occurrence of special positions in which stability can be lost. In addition, there is a nonlinear dependence of the kinematics and dynamics of the mechanism depending on the point of the workspace, which leads to anisotropy and inhomogeneity of dynamic, elastic and speed properties. In this regard, the solution of these issues attracts the attention of many researchers [1]-[19].

2. Main part

This paper proposes the use of Adams - Matlab co-simulation for testing a given trajectory of movement of the end-effector of a parallel manipulator and studying the torque characteristics that occur during movement. This computational approach makes it possible to numerically solve problems of kinematics, dynamics, and motion control, as well as significantly reduce analytical and programming efforts. When using classic Simulink schemes to simulate the movement of a mechanism, it is necessary to determine the acting forces and use them as input parameters of the model, which in some cases is a separate, difficult task. One of the advantages of Adams - Matlab co-simulation is the ability to omit this step and apply to the input of the model not a force, but a kinematic parameter, for example, the extension of the rod when simulating the movement of a parallel manipulator such as the Stewart platform. This is possible by using Adams special functions (Joint Motion), responsible for the implementation of the movement of the mechanism.

To implement the proposed approach, the following main tasks have been implemented:

- creation of a virtual prototype in the Adams environment ;
- building a control system in Simulink ;
- export and integration of physical and mechanical parameters of a solid model from Adams into a control system created in Simulink ;
- Adams View - Matlab Simulink co-simulation.

A virtual prototype of the robotic platform has been developed for simulation modeling of kinematic and dynamic parameters that characterize operating conditions under the action of workloads. It shown in Fig. 1. A digital layout with the properties of a parameterized simulation model was created in the MSC Adams software package and consists of 14 main idealized elements (details): a base, a movable platform, six rods and sleeves.

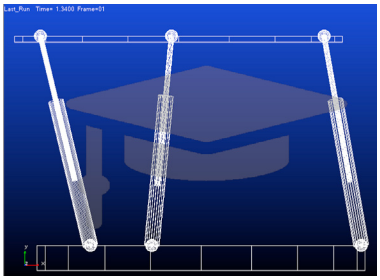

Fig. 1. Digital simulation model of the RMP, made in MSC Adams.

To control the parameterized model with the possibility of its automated rebuilding in MSC Adams , the interface of the high-level general-purpose object-oriented programming language Python was used. The Python programming language is used as an alternative to the Adams View internal command language for creating and iteratively modifying modeling objects in Adams. The Adams -Python interface is an application programming interface that allows to interact with Adams using an object-oriented structure in which each entity in Adams is mapped to a class in Python that has properties and methods.

The choice of Python is due to the ability to solve the task of optimizing structural elements and finding the optimal geometric design of the platform in accordance with the selected optimality criteria by conducting a series of experiments consisting in sequential multiple changes in geometric parameters, subsequent simulation of the model and analysis of the results in order to find design options that meet the specified criteria . The use of Python allows to automate each of the described steps of the computational experiment using special procedures and functions, while the software implementation eliminates the need for time-consuming manual execution of the listed manipulations. Thus, the use of Python can significantly increase the effectiveness of a computational experiment by replacing manual manipulations of creating and rebuilding solid elements in Adams with automated software procedures, reducing labor intensity, increasing the arbitrariness of the process and the number of possible computational simulations.

To implement the above task, the following special procedures and functions have been developed:

— procedure FindPoint for determining the coordinates of the points of conjugation of the electric cylinders with the base and the table, which sets the coordinates of the corresponding points in the polar coordinate system;

— the CreateModel procedure for creating a platform model in AdamsView , in which, using the Adams Python interface, the necessary procedures are called to create model components;

— the procedure ChangeModel for changing the geometric parameters of the model, which recalculates the geometric parameters, such as location and orientation for all model components that have these properties;

— function Simulations (qt , number_of_steps , end_time) for performing a computational experiment associated with multiple design changes and subsequent simulations, which takes the necessary parameters as input: qt is the required number of simulations, number_of_steps — the number of steps in the simulation, affecting the accuracy and speed of the process simulation, end_time is the end time of the simulation. In this function, in a loop of size qt , the changes in geometric parameters necessary for the experiment, rebuilding the model (ChangeModel) and performing the simulation itself are performed using the appropriate call to the Adams Python interface command. The function returns a tuple consisting of three arrays of results, including the amplitude and average values of the parameter with respect to which the optimization is performed, as well as an array of geometric values;

- procedure AnalisesOfRes uses the output parameters of the Simulations function to analyze the computational experiment results and search for simulations that correspond to the studied geometric parameters of the model according to the specified optimality criteria. The results of the analysis are output to the Adams command line.

To simulate real constructive interfaces of RMP, the following special software operators of the Adams application were used : the Base is fixed to Ground using FixedJoint , the sleeve is attached to the base using SphericalJoint , the EC rods are similarly paired with the working surface of the platform. To simulate the movement of an electric cylinder, the sleeve and the rod are interconnected at the points of contact by a TranslationalJoint. As external forces, the force of gravity directed vertically downwards (in the direction of the axis - OY) and the payload applied at the point of the center of mass, which is specified in accordance with the requirements of the designed RMP industrial design, are set.

Figure (2) shows the Simulink scheme used to simulate the movement of the end-effector of a parallel manipulator. Let us consider in more detail the functional purpose of individual blocks. Euler block XYZ transforms a set of Euler angles into an appropriate rotation matrix. Block Inverse Kinematics Module is designed to solve the inverse problem of kinematics, generating the required extension lengths of the rods at the output. The Saturation block simulates the physical constraints on the movement of electric cylinders associated with their design. A feature of this scheme is the block Adams_sub , exported to Matlab from Adams . The Adams_sub block contains the physical and mechanical parameters of a solid model created in Adams and allows to visualize the trajectory of the end-effector, as well as determine the necessary force- torque characteristics of the mechanism. Integration of this block provides Adams View - Matlab Simulink co-simulation process. For proper integration of the block and the implementation of co-simulation, it is necessary to set the input and output parameters of the system. As input parameters, the coordinates of a given trajectory of movement of the end-effector, which change in time, are used. The point located in the center of the movable platform is taken as the coordinate of the end-effector. At the output of the Adams_sub block, the actual coordinates of the end-effector are generated, taking into account the design parameters of the mechanism and its physical and mechanical properties. If the specified trajectory of movement does not correspond to the real parameters of the mechanism, a simulation error will occur. This can happen, for example, when peak force loads exceed the allowable ones. Thus, the implementation of joint simulation allows to check and work out the necessary trajectories of motion, determined in accordance with the functional purpose of the manipulator.

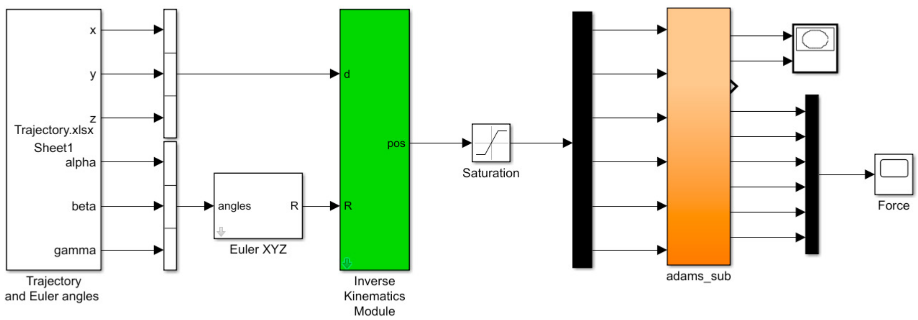

Fig. 2. Simulink scheme for working out the trajectory of the movement of the end-effector of a parallel manipulator.

Two coordinate systems were used for simulation: a global Cartesian coordinate system with the origin at the geometric center of the base and a local relative Cartesian coordinate system with the origin at the geometric center of the end-effector (movable platform). The input parameters of the system are given by the coordinate vector of the points of the trajectory being worked out as an increment (change) relative to the zero (initial position), that is, a local relative coordinate system is used. The coordinates of the base joints and the coordinates of the initial positions of the joints of the movable platform are given in the global coordinate system. In the initial position, the directions of the axes of the global and local coordinate systems coincide. When the end-effector moves along a given trajectory, the local coordinate system can turn at certain angles with respect to the global coordinate system. To take this circumstance into account, a generalized rotation (transformation) matrix is used:

$$R_j = \begin{bmatrix} \cos\beta_j\cos\gamma_j & -\cos\beta_j\sin\gamma_j & \sin\beta_j \\ \cos\gamma_j\sin\beta_j\sin\alpha_j + \cos\alpha_j\sin\gamma_j & \cos\alpha_j\cos\gamma_j - \sin\alpha_j\sin\beta_j\sin\gamma_j & -\sin\alpha_j\cos\beta_j \\ \sin\alpha_j\sin\gamma_j - \cos\alpha_j\cos\gamma_j\sin\beta_j & \cos\gamma_j\sin\alpha_j + \cos\alpha_j\sin\beta_j\sin\gamma_j & \cos\alpha_j\cos\beta_j \end{bmatrix} \quad (1)$$

where α , β, γ are the Euler angles, respectively, the angles between the abscissa, ordinate and applicate axes of the two accepted coordinate systems; j is the number of points of the investigated trajectory of the movement of the end-effector.

3. Results

The presented technique was used by the authors to develop and optimize alternative options for the design of a robotic platform based on an analysis of the force conditions of movement along a given trajectory. The relative position of the joints of the movable platform and the fixed base was taken as the studied design parameter, as the optimality criterion - the minimum force required to perform the movement, as the limitation - the excess of the acting force relative to the specified one based on the strength characteristics of the structure. There are many known layouts of the location of the joints, including symmetrical and asymmetrical arrangement [1, 2], as well as various options for the angles of inclination of the platform joints relative to the base joints. The authors studied a symmetrical layout, in which six base joints are located symmetrically and an angle of 60° is formed between all adjacent joints , as well as many options for the angles of inclination of the platform joints relative to the base in the range from 1° to 25°. For example, Fig.3 shows three variants of digital models with inclination angles in pairs: ±1°, ±10° and ±25°.

Six typical platform movements were taken as test variants of the movement trajectory: three translational (vertical, longitudinal and lateral) and three rotational (pitch, yaw and roll). When performing a computational experiment, 50 simulations were carried out for each typical movement. For all series of computational experiments, a periodic sine function was taken as a function characterizing the trajectory of motion in time. The results of the computational experiment are presented in Fig.4 - 6.

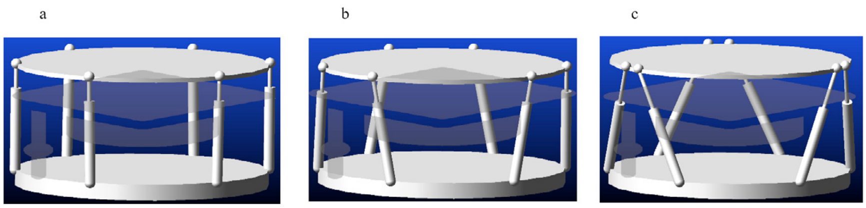

Fig. 3. Options for the relative position of the platform and base joints: a - 1°, b - 10°, c - 25°.

Computational experiments were performed with the following design parameters of the robotic platform: base radius - 1.654 m, table radius - 1.654 m, table height - 1.385 m, rod stroke - 0.2 m, payload - 1000N. Based on the results, it can be concluded that the angle of inclination of the joints of the movable platform relative to the fixed base has a significant impact on the formation of the force characteristics of the movement and on the possibility of working out a given trajectory. Small angles of inclination (less than 5°) form very large loads in the joints (more than 100 kN), which significantly exceed the design operational capabilities of the applied linear motion drives, the nature of the change in forces in the joints is close to exponential dependence, rapidly increasing peak loads prevail (Fig. 4).

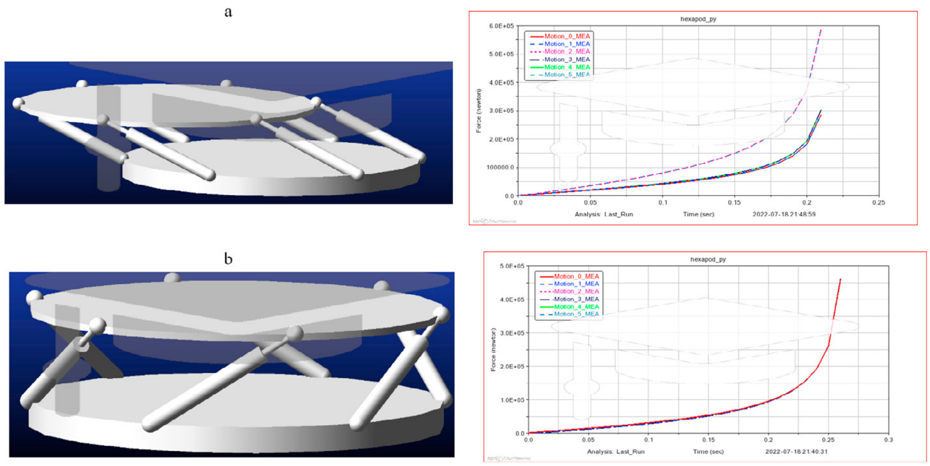

Fig. 4. Results of a computational experiment for a design variant with an angle of inclination of the platform joints relative to the base ±1°: (a) longitudinal displacement ; (b) yaw.

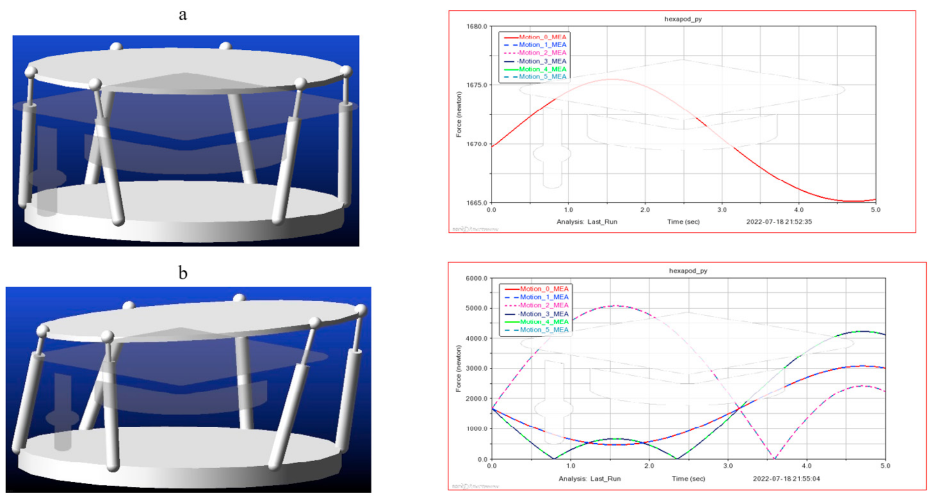

Fig. 5. Results of a computational experiment for a design variant with an angle of inclination of the platform joints relative to the base of ±10°: (a) vertical movement; (b) roll.

Large inclination angles (more than 10°) form softer and more stable force characteristics corresponding to the real operational parameters of linear drives (Fig. 5, 6). Figure 7 shows the force characteristics of all considered typical movements depending on the angle of inclination of the platform joints to the base. The most unfavorable option, which forms a peak load for almost all typical movements, which significantly exceeds the operational capabilities of linear motion drives, are small angles in the range of 3 – 6°. With an increase in the angle up to 10°, the force loads significantly decrease and stabilize, and at angles greater than 10°, the force pattern remains almost constant, with the only exception being the type of vertical movement, where the force load monotonically increases with increasing angle.

4. Conclusions

Presented Matlab Simulink-Adams View Co-Simulation Technique using the Python-Adams interface shows good results and allows to perform kinematic, dynamic and force analysis of the mechanism, taking into account its design features through the use of a virtual prototype . The technique makes it possible to compare alternative design options

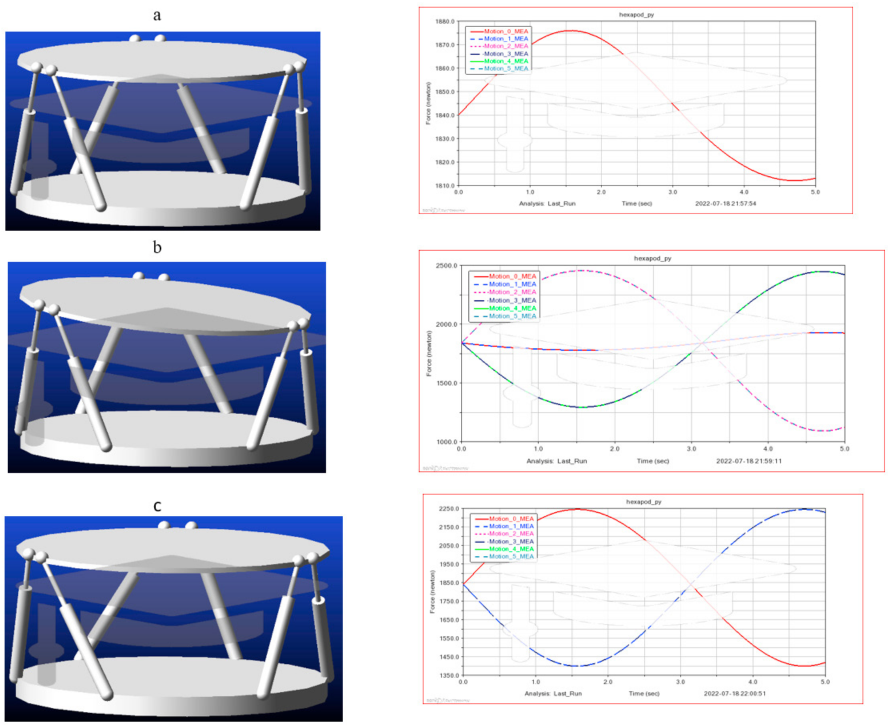

Fig. 6. The results of the computational experiment for the design variant with the tilt angle of the platform joints relative to the base ±25°: (a) vertical movement; (b) roll; (c) yaw.

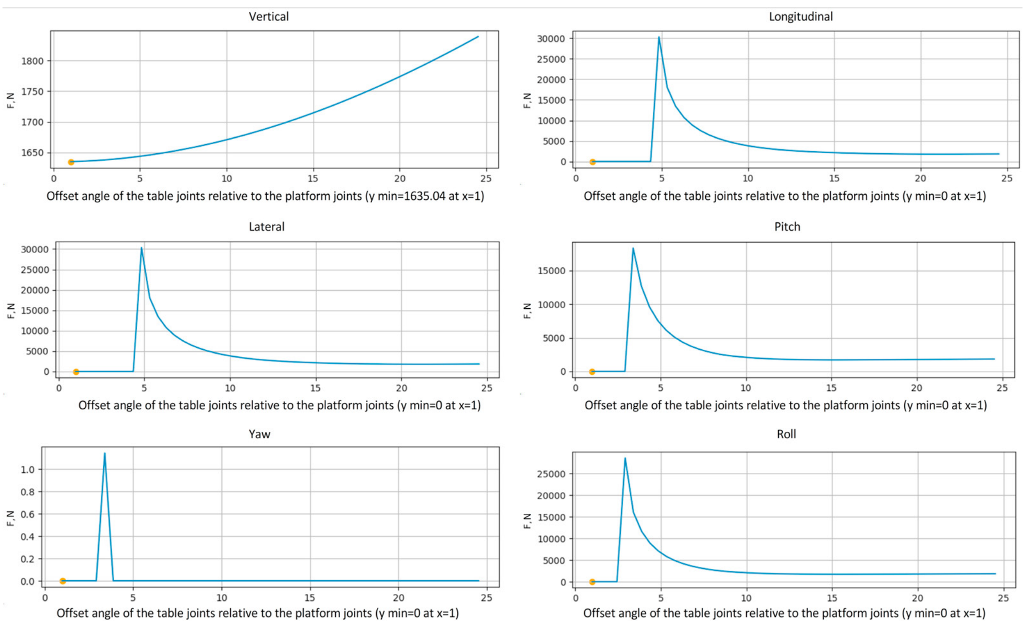

Fig. 7. Force characteristic during trajectory of typical movements depending on the angle of inclination of the platform joints to the base.

in terms of the force characteristics of the process when working out the given trajectories of movement, as well as to identify problem areas and unattainable coordinate positions, including in the automated mode of running simulations and analyzing the results of a computational experiment. The presented approach is applicable in the framework of the development, modernization, optimization of structural elements of parallel manipulators, the definition of the workspace, and the development of motion control systems.

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