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Mathematical Modeling of a Solar Arrays Deploying Process at Ground Tests

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Abstract. This paper focuses on the creating of a mathematical model of a solar array deploying process during ground tests. Lagrange equation was used to obtain the math model. The distinctive feature of this mathematical model is the possibility of taking into account the gravity compensation system influence on the construction in the deploying process and the aerodynamic resistance during ground tests.

1. Introduction
An obligatory stage of the spacecraft creation is the testing of its subsystems [1]. The gravity compensation stands are used for ground testing of the solar array deploying process. Mathematical modeling of the solar arrays deploying process during ground tests is carried out to assess the implementation of the stand weightlessness features of the deployable elements and minimize the impact of added masses and other elements of the stand on the solar array's drives [2, 3]. Math model include kinematic and dynamic models of the solar arrays and dynamic models of the stand tracking systems. The requirements to the stands increase with developing of the space constructions and complication of the solar array structure. It leads to the necessity of creation of the more precise mathematical models.

The article considers the method of the mathematical modeling of the solar arrays deploying process, which is directed at the applied task solution of describing the deploying process for more often useable types of the solar array construction. The distinctive feature of this mathematical model is the possibility of taking into account the gravity compensation system influence and the aerodynamic resistance on the construction in the deploying process during ground tests.

2. Selection of a Solution Approach
There are three approaches of the computing modeling of the solar array deploying process.

The first approach consists in drawing up the differential equations of the mechanical system and their analytical decision. In this case a special mathematical software is used [4-6], which allows carrying out all the necessary operations in a symbolic form. The numerical values of parameters are substituted in the resulting symbolic expressions. This approach was applied for describing the deploying process of solar arrays in work [7]. The disadvantages of this approach include the high costs of computer performance.

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The second approach is called algorithmic. It consists in numerical integration of the differential equations. It is possible to construct a calculation algorithm of dynamic and kinematic movement system characteristics using the set parameters and initial conditions. This approach is widespread in the applied mechanics and robotics. The algorithms of this approach are based on the physical laws and principles, such as D'Alembert principle, Lagrange equations, and others [8]. An example of the second approach of the solar arrays deploying process modeling is in work [8].

The third approach consists in the block diagram creating [9, 10] or using the mechanical assemblies, which are realised by means of CAD applications [11]. This approach is the most popular and easiest way of computer modeling, as it reduces the possibility of mistakes in the model composition.

Let us apply the second approach of modeling of the solar arrays deploying process during ground tests. We have a holonomic system with n degrees of freedom, which is not relieved from the stationary connections. This system consists of the units with known mass and inertial parameters which are consistently connected with the fifth class kinematic couples. The system dynamic could be described by Lagrange equations [6]:

$$\frac{d}{dt}\left(\frac{\partial W}{\partial \dot{q}_i}\right) - \frac{\partial W}{\partial q_i} = Q_i \qquad i = \overline{1,n}, \tag{1}$$

where W – the kinetic energy of the system, q_i – the generalized coordinates, Q_i – the generalized forces.

The kinetic energy of system W is the sum of kinetic energies W_i of its components:

$$W = \sum_{i=1}^{n} W_i, \qquad i = \overline{1,n}. \tag{2}$$

The number of units is equal to the number of degrees of freedom.

In this article we will consider the active suspensory gravity compensation system [12]. The working principle of the active gravity compensation system is applied to each unit mass center of the weight compensation forces. These forces are generated by the electromechanical actuators. The main requirement for the gravity compensation system is the lack of the additional forces and torques due to interaction of the suspensions and solar arrays. For this purpose, all trajectories and velocities of the mass centers could be accurately calculated for all units of the solar array structure. The calculation and the change of the compensation forces are performed in real time in accordance with the parameters of the motion of the structure.

3. Differential Equations of the Movement

We will form the differential equations of the movement in a horizontal plane for the solar arrays of the ‘Express-2000’ platform (Figure 1). Angles $\varphi_i, i = \overline{1,4}$ are taken as the generalized coordinates.

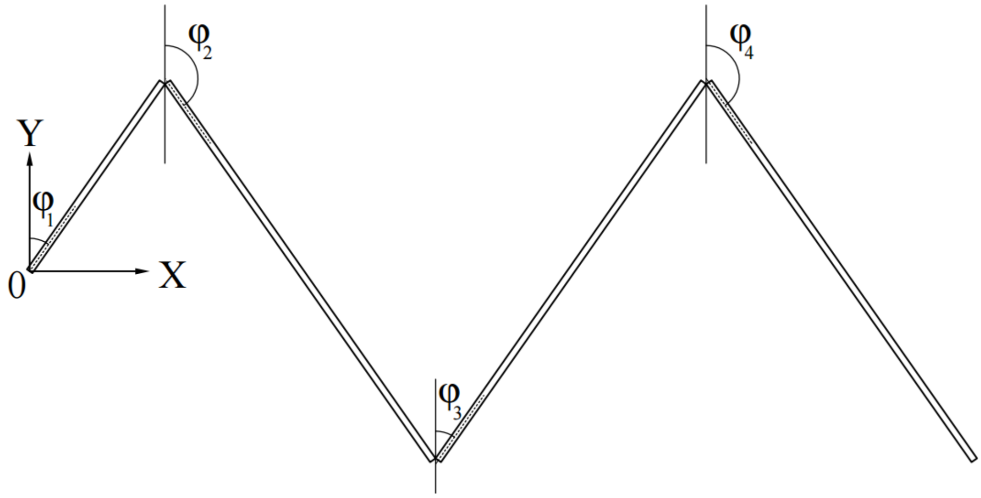

Figure 1. A schematic representation of the solar arrays.

The first unit (rod) makes a rotary motion, the other units make the plane-parallel motions. Let us write the expressions for the kinetic energies of the units:

$$W_1 = J_1 \frac{\dot{\varphi}_1^{\,2}}{2},$$
$$W_i = J_i \frac{\dot{\varphi}_i^{\,2}}{2} + m_i \frac{V_i^{\,2}}{2}, \qquad i = \overline{2,4}, \tag{3}$$

where J_i – the central torques of the inertia, $\dot{\varphi}_i(t)$ – the angles velocities, m_i – the masses, $V_i(t)$ – the linear velocities of the unit mass centers.

The corresponding torques of inertia of the units are:

$$J_1 = \frac{1}{3} m_1 l_1^2, \qquad J_i = \frac{1}{12} m_i l_i^2, \qquad i = \overline{2,4}. \tag{4}$$

We express squares of the linear velocities of the unit mass centers through the generalized coordinates and the generalized velocities:

$$\begin{aligned} V_2^2 &= [l_1\dot{\varphi}_1 \cos(\varphi_1) + 0.5 l_2 \dot{\varphi}_2 \cos(\varphi_2)]^2 + \\ &\quad [l_1\dot{\varphi}_1 \sin(\varphi_1) + 0.5 l_2 \dot{\varphi}_2 \sin(\varphi_2)]^2, \\ V_3^2 &= [l_1\dot{\varphi}_1 \cos(\varphi_1) + l_2\dot{\varphi}_2 \cos(\varphi_2) + \\ &\quad + 0.5 l_3 \dot{\varphi}_3 \cos(\varphi_3)]^2 + [l_1\dot{\varphi}_1 \sin(\varphi_1) + \\ &\quad + l_2\dot{\varphi}_2 \sin(\varphi_2) + 0.5 l_3\dot{\varphi}_3 \sin(\varphi_3)]^2, \\ V_4^2 &= [l_1\dot{\varphi}_1 \cos(\varphi_1) + l_2\dot{\varphi}_2 \cos(\varphi_2) + \\ &\quad + l_3\dot{\varphi}_3 \cos(\varphi_3) + 0.5 l_4\dot{\varphi}_4 \cos(\varphi_4)]^2 + \\ &\quad + [l_1\dot{\varphi}_1 \sin(\varphi_1) + l_2\dot{\varphi}_2 \sin(\varphi_2) + \\ &\quad + l_3\dot{\varphi}_3 \sin(\varphi_3) + 0.5 l_4\dot{\varphi}_4 \sin(\varphi_4)]^2. \end{aligned} \tag{5}$$

The rotation angles of the units are accepted as generalized coordinates. Therefore the generalized forces are represented as the torques of the external and internal forces. The spring torques of deploying systems, the aerodynamic torques, the torques of the joint dry friction and the tension torques of the gravity compensation cables impact on the units. As a result the generalized forces take the following form:

$$\begin{gathered} Q_1 = M_1 = M_{S1} + M_{S2} + M_{F1} + M_{C1}, \\ Q_2 = M_2 = M_{S2} + M_{S3} + M_{A2} + M_{F2} + M_{C2}, \\ Q_3 = M_3 = M_{S3} + M_{S4} + M_{A3} + M_{F3} + M_{C3}, \\ Q_4 = M_4 = M_{S4} + M_{A4} + M_{F4} + M_{C4}, \end{gathered} \tag{6}$$

where $M_{Si}, i = \overline{1,4}$ – the spring torques of deploying systems, $M_{Ai}, i = \overline{1,4}$ – the aerodynamic torques, $M_{Fi}, i = \overline{1,4}$ – the torques of a joint dry friction, $M_{Ci}, i = \overline{1,4}$ – the resulted torques, which are created by the respective compensation cables as a result of imperfections in the process of the gravity compensation.

We substitute expressions (2) - (6) in formula (1). The obtained expression can be presented in the short form:

$$\mathbf{\Pi}(\boldsymbol{\varphi},\boldsymbol{\xi})\ddot{\boldsymbol{\varphi}} + \mathbf{b}(\dot{\boldsymbol{\varphi}},\boldsymbol{\varphi},\boldsymbol{\xi}) = \mathbf{M}, \tag{7}$$

where $\mathbf{\Pi}(\boldsymbol{\varphi},\boldsymbol{\xi})$ – the matrix function of a 4×4 dimension, $\mathbf{b}(\dot{\boldsymbol{\varphi}},\boldsymbol{\varphi},\boldsymbol{\xi})$ – the vector function of the fourth dimension, $\mathbf{M}$ – the vector of torques, which are applied to a four-dimensional body, $\boldsymbol{\xi}$ – the vector of solar array parameters.

When the unit achieves a standard position, the corresponding locking mechanism operates. The additional torque (a locking torque) appears in the hinge device. This torque holds the adjacent units in a determined position. We assume that this torque is directly proportional to the angular position of the adjacent units relative to each other.

For the considered model of the solar array deploying the locking torques are:

$$\begin{aligned} M_{L1} &= sign(\dot{\varphi}_1) k_{L1} \left(\frac{\pi}{2} - \varphi_1\right), \\ M_{L2} &= sign(\dot{\varphi}_2) k_{L2} (\varphi_1 - \varphi_2), \\ M_{L3} &= sign(\dot{\varphi}_3) k_{L3} (\varphi_2 - \varphi_3), \\ M_{L4} &= sign(\dot{\varphi}_4) k_{L4} (\varphi_3 - \varphi_4), \end{aligned} \tag{8}$$

where $k_{Li}, i = \overline{1,4}$ – the angular stiffness of the appropriate locking mechanism.

4. An Algorithm of Differential Equations Solving

It is necessary to determine the system movement by the set of operating influences and initial conditions. We need to solve a system of nonlinear differential equations of the second order (7) for accomplishing the formulated task.

It can be done by numerical integration of this system. The accelerations are defined and the new values of the generalized coordinates and velocities are extrapolated from set initial values of the generalized coordinates and velocities to the next time point. The solution is a multiple performance of this cycle calculations.

We use the forth order Runge–Kutta method for solving equation system (7). We present equations (7) in the form of Cauchy, i.e. in the form of the first order differential equation system, for using the Runge-Kutta method:

$$\mathbf{AX} = \mathbf{B}, \tag{9}$$

where

$$\mathbf{A} = \begin{bmatrix} (\frac{1}{3}m_1+m_2+m_3+m_4)l_1^2, & (\frac{1}{2}m_2+m_3+m_4)\cos(\varphi_1+\varphi_2)l_1l_2, & (\frac{1}{2}m_3+m_4)\cos(\varphi_1-\varphi_3)l_1l_3, & \frac{1}{2}m_4\cos(\varphi_1+\varphi_4)l_1l_4, & 0000 \\ (\frac{1}{2}m_2+m_3+m_4)\cos(\varphi_1+\varphi_2)l_1l_2, & (\frac{1}{3}m_2+m_3+m_4)l_2^2, & (\frac{1}{2}m_3+m_4)\cos(\varphi_2+\varphi_3)l_2l_3, & \frac{1}{2}m_4\cos(\varphi_2-\varphi_4)l_2l_4, & 0000 \\ (\frac{1}{2}m_3+m_4)\cos(\varphi_1-\varphi_3)l_1l_3, & (\frac{1}{2}m_3+m_4)\cos(\varphi_2+\varphi_3)l_2l_3, & (\frac{1}{3}m_3+m_4)l_3^2, & \frac{1}{2}m_4\cos(\varphi_3+\varphi_4)l_3l_4, & 0000 \\ \frac{1}{2}m_4\cos(\varphi_1+\varphi_4)l_1l_4, & \frac{1}{2}m_4\cos(\varphi_2-\varphi_4)l_2l_4, & \frac{1}{2}m_4\cos(\varphi_3+\varphi_4)l_3l_4, & \frac{1}{3}m_4l_4^2, & 0000 \\ 0 & 0 & 0 & 0 & 1000 \\ 0 & 0 & 0 & 0 & 0100 \\ 0 & 0 & 0 & 0 & 0010 \\ 0 & 0 & 0 & 0 & 0001 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} M_{S1}+M_{S2}+M_{F1}+M_{C1}+z_2^2l_1l_2(\frac{1}{2}m_2+m_3+m_4)\sin(\varphi_1+\varphi_2)+ \\ +z_1z_2l_1l_2(m_2+2m_3+2m_4)\sin(\varphi_1+\varphi_2)-z_3^2l_1l_3(\frac{1}{2}m_3+m_4)\sin(\varphi_1-\varphi_3)+ \\ +z_1z_3l_1l_3(m_3+2m_4)\sin(\varphi_1-\varphi_3)+z_1z_4l_1l_4m_4\sin(\varphi_1+\varphi_4), \\ M_{S2}+M_{S3}+M_{A2}+M_{F2}+M_{C2}+z_1^2l_1l_2(\frac{1}{2}m_2+m_3+m_4)\sin(\varphi_1+\varphi_2)+ \\ +z_1z_2l_1l_2(m_2+2m_3+2m_4)\sin(\varphi_1+\varphi_2)+z_3^2l_2l_3(\frac{1}{2}m_3+m_4)\sin(\varphi_1+\varphi_3)+ \\ +z_2z_3l_2l_3(m_3+2m_4)\sin(\varphi_2+\varphi_3)-\frac{1}{2}z_4^2l_2l_4m_4\sin(\varphi_2-\varphi_4)+z_2z_4l_2l_4m_4\sin(\varphi_2-\varphi_4), \\ M_{S3}+M_{S4}+M_{A3}+M_{F3}+M_{C3}+z_1^2l_1l_3(\frac{1}{2}m_3+m_4)\sin(\varphi_1-\varphi_3)- \\ -z_1z_3l_1l_3(m_3+2m_4)\sin(\varphi_1-\varphi_3)+z_2^2l_2l_3(\frac{1}{2}m_3+m_4)\sin(\varphi_1+\varphi_3)+ \\ +z_2z_3l_2l_3(m_3+2m_4)\sin(\varphi_2+\varphi_3)+\frac{1}{2}z_4^2l_3l_4m_4\sin(\varphi_3+\varphi_4)+z_3z_4l_3l_4m_4\sin(\varphi_3+\varphi_4), \\ M_{S4}+M_{A4}+M_{F4}+M_{C4}+\frac{1}{2}z_1^2l_1l_4m_4\sin(\varphi_1+\varphi_4)+ \\ +z_1z_4l_1l_4m_4\sin(\varphi_1+\varphi_4)+\frac{1}{2}z_2^2l_2l_4m_4\sin(\varphi_2-\varphi_4)- \\ -z_2z_4l_2l_4m_4\sin(\varphi_2-\varphi_4)+\frac{1}{2}z_3^2l_3l_4m_4\sin(\varphi_3+\varphi_4)+z_3z_4l_3l_4m_4\sin(\varphi_3+\varphi_4), \\ z_1, \\ z_2, \\ z_3, \\ z_4, \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \end{bmatrix}.$$

It is necessary to carry out checking on the performance of the locking operations during the numerical integration process and to apply the additional torques to the model when it is necessary.

The algorithm of numerical integration is presented in Figure 2.

5. Original Assumptions

Modelling always implies certain assumptions which simplify the real system. We use the following assumptions:

- the solar array panels are the absolutely rigid bodies;

- the gravity compensation stand perfectly compensates the gravitational forces during the solar array deploying;
- the hinge devices do not have a backlash and do not create additional friction torques;
- the locking devices do not have a backlash and is performed at the moment of transition to the operating position;
- the aerodynamic torques are linear functions of the angular velocities of the respective panels;
- the deploying process occurs without the synchronizing devices.

We need to take into account the structure and parameters of the locking mechanisms and hinge devices for more accurate modeling. That requires more detailed information about these devices.

The coefficients of the aerodynamic torques depend on the density of environment (air), the square area of panels and the drag coefficients [13]. The drag coefficient can be found by the computer simulation or experimentally.

It is necessary to check the adequacy of the model to the real process of the solar array deploying.

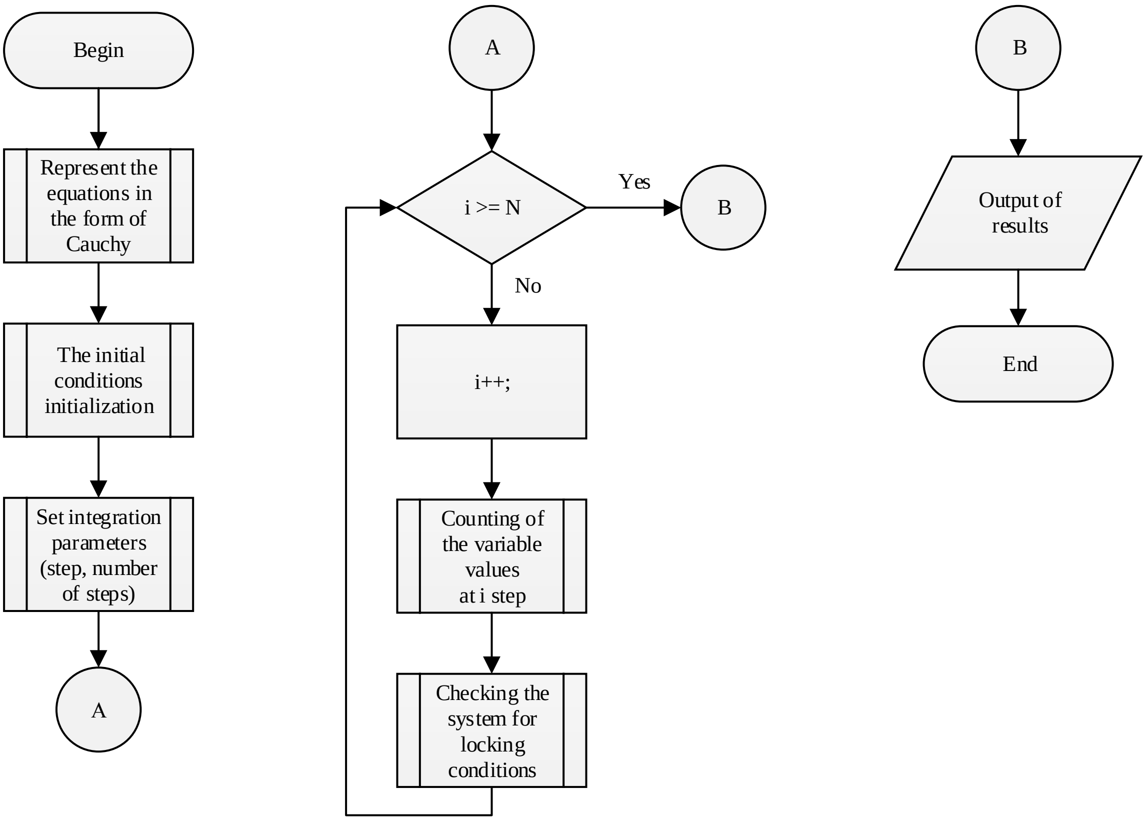

Figure 2. A block diagram of the numerical integration of Runge-Kutta method.

6. An Algorithm Checking on Adequate

We create the model and obtain the numerical solution of the deploying process parameters. The solar array panels of the spacecraft platform ‘Express-2000’ are used for checking. We will set some numerical values, which are length and weight of the panels:

$$l_1 = 2.5\ m, \quad l_2 = 4\ m, \quad l_3 = 4\ m, \quad l_4 = 4\ m,$$
$$m_1 = 10\ kg, \quad m_2 = 30\ kg, \quad m_3 = 65\ kg, \quad m_4 = 27\ kg. \tag{10}$$

Let us represent the spring torques of the hinge devices in the form of:

$$M_{Si}(\varphi) = 8 - 2\varphi_i, \quad where \;\; i = \overline{1,4}. \tag{11}$$

The drag coefficient of the panels equals: $\alpha = 0.01$. The function of the aerodynamic torque assumes:

$$M_{Ai}(\dot{\varphi}_i) = -0.01\dot{\varphi}_i, \quad where \;\; i = \overline{1,4}. \tag{12}$$

We will obtain the following system of equations substituting numerical values (10) - (12) into (9):

$$\mathbf{AX} = \mathbf{B}, \tag{13}$$

where

$$\mathbf{A} = \begin{bmatrix} 2345/3, & 1070\cos(\varphi_1+\varphi_2), & 595\cos(\varphi_1-\varphi_3), & 135\cos(\varphi_1+\varphi_4), & 0\;0\;0\;0 \\ 1070\cos(\varphi_1+\varphi_2), & 1632, & 952\cos(\varphi_2+\varphi_3), & 216\cos(\varphi_2-\varphi_4), & 0\;0\;0\;0 \\ 595\cos(\varphi_1-\varphi_3), & 952\cos(\varphi_2+\varphi_3), & 2336/3, & 216\cos(\varphi_3+\varphi_4), & 0\;0\;0\;0 \\ 135\cos(\varphi_1+\varphi_4), & 216\cos(\varphi_2-\varphi_4), & 216\cos(\varphi_3+\varphi_4), & 144, & 0\;0\;0\;0 \\ 0 & 0 & 0 & 0 & 1\;0\;0\;0 \\ 0 & 0 & 0 & 0 & 0\;1\;0\;0 \\ 0 & 0 & 0 & 0 & 0\;0\;1\;0 \\ 0 & 0 & 0 & 0 & 0\;0\;0\;1 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 16 - 2\cdot\pi - 4\cdot\varphi_1 + 2\cdot\varphi_2 + 270\cdot z_1\cdot z_4\cdot\sin(\varphi_4+\varphi_1) - 595\cdot\sin(\varphi_1-\varphi_3)\cdot z_3{}^2 + 1190\cdot\sin(\varphi_1-\varphi_3)\cdot z_1\cdot z_3 + \\ + 1070\cdot\sin(\varphi_2+\varphi_1)\cdot z_2{}^2 + 2140\cdot\sin(\varphi_2+\varphi_1)\cdot z_1\cdot z_2, \\ 0.01\cdot z_2 - 0.01\cdot z_1 + 16 - 4\cdot\pi - 2\cdot\varphi_1 + 4\cdot\varphi_2 - 2\cdot\varphi_3 - 216\cdot z_4{}^2\cdot\sin(-\varphi_4+\varphi_2) + 432\cdot z_2\cdot z_4\cdot\sin(-\varphi_4+\varphi_2) + \\ + 952\cdot\sin(\varphi_3+\varphi_2)\cdot z_3{}^2 + 1904\cdot\sin(\varphi_3+\varphi_2)\cdot z_2\cdot z_3 + 2140\cdot\sin(\varphi_2+\varphi_1)\cdot z_1\cdot z_2 + 1070\cdot\sin(\varphi_2+\varphi_1)\cdot z_1{}^2, \\ -0.01\cdot z_3 - 0.01\cdot z_2 + 16 - 4\cdot\pi - 4\cdot\varphi_3 + 2\cdot\varphi_2 + 2\cdot\varphi_4 + 216\cdot\sin(\varphi_3+\varphi_4)\cdot z_4{}^2 + 432\cdot\sin(\varphi_3+\varphi_4)\cdot z_4\cdot z_3 - \\ - (-1904\cdot\sin(\varphi_3+\varphi_2)\cdot z_2 + 1190\cdot\sin(\varphi_1-\varphi_3)\cdot z_1)\cdot z_3 + 952\cdot\sin(\varphi_3+\varphi_2)\cdot z_2{}^2 + 595\cdot\sin(\varphi_1-\varphi_3)\cdot z_1{}^2, \\ 0.01\cdot z_4 - 0.01\cdot z_3 + 8 - 2\cdot\pi - 2\cdot\varphi_3 + 2\cdot\varphi_4 - (432\cdot z_2\cdot\sin(-\varphi_4+\varphi_2) - 270\cdot z_1\cdot\sin(\varphi_4+\varphi_1) - \\ - 432\cdot\sin(\varphi_3+\varphi_4)\cdot z_3)\cdot z_4 + 135\cdot z_1{}^2\cdot\sin(\varphi_4+\varphi_1) + 216\cdot z_3{}^2\cdot\sin(\varphi_3+\varphi_4) + 216\cdot z_2{}^2\cdot\sin(-\varphi_4+\varphi_2), \\ z_1, \\ z_2, \\ z_3, \\ z_4, \end{bmatrix},$$

$$\mathbf{X} = \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \end{bmatrix}.$$

Write the function of the locking for this type of solar arrays:

$$\begin{aligned} M_{L1} &= 20000\cdot(\frac{\pi}{2} - \varphi_1), \\ M_{L2} &= -8000\cdot(\varphi_1 - \varphi_2), \\ M_{L3} &= 6000\cdot(\varphi_2 - \varphi_3), \\ M_{L4} &= -2000\cdot(\varphi_3 - \varphi_4), \end{aligned} \tag{14}$$

We use a numerical integration algorithm, which is shown in Figure 2. The calculations are made in the Mupad mathematical package of the Matlab software. The results are the sets of graphs. The graphs show the dependence of the generalized angles on time (Figures 3 and Figures 4).

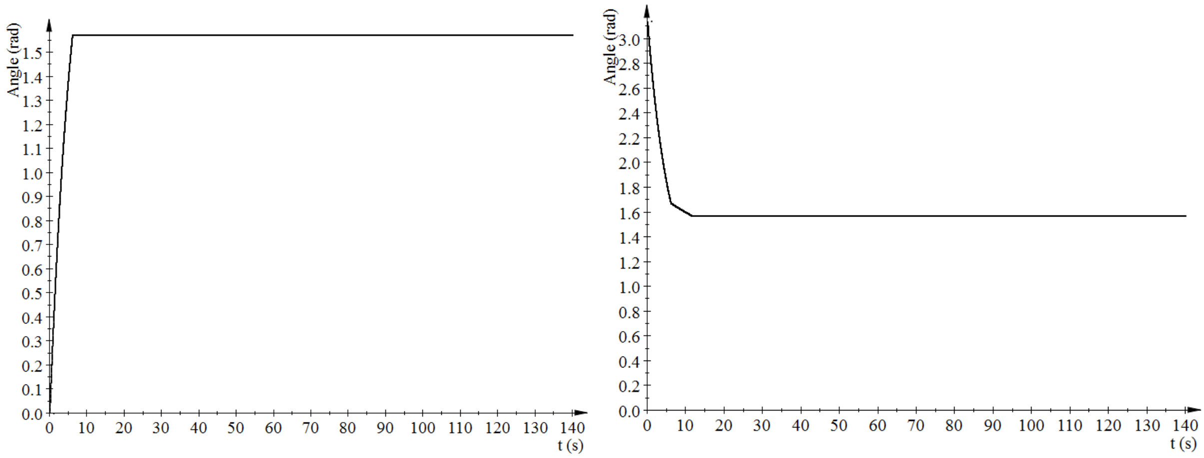

Figure 3. The functions of the first and second hinge angles from time dependence appropriately.

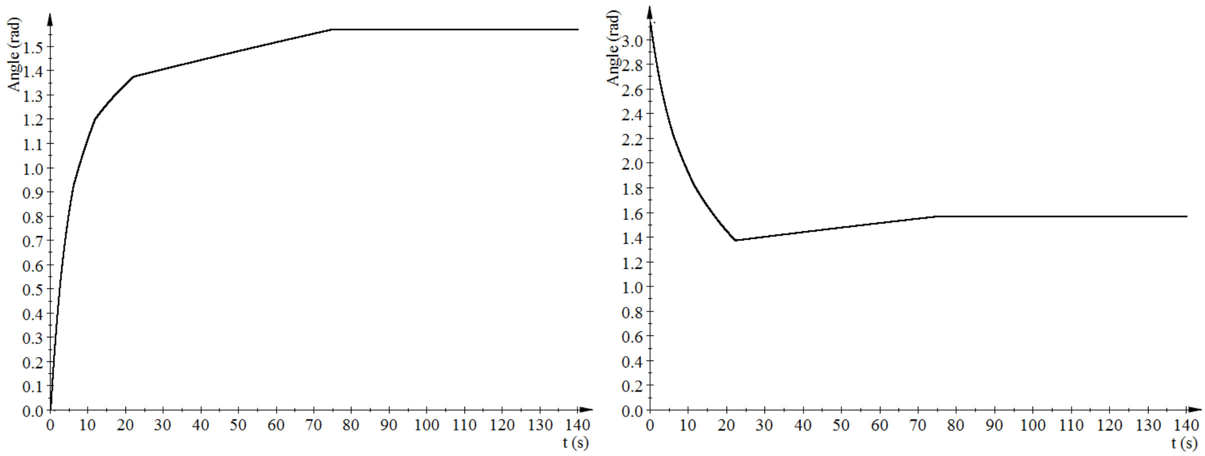

Figure 4. The functions of the fourth and fifth hinge angles from time dependence appropriately.

We can find the kinematic and dynamic characteristics of the motion using these results. In particular, the trajectories of the unit mass centers in the plane are presented in Figure 5.

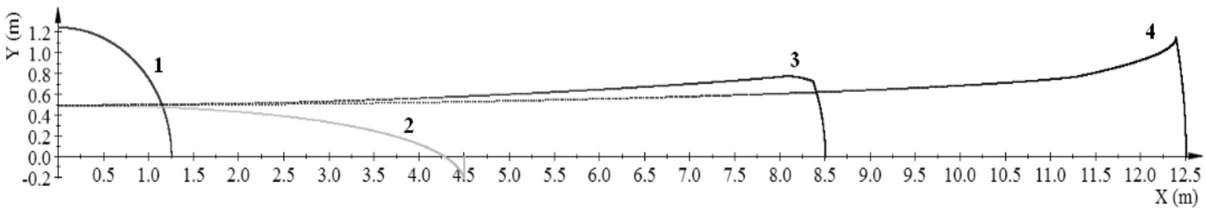

Figure 5. The trajectories of the unit mass center motions in the plane

7. Conclusion

The results allow considering the model as adequate:

- the system is stable and reaches desired conditions;
- the trajectories of the unit mass center motions correspond to reality.

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These calculations and figures should be considered in the programming motions of the suspension system carriages for the absence of the additional forces and torques due to the errors of gravity compensation.

This model can be developed and improved, bringing it closer to the real mechanism. In particular, it is possible to take into account the flexibility of the solar array panels and its impact on the properties of the gravity compensation system.

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