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DEVELOPMENT OF THE SACS-3D OF TEST BENCH

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Abstract

The article presents the problem of developing a mathematical model for controlling the triaxial orientation of a nanosatellite using three flywheels installed along its main central axes of inertia is considered, and a 3D model of the flywheel is also designed. To solve the problem, it is necessary to determine the law of change of the vector of the control moment or the law of control of the movement of the flywheels, which allows you to transfer the nanosatellite from the current angular position to another required angular position. The model can be a useful tool for developing a system for controlling the orientation of satellites of a similar type operating in real time.

Keywords: Flywheel, nanosatellite, triaxial orientation, machine.

1. INTRODUCTION

The achievements of recent years in the field of microelectronics, micro electro mechanics and integrated circuit manufacturing technology have made it possible to create small spacecraft (mini-, micro- and nanosatellites) with low cost and short preparation time, but with a high level of functional parameters. On a satellite of this class, almost all onboard systems inherent in a large spacecraft can be installed: an orientation control system, an energy supply system, a communication system, an on-board control complex [1].

The jet wheel (JW) is mainly used by spacecraft for three-axis orientation control and does not require rockets or external torque applicators. They provide high precision guidance and are especially useful when the spacecraft has to rotate by very small amounts, for example, to keep the telescope pointed at a star.

The jet wheel is sometimes used as (and referred to as) like a pulse wheel, operating at a constant (or almost constant) rotational speed to provide the satellite with a large margin of angular momentum. This changes the dynamics of the spacecraft's rotation, so that the disturbing moments perpendicular to one axis of the satellite (the axis parallel to the axis of rotation of the wheel) do not directly lead to the angular motion of the spacecraft around the same axis as the disturbing moment; instead, they result in a (usually smaller) angular motion, this axis of the spacecraft relative to the perpendicular axis. This has the effect of trying to stabilize the axis of the spacecraft so that it points in an almost fixed direction, which allows the use of a less complex orientation control system. Satellites using this "pulse-displacement" stabilization approach include SCISAT-1; by orienting the axis of the pulse wheel so that it is parallel to the normal vector to the orbit, this satellite is in a "pitch pulse displacement" configuration.

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The orientation control system ensures the stabilization of the nanosatellite and its orientation in a given direction during flight. Solving these problems requires determining the orientation of the nanosatellite using orientation sensors and controlling it with the help of executive bodies.

The control of the angular position of spacecraft consists of three stages: determination of the state vector of the spacecraft, calculation of the control vector, transformation of the control vector into the control moment. In traditional flywheel systems, the implementation of the control vector is not difficult: the three components of the control vector are implemented by three independent flywheel motors. In a ball flywheel motor, the components of the control vector are implemented by three arc stators. In redundant systems, an additional problem arises about the distribution of the control vector between individual flywheel motors. The process of converting the control vector of the spacecraft into the required moments of the flywheel engines will be called the control algorithm of the flywheel system. Similar tasks appear in redundant gyro-force systems and ball-flywheel motors with induction coils.

The orientation of the nanosatellite can be controlled both with the help of passive executive bodies (gravity rod, permanent magnet) and with the help of active executive bodies (inertial executive bodies – flywheels and electromagnetic executive bodies). Orientation control systems using active executive bodies are capable of more complex spatial maneuvers.

In this paper, the problem of developing a mathematical model for controlling the triaxial orientation of a nanosatellite using three flywheels installed along its main central axes of inertia is considered. To solve the problem, it is necessary to determine the law of change in the vector of the control moment or the law of control of the movement of the flywheels, which allows the nanosatellite to be transferred from the current angular position to another required angular position. The SACS-3DOF test bench consists of three parts:

1) Compressor – a machine that creates increased pressure in an aerodynamic tube.
2) Aerodynamic tube – creates a directional trajectory of air movement.
3) SACS-3DOF – simulates the operation of the satellite orientation control system.

As a result, SACS - 3 DEGREES OF FREEDOM is a satellite orientation control system with three degrees of freedom (pitch, yaw, roll), the activators of which are flywheels.

The essence of the dynamics of rotational motion of SACS-3DOF is described by the Euler dynamic equation for the rotational motion of a rigid body with a fixed point [2].

The main dynamic parameters of the flywheel engine that affect the speed of angular maneuvers of the spacecraft are the maximum kinetic and maximum control moments. They determine the mass and energy consumption of the flywheel system. The main dynamic parameters of the flywheel engine should ensure the performance of two modes of motion of the spacecraft: stabilization and program turns. In the stabilization mode, the flywheel engine must accumulate an external perturbing moment pulse,

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maintaining the angular position of the spacecraft with high accuracy. In the program turns mode, a high speed of maneuvers should be provided.

In the stabilization mode, the flywheel motors of the orientation system must ensure the accumulation of the pulse of the periodic component of the external disturbing moment. So far, one channel of the orientation system has been considered, simplified (linearized) equations of motion of the spacecraft have been used. If the kinetic moments of the flywheel engines vary in a wide range, cross-links arise between the orientation channels, which must be considered in the equations of motion of the spacecraft.

The design forms of flywheels can be different, but when choosing, they strive for the following requirements: 1. the optimal combination of weight and size of the flywheel to obtain the required moment of inertia; 2. Minimum dimensions; 3. Minimum angles of deflection of the suspension framework; 4. Minimum aerodynamic torque.

2. COMPARATIVE ANALYSIS OF UNIAXIAL AND TRIAXIAL STABILIZATION SYSTEMS

With uniaxial rotation stabilization, the entire spacecraft rotates around its own vertical axis. This allows to control the orientation of the spacecraft in space. These are flywheels used to control the orientation and stability of the spacecraft. By adding or removing energy from the flywheel, torque is applied to one axis of the spacecraft, causing it to react by rotation. By maintaining the rotation of the flywheel, called momentum, the only axis of the spacecraft is stabilized.

In triaxial stabilization, satellites have small rotating wheels called reaction wheels or pulse wheels that rotate in such a way as to keep the satellite in the desired orientation relative to the Earth and the Sun. If satellite sensors detect that the satellite is deviating from the correct orientation, the rotating wheels accelerate or slow down to return the satellite to the correct position. Some spacecraft may also use small propulsion system motors to constantly move the spacecraft back and forth to keep it within an acceptable position.

Advantages of uniaxial stabilization:

a) Simplicity. The advantage of uniaxial stabilization is that it is a very simple way to keep the spacecraft pointed in a certain direction.

b) Resistance to disturbing forces. A rotating spacecraft resists disturbing forces, which, as a rule, are small in space.

c) Continuity of movement. The rotation-stabilized device provides continuous sweeping motion, which is desirable for devices with fields and particles, as well as for some optical scanning devices.

d) Minimum fuel reserve. The propulsion systems are started only occasionally to make the desired changes in the rotation speed or in the position stabilized by rotation. Therefore, not so much fuel has to be transported or used during its service life.

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Advantages of three-axis stabilization:

a) Minimum amount of maneuver. The advantage of 3-axis stabilization is that optical instruments and antennas can be aimed at desired targets without the need to perform a maneuver.

b) Accuracy. This method is accurate and is therefore used where precise antenna guidance accuracy is required.

Disadvantages of uniaxial stabilization:

a) Power. The disadvantage of this type of stabilization is that the satellite cannot use large solar panels to receive energy from the Sun. Thus, it requires a large amount of battery power.

b) Devices or antennas must also perform maneuvers so that the antennas or optical devices point to the desired targets.

The disadvantage of triaxial stabilization:

a) It will be necessary to perform special turning maneuvers to make the best use of particle fields and tools.

b) Optical observation devices, such as imaging, should be developed considering the fact that the spacecraft is always slowly rocking back and forth, and not always accurately predictable.

c) Jet wheels provide much more stable conditions for conducting observations, but they increase the mass of the spacecraft, have a limited mechanical service life and require frequent pulse desaturation maneuvers, which can disrupt navigation decisions due to accelerations created by the use of engines.

3. MATHEMATICAL MODEL OF THE ORIENTATION CONTROL SYSTEM

Geometry and material selection.

The kinetic energy for any rotating body is determined by equation (1)

$$E_k = \frac{1}{2} I * \omega^2$$

This shows that for maximum energy accumulation by any rotating body, it is necessary to increase either the moment of inertia (I) or the working angular velocity (ω).

The moment of inertia of any geometry is given by equation (2)

$$I = \int r^2 \, dm$$

Where r is the radius of any differential body mass, dm, from the axis of rotation. Using this, a study was conducted to select the desired geometry.

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A solid disk is selected for the flywheel, its moment of inertia is given by equation (3),

$$I_{sd} = \frac{1}{2} M * R^2$$

Where M is the mass and R is the radius of the wheel.
Substituting equation (3) into equation (1), we get

$$E_k = \frac{1}{2} M * R^2 * \omega^2$$

Now, considering the mass density (ρ) and the circumferential velocity (V), equation (4) becomes

$$E_k = \frac{1}{2} R^2 * \omega^2 \ \rho$$

The energy stored in the flywheel is maximal only when the angular velocity is maximal, which is directly proportional to the specific tensile strength (σ_{max}), i.e.

$$E_{kmax} \propto \omega_{max} \text{ и } \omega_{max} \propto \sigma_{max}$$

The ratio between ω_{max} and σ_{max} is given by equation (7).

$$\sigma_{max} = \rho r^2 \omega_{max}{}^2 \frac{(3+v)}{8}$$

Where v is the Poisson's ratio. Substituting the values of ω_{max} of equation (7) into equation (3) it can be obtained

$$E_{k\ max} = \frac{1}{4} V \frac{\sigma_{max}}{\frac{(3+\vartheta)}{8}}$$

Equation (8) can be written as

$$E_{k\ max} = kV\sigma_{max}$$

Here k is known as the coefficient of the form.

$$k = \frac{8}{4(3+\vartheta)}$$

The relation in equation (6) gives a general solution for the maximum stored energy in a flywheel of any geometry.

Using equation (9), the energy density per unit mass and the volume energy density are defined as

$$e_V = \frac{E_{k\ max}}{V} = k\sigma_{max}$$

$$e_m = K \frac{\sigma_{max}}{\rho}$$

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Thus, it is clearly seen from equation (10) that the energy density depends on the specific tensile strength.

Design

The distribution matrix of n reaction wheels consists of n columns corresponding to each of the reaction wheels.

The element in each column gives the distribution of the torque generated by the wheels along the axes of rotation of the satellite.

The advantage of a four-sided wheel arrangement is that the maximum torque on the axle is twice as much as with a single wheel formula. The distribution matrix for the same can be represented as

$$D = [r_1 \quad r_2 \quad r_3 \quad r_4]$$

$$D = \begin{bmatrix} r_x^1 & r_x^2 & r_x^3 & r_x^4 \\ r_y^1 & r_y^2 & r_y^3 & r_y^4 \\ r_z^1 & r_z^2 & r_z^3 & r_z^4 \end{bmatrix}$$

When the system is used in the gyroscope control torque mode, the flywheels operate at a constant speed, and the necessary torque is created due to the gyroscopic effect associated with the rotation of the imbals. When the system is used in JW mode, the flywheels are accelerated to create the required torque, and the imbals are held in a fixed position.

Where $B_{\tau_G} = I_\omega A \widehat{\Omega} \dot{\delta}$ gyroscopic moment and $B_{\tau_D} = I_\omega AB\,\widehat{\Omega}$ direct moment. I is the inertial moment of inertia of the flywheel relative to its axis of rotation, $\widehat{\Omega} = diag(\Omega_1, \Omega_2, \Omega_3, \Omega_4)^T$, $\dot{\Omega} = [\dot{\Omega}_1, \dot{\Omega}_2, \dot{\Omega}_3, \dot{\Omega}_4]^T$ where Ω_i is the angular velocity of the i-th flywheel, $\dot{\delta}$ is its cardan velocity.

Matrices A and B display, respectively, the gyroscopic and direct torques of the drives from the frame, the control moment of the gyroscope. For the pyramidal configuration shown in Figure 1, the angles of the distance between the hinges are $\varphi = [0,90,180,270]^T$ degrees, the angle of the pyramid is θ, and the angles of the hinge are $\delta = [\delta_1, \delta_2, \delta_3, \delta_4]^T$ for this configuration of the matrix A and B:

$$A = \begin{bmatrix} cos\theta\ sin\ \delta_1 & -cos\delta_2 & cos\theta\ sin\ \delta_3 & cos\delta_4 \\ cos\delta_1 & -cos\theta sin\,\delta_2 & -cos\delta_3 & cos\theta\ sin\ \delta_4 \\ sin\theta sin\,\delta_1 & sin\theta sin\,\delta_2 & sin\theta sin\,\delta_3 & sin\theta sin\,\delta_3 \end{bmatrix}$$

$$B = \begin{bmatrix} cos\theta\ cos\ \delta_1 & -sin\delta_2 & cos\theta\ cos\ \delta_3 & sin\delta_4 \\ sin\delta_1 & -cos\theta cos\delta_2 & -sin\delta_3 & cos\theta\ cos\ \delta_4 \\ sin\theta cos\delta_1 & sin\theta cos\delta_2 & sin\theta cos\,\delta_3 & sin\theta cos\,\delta_3 \end{bmatrix}$$

In space, there are disturbances (such as aerodynamic torque (at LEO), gravity gradient torque, and solar radiation pressure torque) that create external torques (Ne) for the

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satellite, which tend to destabilize the satellite. Therefore, it is necessary to understand the dynamics of the satellite and simulate it to actively control the position of the satellite.

The total moment of the amount of motion of the system (satellite body + flywheel) relative to the center of mass of the system can be written as

$$M_{tot} = M_{sat} + M_{wheel}$$

When dealing with the dynamics of satellites, we need a rotating frame of reference. The rate of change of a vector in two frames can be related by the equation:

$$\frac{d}{dt}|_I = \frac{d}{dt}|_B + \omega|_{B/N}$$

Where I and B are two frames, and $\omega|_{B/N}$ is the angular velocity of frame B relative to frame N.

Now there is another relationship linking the torque applied to the system and the change in the angular momentum of the system:

$$\dot{H}_p = L_p + M\ddot{R}_p * (R_c - R_p)$$

To describe the orientation of the nanosatellite, we introduce a fixed inertial coordinate system OXYZ with the origin at the center of mass of the Earth and a related coordinate system Cxyz with the origin at the center of mass of the nanosatellite. To describe the dynamics of the rotational motion of a nanosatellite, the dynamic Euler equations for the rotational motion of a rigid body with a fixed point are applied [3]:

$$\mathrm{J}\dot{\vec{\omega}} + \vec{\omega} \times \mathrm{J}\vec{\omega} = \overrightarrow{\mathrm{M}_{\text{вн}}}$$

where $\mathrm{J} = \{\mathrm{J}_1, \mathrm{J}_2, \mathrm{J}_3\}$ is the diagonal (3×3) matrix of the inertia tensor of the nanosatellite; $\vec{\omega} = (\omega_1, \omega_2, \omega_3)^{\mathrm{T}}$ is the vector of the absolute angular velocity of the nanosatellite in projections on the axis of the coordinate system Cxyz; $\overrightarrow{\mathrm{M}_{\text{вн}}} = (\mathrm{M}_{\text{вн}1}, \mathrm{M}_{\text{вн}2}, \mathrm{M}_{\text{вн}3})^{\mathrm{T}}$ is the vector of the main moment of external forces in projections on the axis of the coordinate system Cxyz. Since the three flywheels mounted on nanosatellites have elements moving relative to it, the nanosatellite should be considered as a system of four solid bodies. Accordingly, the forces and moments of interaction of the flywheels with the nanosatellite should be considered as internal forces and moments. In this case, the external forces and moments acting on the nanosatellite are zero:

$$\overrightarrow{\mathrm{M}_{\text{вн}}} = 0.$$

Consequently, the total kinetic moment of the nanosatellite and flywheels, according to the kinetic moment change theorem, will be a constant value:

$$\mathrm{J}\vec{\omega} + \mathrm{J}_m\vec{\omega}_m = \mathrm{const}_{\mathrm{T}}$$

Where $\mathrm{J}_m = \{\mathrm{J}_{m1}, \mathrm{J}_{m2}, \mathrm{J}_{m3}\}$ is the diagonal (3×3) matrix of the inertia tensor of the flywheels; $\vec{\omega}_{\text{м}} = (\omega_{m1}, \omega_{m2}, \omega_{m3})^{\mathrm{T}}$ is the vector of angular velocities of the flywheels

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installed along the x, y, z axes, respectively. Differentiating equality (14) in time, Euler's dynamic equations in the form are obtained:

$$J\dot{\vec{\omega}} + \vec{\omega} \times (J\vec{\omega} + J_m\overrightarrow{\omega_m}) = \vec{M}$$

Where via

$$\vec{M} = -J_m\overrightarrow{\dot{\omega}_m}$$

The vector of the control moments of the flywheels is indicated.

The dynamic equation is supplemented by kinematic equations. When using a quaternion, the following vector equation is obtained:

$$\begin{pmatrix} \frac{d\mathbf{q}}{dt} \\ \frac{dq_0}{dt} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{pmatrix}\begin{pmatrix} \mathbf{q} \\ q_0 \end{pmatrix}$$

The use of angles does not imply a single type of kinematic relations in this work. Depending on the driving mode, it may be convenient to use one or another sequence of turns describing the movement of the associated coordinate system relative to the reference one. As an example, let's consider the widely and most used sequence of turns 2-3-1 in this work. In this case, the first rotation by angle α is made around the second axis of the reference system, the second rotation by angle β is made around the third axis of the new system, and the last rotation by angle γ is made around the first axis. The kinematic equations for such a sequence of turns have the form

$$\frac{d\alpha}{dt} = \frac{1}{\cos\beta}(\omega_2\cos\gamma - \omega_3\sin\gamma),$$

$$\frac{d\beta}{dt} = \omega_2\sin\gamma + \omega_3\cos\gamma,$$

$$\frac{d\gamma}{dt} = \omega_1 - tg\beta(\omega_2\cos\gamma - \omega_3\sin\gamma)$$

4. DEVELOPMENT ENVIRONMENT

To carry out more specific calculation data, an SLM model was designed for 3D printing in the SolidWorks modeling environment. This program helped to visualize calculations in a solid-state model, as well as calculations on structural strength were carried out using the SLM model.

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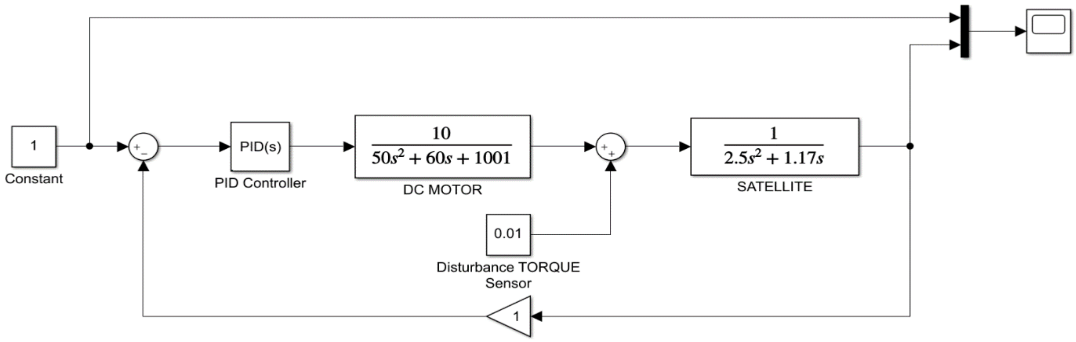
Fig. 1: Modeling of an SLM model for 3D printing in SolidWorks

After designing the SLM model, a flowchart of the flywheel control system was created in the Matlab development environment. The general view is shown in Fig. 2.

Fig. 2: Calculations of dynamic equations along one axis in the Matlab environment



When creating the Matlab model, a PID controller was added, which allows adjusting the orientation control parameters to obtain various types of experimental data.

5. RESULTS

Calculations were carried out on the deformation of the structure, as well as on the determination of the center of mass and the transition process. Calculations of this type helped to assess the reliability of the design

When checking the mesh volume, the mesh volume of the solid or shell is determined. For comparison, the volume of these bodies is indicated, measured by SOLIDWORKS by mass characteristics. A significant discrepancy between the two values can lead to unexpected simulation results, especially if gravity or other acceleration values are used in the study.

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Fig. 3: **Comparison of results**

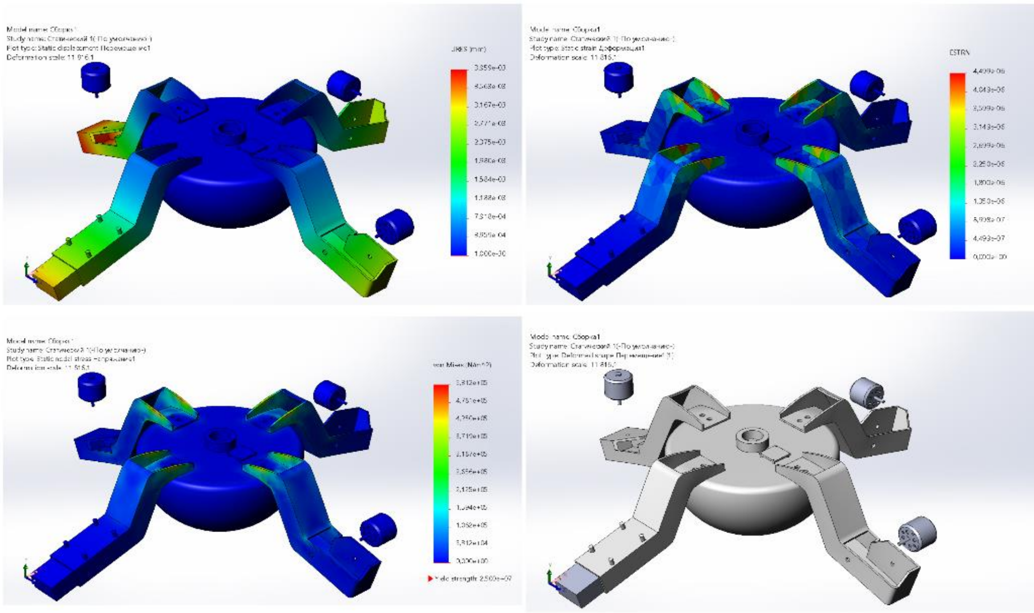
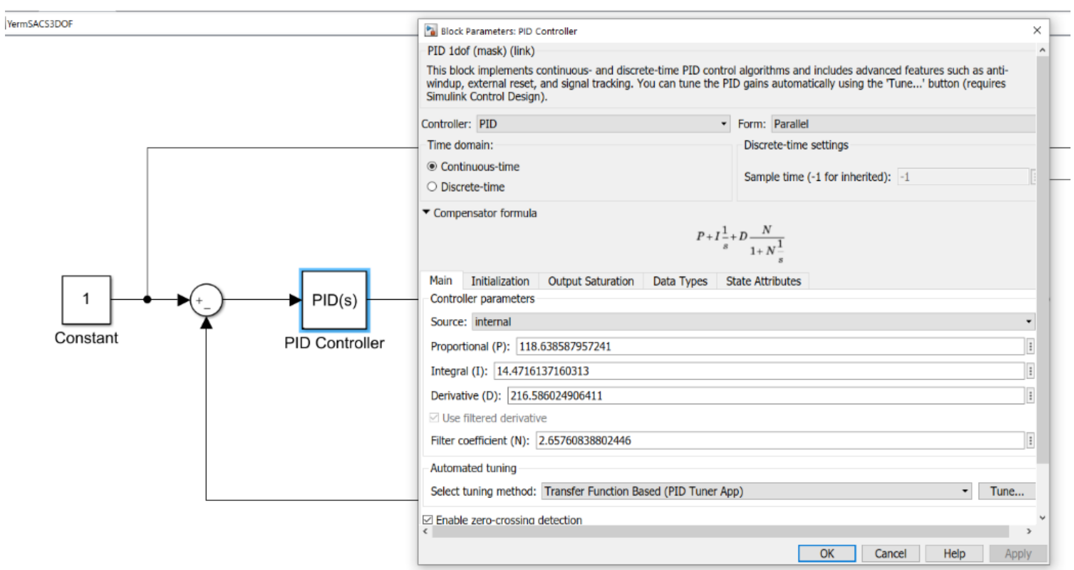


Figure 4 shows the parameters entered into the PID controller for conducting the flywheel stabilization time experiment on one axis.

Fig. 4:Input parameters to the PID controller



The result of the flywheel stabilization time on one axis is obtained in the form of a graph Taken from the PID controller is shown in Fig.5.

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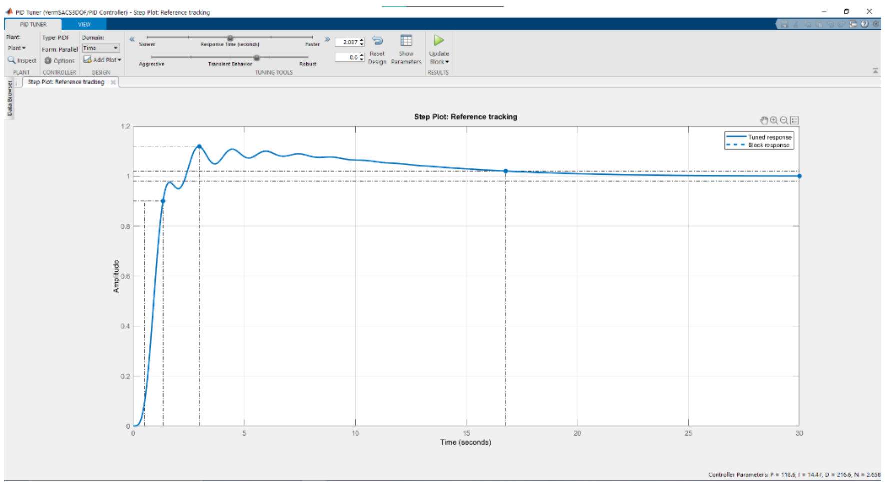
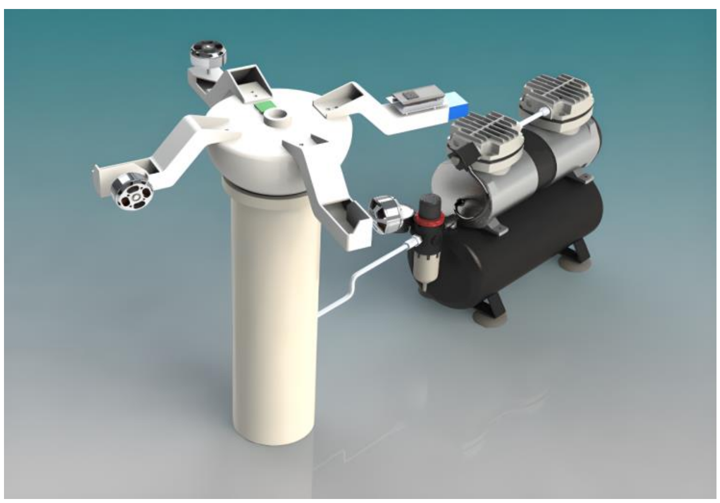
Fig. 5: The time of stabilization of the flywheel on one axis



After the calculations, the final SLIM model of the stand was created in assembled form as shown in Fig. 6.

Fig. 6: The type of the test bench during assembly



6. CONCLUSION

In the course of this work, a model of a free, three-stage orientation system with actuators in the form of flywheels was assembled, the computational and dynamic data of which were obtained in MATLAB software. The digital counterpart of the 3D SLM model for 3D printing was made in the SolidWorks environment.

The software architecture allows, with the help of "PID" regulation, to adjust the parameters of the orientation control laws for a different number of cases.

It was found that the total mass of SACS-3DOF is about 2.7 kg, which requires no more

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than 50% filling of the model with material of the "PLA" type. This factor has a positive effect on financial expenses and does not limit possible improvements in the future.

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