Modeling a Microgravity System for Ground Testing of Transformable Space Structures

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Abstract. The article develops a mathematical model of a microgravity system that simulates the conditions of weightlessness during ground tests of spacecraft. The microgravity system consists of vertical and horizontal control channels, providing a link opening in a two-dimensional coordinate system. The channels are two-mass electromechanical systems with elastic connections. To simulate the microgravity system, mathematical models of these channels are obtained. To check the adequacy of the obtained models in Simulink Matlab, we simulated the opening of a link of a mechanical system. As a result of modeling, the permissible indicators of the accuracy of simulating weightlessness were obtained.

1. Introduction

At present, to increase the reliability of the deployment of transformable spacecraft links, it is necessary to test them in underground conditions. For this purpose, it is necessary to create special microgravity (SM) systems that would allow reproducing the dynamics of motion of large space structures with parameters close to zero-gravity conditions. Therefore, the development of the SM is an important and urgent task [1] - [13].

The SM, the kinematic diagram of which is shown in Fig. 1, consists of a link of a mechanical system 1, a cable 2, a carriage 3 moving along horizontal guides, electric drives 4, a cable deviation sensor from a vertical position 5, a cable tension sensor 6.

![Figure 1. Kinematic diagram of SM.](image)
The moving link is suspended from the center of mass. The test consists of experimental verification of the possibility of transferring a link from one position to another using the installed drives in conditions when the link is balanced. A link is considered balanced if the vector of the tension force in the cable at the suspension point is equal in magnitude and opposite in direction to the force vector of the weight of the balanced link. The presence of friction forces in the cable-block system and the inertial mass of the carriage leads to the fact that the balancing condition is not met. This causes the movement of the link to deviate from its movement in zero gravity. The purpose of using the SM is to improve the accuracy of balancing the link during its movement and, consequently, to increase the test results.

The movement of each link can be considered as the movement of the center of mass (CM) under the action of forces applied to it (Fig. 2).

![Figure 2. The forces acting on the CM link.](image)

where $F_{of}$ is the force of the link opening drive; $F$ is cable tension force; $P$ is the force of the link weight. The imperfection of balancing is expressed in the presence of an error, defined as the sum of two vectors:

$$\Delta F(t) = F(t) + P.$$

The error vector can be decomposed into vertical $\Delta F_{y}$ and horizontal $\Delta F_{x}$ components

$$\Delta F_{y} = F \sin \alpha; \quad \Delta F_{x} = F \cos \alpha - P. \quad (1)$$

where $\alpha$ – is the angle of deviation of the cable from the vertical; $F$ – modulus of the cable tension force.

To simplify the analysis, we will consider the vertical movement ($\alpha = 0$) and horizontal movement ($F = P$) of the center of mass of the link. In this case, equations (1) can be rewritten as:

$$\Delta F_{y} = P \sin \alpha; \quad \Delta F_{x} = F - P.$$ and, consequently, to reduce the problem of SM modeling to modeling independent vertical and horizontal channels. The kinematic diagrams are shown in Figures 3 and 4, respectively.
2. Mathematical model of the vertical channel SM

The vertical channel (VC) of the SM is a two-mass electromechanical system with elastic coupling (Fig. 3). When compiling differential equations describing the movement of a link under the action of forces applied to it, the following assumptions were made:

- the mass of the tension sensor is zero;
- the rigidity of the elastic element of the tension sensor is equal to infinity.

As a result of the description of the control object of the VC SM, a system of equations was obtained:

\[ m \frac{d^2V_y}{dt^2} = \Delta F_y - \Delta F_{\text{ed}}; \quad \frac{d\Delta V_y}{dt} = \left( C + \frac{dy}{dt} \right) (\Delta V_y - \Delta V_{\text{ed}}); \quad \frac{J}{r^2} \frac{d\Delta V_{\text{ed}}}{dt} = (\Delta F_{\text{ed}} + \Delta F_y); \quad \Delta F_{\text{ed}} = k_1 \Delta U_e, \]

where \( m \) is the mass of the link; \( r \) – drum radius; \( C \) – the coefficient of stiffness of the cable; \( \chi \) – coefficient of elasticity loss; \( \Delta V_y \) – vertical speed of CM link; \( \Delta V_{\text{ed}} \) – linear speed of the electric drive; \( k_1 \) – amplification factor of the electric part of the drive; \( \Delta F_y \) – disturbing force; \( \Delta F_{\text{ed}} \) – cable tension force; \( J \) – the reduced moment of inertia of the motor.

The VC SM regulator has a transfer function \( W_c(s) \): \( W_c(s) = k_2 \frac{(Ts + 1)}{s} \), where \( k_2 \) is the PI-controller transfer ratio; \( T \) – time constant of the PI controller. The input action of the VC SM is force \( \Delta F_y \), and the output signal is the deviation of the tension force of cable \( \Delta F_{\text{ed}} \).

As a result of the mathematical description, the structural diagram of the VC SM will take the form shown in Figure 5.
3. **Mathematical model of the horizontal channel SM**

The horizontal channel (HC) of the SM is also a two-mass electromechanical system (Fig. 4). To construct a structural diagram of the HC SM, we write down the differential equations of all elements:

\[
\begin{align*}
    m \frac{d\Delta V_x}{dt} &= \Delta F_h - \Delta F_x; \\
    m_c \frac{d\Delta V_y}{dt} &= \Delta F_h + \Delta F_{ed}; \\
    \frac{d\Delta F_h}{dt} &= C_x (\Delta V_x - \Delta V_y); \\
    \Delta F_{ed} &= k \Delta U_p, 
\end{align*}
\]

where \( m \) is the mass of the carriage; \( C_x = \frac{mg}{l} \) — coefficient of equivalent stiffness of mechanical connection; \( l \) — link suspension length; \( g = 9.8 \text{ m/s}^2 \) — acceleration of free fall; \( \Delta V_x \) — horizontal speed of the CM link; \( \Delta V_y \) — carriage speed; \( \Delta F_h \) — disturbing force; \( \Delta F_{ed} \) — balancing force; \( k \) — amplification factor of the electric part of the drive.

The HC SM regulator has the transfer function of the PI\(^2\)-regulator: \( W_p(s) = \frac{k_s}{s^2 + k_h s} \). The input action of the HC SM is force \( \Delta F_x \), and the output signal is the deviation \( \Delta V \) of the carriage speed from the horizontal speed of the CM link.

As a result of the mathematical description, the structural diagram of the HC SM has the form shown in Fig. 6.

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4. **Modeling the process of link movement in microgravity conditions**

One of the problems in compiling a mathematical description of the SM control object is the problem of obtaining a model of the movement of a link of a mechanical system since the type of model depends on the specific type of the tested structure. We get a simplified model of a link of a mechanical system that would apply to any type of structure. Let us apply the assumption that the links of the mechanical system are absolutely rigid and their entire mass is concentrated at the suspension points. As an example, consider the movement of the center of mass of a link (Fig. 7) under the action of an external disturbance - the force of the link opening drive.

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**Figure 5.** Structural diagram of VC SM.

**Figure 6.** Structural diagram of HC SM.

**Figure 7.** Movement of the center of mass of the link.
In fig. 7 denotes $\gamma$ – the angle of rotation of the link.

External disturbances for the horizontal and vertical channels SM can be described, respectively, by the following expressions:

$$
\Delta F_x = \Delta F_{\text{jd}} \cos \varphi; \quad \Delta F_y = \Delta F_{\text{jd}} \sin \varphi
$$

(2)

During the rotation of the link from vertical to horizontal ($\varphi \in [0^\circ; 90^\circ]$), the length of the suspension will increase by a distance of $\Delta l = R(1 - \cos \varphi)$. This must be taken into account when modeling, because

$$
C = \frac{C_{\text{sc}}}{l_0 + \Delta l}; \quad \chi = \frac{X_{\text{sc}}}{l_0 + \Delta l}; \quad C_e = \frac{m \cdot g}{l_0 + \Delta l}.
$$

(3)

where $l_0$ is the minimum suspension length for the vertical position of the link.

Based on the obtained models HC and VC SM and taking into account expressions (2), (3), we will compose a mathematical model of SM in the form of its structural diagram.

**Figure 8.** Structural diagram of SM.

Based on the structure in Fig. 8, the system was simulated in horizontal and vertical modes. External influences $\Delta F_x$ and $\Delta F_y$ on HC and VC are shown in Figures 9a and 10a, respectively. In this case, $\Delta F_{\text{jd}}$ is taken equal to 20 N. The output signals HC and VC are shown in Fig. 9b and 10b, respectively. The graph in Figure 9b shows that the maximum deviation $\Delta V$ of the carriage speed from the CM speed is 0.02 m / s. From the graph in Figure 10b, it can be concluded that the maximum deviation of the tension force $\Delta F_{\text{jd}}$ is 0.17 N.
Figure 9. Graph of a) external influence $\Delta F_x$ b) deviation $\Delta V$ of the carriage speed from the CM speed.

Figure 10. Graph a) external influence $\Delta F_y$ b) deviation of the cable tension force $\Delta F_{t_x}$.

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