Reorienting nanosatellites to a predefined attitude using angular displacements of movable modules

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Abstract. The dynamics of the spatial motion of a nanosatellite with a movable module tilted relative to the main body is considered. Control laws are developed to implement attitude dynamics with suppressing the precession-nutational motion, as well to bringing the nanosatellite into a predefined spatial orientation.

1. Introduction

The study of the dynamics of the spatial motion of spacecraft is one of the main problems in the dynamics of space flight [1]. The relevance of developing new simplest schemes and laws of angular motion control is increasing due to the widespread use of structural schemes of nanosatellites (NS), which use their own moving elements to control their motion [1-4]. The paper considers the dynamics of the spatial motion of a composite NS with a tiltable movable module and a simple jet engine rigidly mounted on the main module (body carrier). The movable module can be attached to the carrier body in various ways, including also flexible rods of variable length, and can be any functionally equipment, for example, an optical element, an antenna, etc. Due to the inclination of the movable module with respect to the main body-body, geometric displacement is carried out the center of mass of the entire mechanical system and a shoulder is created for constant reactive thrust. Thus, the movable module, in addition to its main functional purpose, can perform the function of a working element of the NS orientation and stabilization control system.

In this work, laws for controlling a mobile module based on the feedback principle are developed to ensure suppression of the precession-nutational motion of the NS, as well as its reorientation of the inertial space.

The coordinates systems are:
- CXYZ – the coordinate frame with the origin in the mass center, which axes are parallel to the main axes of the main body. y. The point C is the center of mass of the complete nanosatellite;
- C1X1Y1Z1 – the frame with the origin in mass center of the main body, which axes are parallel to the main axes of the main body. The point C1 is the mass center only of the main body;
- C2X2Y2Z2 – the main connected frame of the movable module. The point C2 is the mass center only of the movable unit.

2. Mathematical model

The mathematical model of the NS can be build based on the law of the change of the angular momentum, written in the moving references frame CXYZ:
\[
\frac{dK}{dt} + \omega_1 \times K = M
\]  

(1)

where \( K \) is the angular moment of the NSHC, \( \omega_1 = [p, q, r]^T \) is the angular velocity of the main body of the NS in projections onto axis CXYZ, \( M \) is the torque of external forces (does not take into consideration in this paper) and the jet-engine thrust.

**Figure 1.** Configurable nanosatellite: 1 – main body, 2 – control system elements, 3 – movable module, 4 – flexible roads.

The angular moment of the NS represents the sum of the angular momentums of bodies of NS:

\[
K = K_1 + (\sigma \times K_2)
\]

(2)

where \( K_1 \) is angular momentums of the main body calculated in frame \( C_X Y Z \), \( K_2 \) – angular momentums of the movable module calculated in frame \( C_X Y Z \), \( \sigma \) – is the transition matrix in the coordinate system \( C_X Y Z \) from the coordinate system \( C_1 X Y Z_1 \):

\[
\sigma_1 = \begin{bmatrix}
\cos \beta \alpha & \sin \beta \cos \alpha \beta & \sin \beta \\
0 & \cos \alpha & -\sin \alpha \\
-\sin \beta & \cos \beta \sin \alpha & \cos \beta \cos \alpha
\end{bmatrix}
\]

(3)

The kinematical equations for Krylov’s angles angles defining the position of the movable frame CXYZ relative the inertial space should be added:

\[
\begin{align*}
\dot{\alpha} &= \frac{p \cos \lambda - q \sin \gamma}{\cos \beta} \\
\dot{\beta} &= \frac{p \sin \gamma + q \cos \gamma}{\cos \beta} \\
\dot{\gamma} &= r - \frac{p \cos \gamma \sin \beta - q \sin \gamma \sin \beta}{\cos \beta}
\end{align*}
\]

(4)

where \( \alpha \) is the roll, \( \beta \) is the pitch, \( \gamma \) is the yaw.

**3. Simulation of the controlled dynamics**

Let us consider the case in which the movable module has only one degree of freedom \( (\beta = 0) \).

For the spatial orientation of the composite nanosatellite, the following law was chosen to control the angle of the movable module:
\[ \alpha_z = -k_\alpha (\dot{\alpha} + (\alpha - \alpha_z)) \cos \gamma \cos \beta - k_\gamma (\dot{\beta} + (\beta - \beta_z)) \sin \gamma \]  

(5)

where \( k_\alpha \) and \( k_\beta \) is feedback coefficients, at angles \( \alpha \) and \( \beta \) respectively, \( \alpha_z \) and \( \beta_z \) – required roll and pitch angles. Initial conditions for simulation: \( \alpha (0) = 0 \) [rad]; \( \alpha_z = 0.25 \) [rad]; \( \beta (0) = -0.3 \) [rad]; \( \beta_z = 0 \) [rad]; \( \gamma (0) = 0 \) [rad]; \( p = q = r = 1 \) [rad/s]; \( k_\alpha = -0.2 \); \( k_\beta = -0.2 \). Inertial mass parameters of the NS: main body mass 2[kg], movable unit mass 1[kg], moments of inertia of the main body: \( A_\alpha = 0.013 \) [kg*m^2], \( B_\alpha = 0.009 \) [kg*m^2], \( C_\alpha = 0.006 \) [kg*m^2], moments of inertia of the movable unit: \( A_u = B_u = 0.0025 \) [kg*m^2], \( C_u = 0.0035 \) [kg*m^2], jet-engine thrust \( P = 2 \) [N]. The simulation results are presented in Figures 2-5.

\[ \alpha_z = -k_\alpha (\dot{\alpha} + (\alpha - \alpha_z)) \cos \gamma \cos \beta - k_\gamma (\dot{\beta} + (\beta - \beta_z)) \sin \gamma \]  

(6)

Figure 2. Components of the angular velocity \( p \) (red), \( q \) (blue), \( r \) (green).

Figure 3. The angle of the NS rotation \( \alpha \).

The control law (5) successfully solves the problem of completely reorienting the NS to a predetermined orientation position using the angular displacement of one movable module and the constant thrust of the jet engine of the NS main body. We also carry out simulation without restrictions on the degrees of freedom of the movable module. For the spatial orientation of the NS, the following law was chosen to control the angle of the movable module:

\[ \alpha_z = -k_\alpha (\dot{\alpha} + (\alpha - \alpha_z)) \cos \gamma \cos \beta - k_\gamma (\dot{\beta} + (\beta - \beta_z)) \sin \gamma \]  

(6)
Figure 4. The angle of the NS rotation $\beta$.

Figure 5. The angle of the NS rotation $\gamma$.

Figure 6. Components of the angular velocity $p$ (red), $q$ (blue), $r$ (green).
4. Conclusion
The dynamics of the spatial motion of a nanosatellite with a movable module tilted relative to the main body was considered. Control laws was developed to implement attitude dynamics with suppressing
the precession-nutational motion, as well as bringing the nanosatellite into a predefined spatial orientation.

The presence of an additional degree of freedom of the movable module reduces the time of orientation and stabilization of the rotational motion of the NS, which in turn affects the economy of the working fluid. Also, when using two degrees of freedom, the final speed of rotation of the NS around the longitudinal axis decreases.

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6. References
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