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Stabilization of the Small Spacecraft with Electromagnetic Actuator in the Presence of a Residual Magnetic Moment

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Abstract

This paper deals with analysis of the small spacecraft motion in the Earth's magnetic field. Influence of the residual magnetic moment on the angular velocity damping algorithm is studied. Comparative analysis is performed for the different values of the residual magnetic moment.

Keywords: small spacecraft, stabilization of the small spacecraft, electromagnetic actuators, residual magnetic moment

1 Introduction

During recent years, the problem of the spacecraft control by using only electromagnetic actuators is investigated extensively, due to the reason of simplicity, low cost and low power consumption of such control system. This technique is particularly convenient to use for the small spacecraft, due to reasonable requirements for attitude control system. The principle of magnetic orientation of the system is based on the interaction between the magnetic moment of spacecraft and the Earth's magnetic field; in consequence, the control torque for the spacecraft is generated. The method has both advantages and disadvantages. The main advantages were mentioned before; the main disadvantage consists in the fact that the spacecraft orientation in direction, which coincides with the magnetic induction vector, is impossible. Nevertheless, the control system, based only on electromagnetic actuators, may be used for many other goals. As an example of such control system, successfully applied at the real satellite, “Orsted” satellite may be mentioned, which was developed in Denmark [1].

Typical satellite disturbance torques include gravitational torque, the moments of aerodynamic drag and solar pressure [2]. Interaction between a satellite residual magnetic moment and the Earth’s magnetic field causes an additional disturbance torque on the satellite. The magnitude of typical disturbance torques is a function of mass properties (position of the mass center and the inertia matrix) and depends on the spacecraft attitude, while the additional torque has the time-varying nature due to the residual magnetic moment. Current loops from electrical devices and magnetic materials are the major sources of the residual magnetic moment [3]. Its magnitude depends on temperature, eclipse and position of the Sun but does not depend on the satellite sizes. For nanosatellite with the certain configuration, the residual torque is the dominant disturbance torque, acting on the satellite [4]-[5]. Development of magnetic control is a very difficult problem due to the time-varying nature of the magnetic field and the nonlinear dynamics of the system. In the paper gravitational and residual magnetic torques are considered as the external disturbance torques; the residual magnetic moment is assumed constant.

2 Mathematical model and problem formulation

Within this study, motion of the small spacecraft in the low Earth orbit in presence of a residual magnetic moment is considered. The mathematical model of the motion is described by the Euler’s dynamic equations and kinematic equations [6]:

$$\overline{\omega}^b = 2\overline{q}^* \otimes \dot{\overline{q}}, \tag{1}$$

$\overline{\omega}^b$ is an angular velocity of spacecraft in body coordinate system, $\overline{q}$ is a quaternion characterizing the current angular position of the spacecraft in inertial coordinate system, $\overline{q}^*$ is a quaternion inverse to $\overline{q}$.

Euler’s dynamic equations have the following form:

$$I\overline{\omega}^b + \overline{\omega}^b \times (I\overline{\omega}^b) = \overline{M}_{grav} + \overline{M}_a + \overline{M}_{res}, \tag{2}$$

where $I = \{I_x, I_y, I_z\}$ are inertia moments of the satellite, $\overline{M}_{grav}$, $\overline{M}_a$, $\overline{M}_{res}$ are the gravitational torque, the magnetic torque of electromagnetic actuators and the residual magnetic torque respectively. Basing on the known formula [7] for the spacecraft with a diagonal matrix of the inertia moments, we may obtain the gravitational torque in quaternion in the following form:

$$\overline{M}_{grav} = 3\omega_0^2 \begin{bmatrix} (I_z - I_y)2(q_2q_3 + q_0q_1)(1-2(q_1^2 + q_2^2)) \\ (I_x - I_z)(1-2(q_1^2 + q_2^2))2(q_1q_3 + q_0q_2) \\ (I_y - I_x)2(q_1q_3 + q_0q_2)2(q_2q_3 + q_0q_1) \end{bmatrix}. \tag{3}$$

The magnetic moment, generated within the spacecraft interacts with the Earth's magnetic field, produces a torque according to [2]:

$$\overline{M}_a = \overline{m} \times \overline{B}, \tag{4}$$

where $\overline{m}$ and $\overline{B}$ are the magnetic moment of the electromagnetic actuator and the intensity vector of the Earth's magnetic field respectively.

Residual magnetic moment is generated due to the presence of the current loop on spacecraft board and it has a significant disturbing effect on the spacecraft rotational motion. Magnitude of the residual magnetic torque is defined by the following formula:

$$\overline{M}_{res} = \overline{m}_{res} \times \overline{B}, \tag{5}$$

where $\overline{m}_{res}$ is the spacecraft residual magnetic moment.

If the Earth's rotation is not taken into account, the magnetic field intensity is approximated as [2]:

$$\overline{B} = \frac{\mu_m}{a^3} \begin{bmatrix} \cos(\omega_0 t)\sin i_m \\ -\cos i_m \\ 2\sin(\omega_0 t)\sin i_m \end{bmatrix},$$

where, ω_0 is orbital velocity of the spacecraft, i_m is an inclination of the spacecraft orbit with respect to the magnetic equator, a is a semi-major axis of the orbit and μ_m is the magnetic dipole strength ($\mu_m = 7.9 \times 10^{15}\ Wb \cdot m$).

In order to stabilize rotational motion of the spacecraft we consider the «B-dot» control algorithm, which is one of the commonly used algorithms for stabilizing the spacecraft by using electromagnetic actuators. The electromagnetic actuator, which fixed along one axis, damps the angular velocity in other two axes at the same time [8]:

$$M_i = -K_d \dot{B}_i, \tag{6}$$

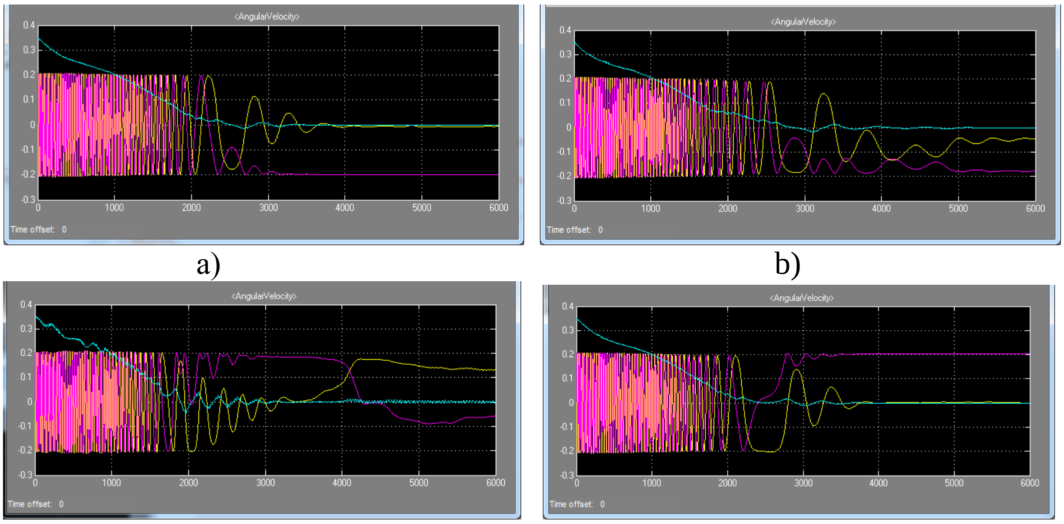
where, K_d is a control gain, positive number and B_i is a component of the magnetic field vector in body coordinate system. In practice $\dot{B}_i$ is represented by the following approximation:

$$\dot{B}_{i,k} \approx \frac{B_{i,k} - B_{i,k-1}}{\Delta t}, \tag{7}$$

where Δt is the sampling time.

3 Numerical solutions

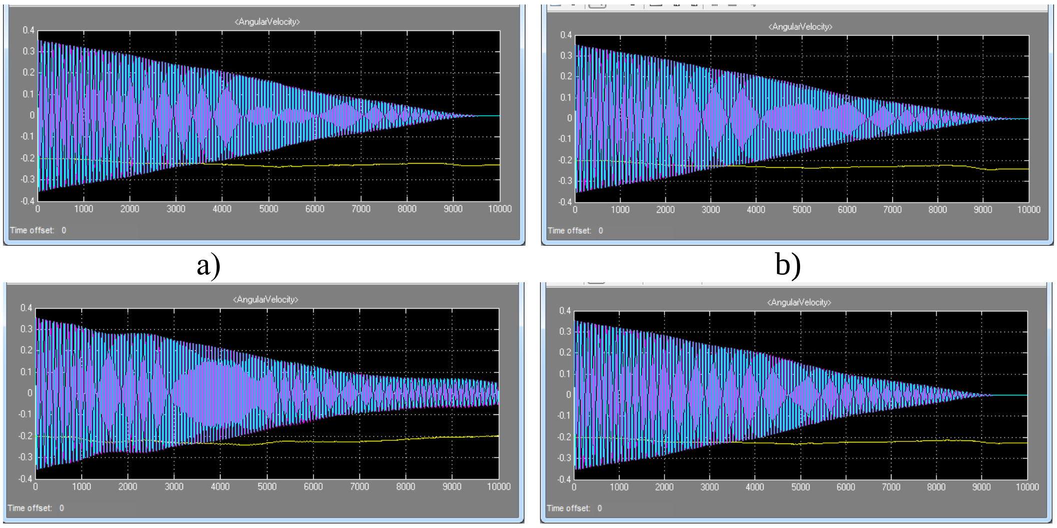
Results of numerical calculations of the angular velocity stabilization problem in Simulink/Matlab are shown at the Fig. 1 - 5 (a, b, c, d). During the numerical calculation, the following values of the residual magnetic moment were used: $\overline{m}_{res} = [0.005\ 0.0\ 0.0]$ $(A \cdot m^2)$ (case a), $\overline{m}_{res} = [0.05\ 0.0\ 0.0]$ $(A \cdot m^2)$ (case b), $\overline{m}_{res} = [0.5\ 0.0\ 0.0]$ $(A \cdot m^2)$ (case c), $\overline{m}_{res} = [0.0\ 0.0\ 0.0]$ $(A \cdot m^2)$ (case d). The orbit is assumed the 600 km circular sun-synchronous orbit; the period of one turn is 6024 s., the magnetic moment of coil is 0.2 $A \cdot m^2$. The coils are placed along three general axes of the spacecraft.



a) b)

c) d)

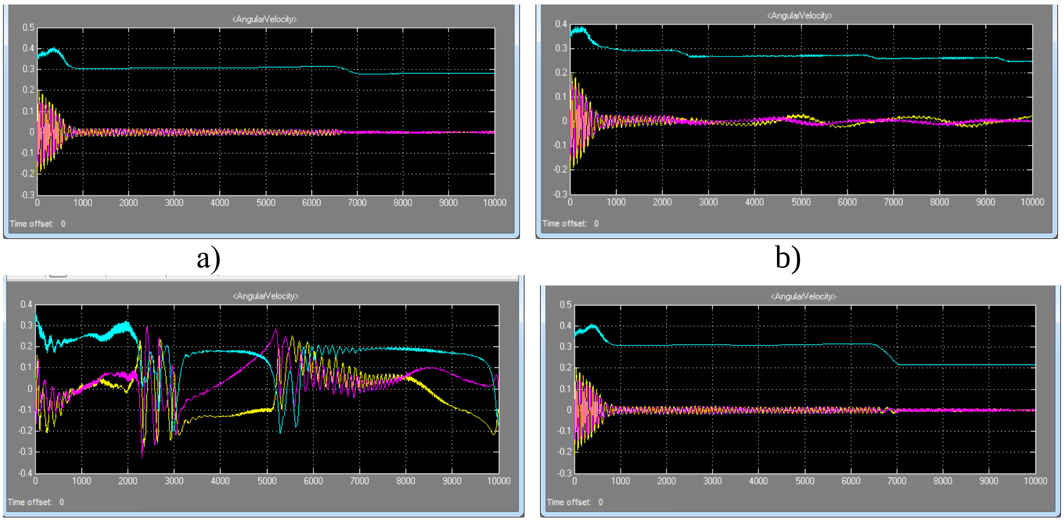
Figure 1 – Change of angular velocity of the spacecraft by $\mathbf{I} = [0.0505\ \ 0.0505\ \ 0.0109]$ (kgm^2)



a) b)

c) d)

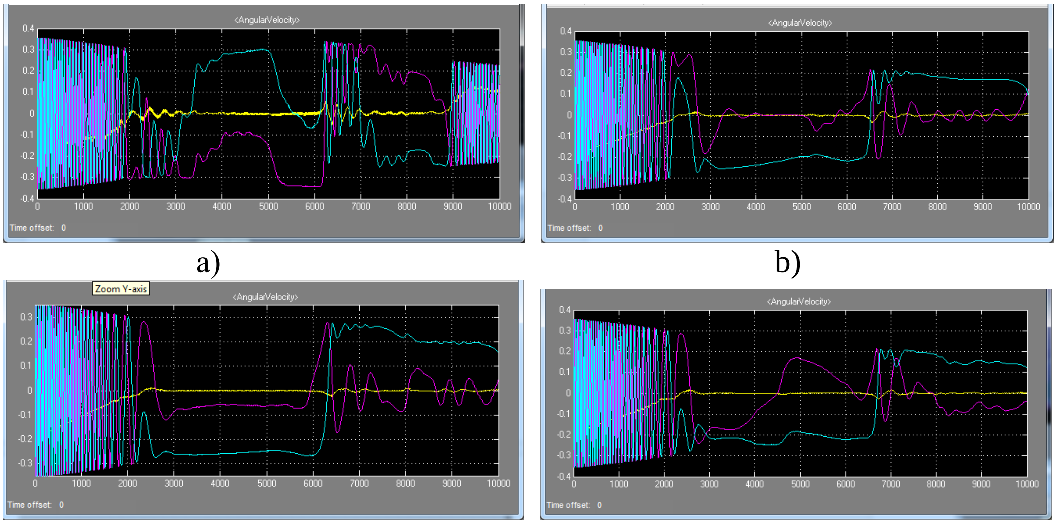
Figure 2 – Change of angular velocity of the spacecraft by $\mathbf{I} = [0.0459\ \ 0.0328\ 0.0328]$ (kgm^2)



a) b)

c) d)

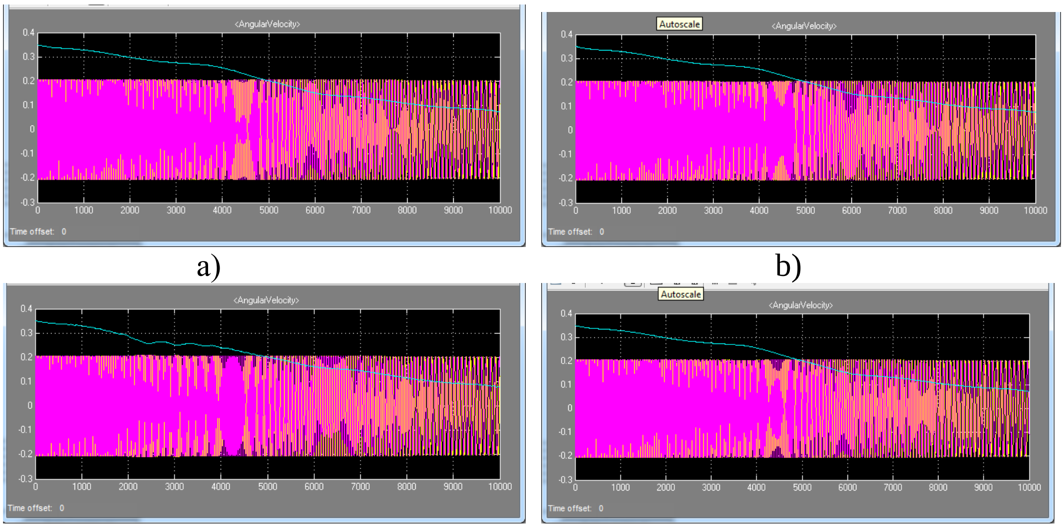
Figure 3 – Change of angular velocity of the spacecraft by $\mathbf{I} = [0.0017\ \ 0.0015\ 0.0020]$ (kgm^2)



a) b)

c) d)

Figure 4 – Change of angular velocity of the spacecraft by $\mathbf{I}=[0.0067\ \ 0.0333\ 0.0333]\ \ (kgm^2)$



a) b)

c) d)

Figure 5 – Change of angular velocity of the spacecraft by $\mathbf{I}=[0.4\ \ 0.4\ 0.08]$ (kgm^2)

3 Conclusions

The rotational motion of the small spacecraft around the mass center under the residual magnetic moment influence was studied. Several cases for different values of the inertia moments were considered. The values of the inertia moments are commensurable with the size and mass of the spacecraft. Figs. 1-2 show that in the absence of residual magnetic moment, two components of the spacecraft's angular velocity tends to zero, the third component is stabilized around some other value (case a) and in presence of the residual torque the spacecraft angular velocity is stabilized worse and the process takes more time (cases b, c, d). Figs. 3-4 show that the residual magnetic moment have big impact for the small satellites (1U and 3U Cubesats), while for more large satellite influence of the residual magnetic moment has a slight effect (fig. 5). Thus, even the constant residual magnetic moment acting along only one axis has significant influence on the small spacecraft. Therefore, by development of the small satellite this fact should be taken into account.

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