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Stabilization of a programmed rotation mode for a satellite with electrodynamic attitude control system

A.Yu. Aleksandrov [a], E.B. Aleksandrova [b], A.A. Tikhonov [a,c,*]

[a] Saint Petersburg State University, 7-9 Universitetskaya nab., Saint Petersburg 199034, Russia
[b] ITMO University, 49 Kronverksky Ave., Saint Petersburg 197101, Russia
[c] Saint Petersburg Mining University, 2, 21st Line, Saint Petersburg 199106, Russia

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Abstract

The paper deals with a dynamically symmetric satellite in a circular near-Earth orbit. The satellite is equipped with an electrodynamic attitude control system based on Lorentz and magnetic torque properties. The programmed satellite attitude motion is such that the satellite slowly rotates around the axis of its dynamical symmetry. Unlike previous publications, we consider more complex and practically more important case where the axis is fixed in the orbital frame in an inclined position with respect to the local vertical axis. The satellite stabilization in the programmed attitude motion is studied. The gravitational disturbing torque acting on the satellite attitude dynamics is taken into account since it is the largest disturbing torque. The novelty of the proposed approach is based on the usage of electrodynamic attitude control system. With the aid of original construction of a Lyapunov function, new conditions under which electrodynamic control solves the problem are obtained. Sufficient conditions for asymptotic stability of the programmed motion are found in terms of inequalities for the values of control parameters. The results of a numerical simulation are presented to demonstrate the effectiveness of the proposed approach.

Keywords: Satellite; Attitude motion; Stabilization; Biaxial rotation; Asymptotic stability

1. Introduction

Electrodynamic interaction between a satellite and the Earth's magnetic field considerably influences the satellite attitude dynamics (Abdel-Aziz, 2007) and can be used for designing satellite attitude control systems (Yu and Yang, 2016). Magnetic control systems based on the usage of magnetic interaction torque, their advantages, specific features and shortcomings are described in Wertz (1985), Hughes (1986), Bushenkov et al. (2002) and in papers cited therein. The known shortcoming of magnetic control systems is underactuation since control torque is always orthogonal to the induction vector of the Earth's magnetic field. This underactuation issue was addressed in many papers among which we mention only Guelman et al. (2005) and Ivanov et al. (2017) where it overcame without additional actuators. Also, underactuated spacecraft hovering is of great importance in view of the restrictions on the total mass and cost of spacecraft (Godard et al., 2014; Huang et al., 2015b).

An attitude control system applying only the electrodynamic effect of the Lorentz torque acting upon a charged satellite moving in the Earth's magnetic field was suggested in 1988, covered by patents in 1998 and 2001 (Petrov and

* Corresponding author at: Saint Petersburg State University, 7-9 Universitetskaya nab., Saint Petersburg 199034, Russia.
E-mail addresses: a.u.aleksandrov@spbu.ru (A.Yu. Aleksandrov), star1460@yandex.ru (E.B. Aleksandrova), a.tikhonov@spbu.ru (A.A. Tikhonov).

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Tikhonov, 2001) and published in article Tikhonov (2003). The Lorentz attitude control system was significantly inspired by the problem of radiation protection for habitable spacecrafts and satellite onboard equipment from the harmful effects of galactic cosmic rays, Earth's radiation belts, solar particle events, etc. As conventional radiation shielding strategies based on bulk material have obvious drawbacks, the concept of active shielding based on the use of an electromagnetic field to deflect the charged particles from the protected volume of the satellite is an attractive alternative to passive material shielding (Sussingham et al., 1999). In particular, electrostatic space radiation shielding proposed in the 1960s (Trukhanov et al., 1970) has been actively studied and revised in the last few years due to recent technological improvements (Spillantini, 2007; Tripathi et al., 2008; Joshi et al., 2013a,b). The system of active electrostatic shielding is based on the use of electrostatically charged shield covering the protected volume and deflecting charged particles from the surface. When a satellite equipped with active electrostatic shielding is moving in a near-Earth orbit, the interaction of the electric charge of the shield with the geomagnetic field causes the moment of Lorentz forces acting on the satellite. Since the Lorentz torque has a stabilizing effect on a satellite attitude motion, this fact can be considered as the basis for the creation of controlled Lorentz torque to provide programmed modes of a satellite attitude motion (Petrov and Tikhonov, 2001; Tikhonov, 2003). Such a feedback control law requires to provide active changing the radius vector of the satellite center of charge relative to its center of mass. This requirement is practically feasible. The method and device that permits us to actively control the position of the satellite center of charge relative to its center of mass were suggested in the patent (Petrov and Tikhonov, 2001).

Paper Giri et al. (2015), where the term "Magnetocoulombic Attitude Control" is used for Lorentz attitude control system, presents the general approach of control theory to the problem of 3-axis active nonlinear attitude control of a charged body with the aid of Lorentz torque, and addresses the fault-tolerance issue of this method of control.

It is shown (Antipov and Tikhonov, 2007) that the Lorentz control systems have an underactuation similar to that of magnetic control systems. At the same time, the integrated system which use simultaneously the torques of magnetic interaction and the Lorentz one is free of the mentioned shortcomings and is more effective than each one of magnetic and Lorentz attitude control systems taken alone. In papers Antipov and Tikhonov (2007, 2014) this integrated system, called electrodynamic attitude control system, was used for the problem of satellite attitude stabilization in the orbital frame. Mathematical justification of the method is based on consideration of differential equations in linear approximation. The existence of a domain of values for parameters of a satellite and its orbit providing total stability of the equilibrium position is proved with the use of results of numerical analysis of the roots of the characteristic polynomial.

A nonlinear approach to the problem of electrodynamic satellite attitude stabilization in the orbital frame was first given in paper Aleksandrov and Tikhonov (2012a) where asymptotic stability was justified analytically. Sufficient conditions for the asymptotic stability of the satellite equilibrium under the perturbing action of the gravitational torque were established on the basis of the Lyapunov direct method by development of the approaches to constructing Lyapunov functions proposed in Zubov (1978) and Smirnov (1980).

In this paper, we consider a satellite with electrodynamic attitude control system and solve a problem of satellite attitude stabilization in a programmed motion. This study is along the same line with Sazonov et al. (2000), Aleksandrov and Tikhonov (2012b), where the spin rate of the satellite about the symmetry axis is controllable. The programmed satellite attitude motion is such that the satellite slowly rotates around the axis of its dynamical symmetry, and the axis is fixed in the orbital frame and inclined at an angle φ with respect to the local vertical axis.

The spin-axis stabilization problem was considered in a lot of papers with various formulations and different approaches for their solution since it has numerous applications. The stabilization of a dynamically symmetric spacecraft about its axis of symmetry has practical meaning, for example, in the case where this axis is the axis of a communications antenna, the boresight or line of sight of an onboard telescope or a camera, etc. (Tsiotras, 1997; Tsiotras and Luo, 2000; Zhang et al., 2008). In some cases the relative rotation of the camera or onboard telescope has no influence on the clarity of the photograph or the communication quality. Therefore, the satellite relative rotation about the axis of symmetry is irrelevant (Tsiotras, 1997; Tsiotras and Luo, 2000; Zhang et al., 2008) as in the problem of line-of-sight pointing control. Most importantly, spin-stabilized satellite also falls into this category (Tsiotras, 1997; Gui and Vukovich, 2015; Chaikin, 2017). Spin-axis stabilization is of prime practical importance, since it is often utilized during deployment and station-keeping of modern satellites in orbit (Tsiotras and Longuski, 1994). In some applications a uniform rotation of a satellite with prescribed relative angular velocity is required to provide a more uniform heating of satellite by the Sun's rays and to reduce the undesirable effects caused by the temperature gradient of the satellite (Sazonov et al., 2000). This imposes requirement on the satellite angular velocity about the spin axis.

A special case of the stated problem was studied in paper Aleksandrov and Tikhonov (2012b) where the axis of satellite dynamical symmetry was stabilized along the local vertical, i.e., $\varphi = 0$. Such rotation modes also referred to as "Biaxial rotation mode" (Sazonov et al., 2000). It should be noted that the stated problem is more complex than that of the monoaxial attitude stabilization of a satellite, and previously it was not treated with the use of the