Acta Astronautica 128 (2016) 210–216

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Nanosatellite spin-up using magnetic actuators: ESTCube-1 flight results

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ARTICLE INFO

Article history:
Received 15 November 2015
Accepted 22 July 2016
Available online 25 July 2016

Keywords:
CubeSat
ESTCube-1
Nanosatellite
Magnetic attitude control
High spin rate
Flight results

ABSTRACT

This paper presents the in-orbit performance of the ESTCube-1 attitude control system that used electromagnetic actuators to achieve a high angular velocity. ESTCube-1 is a one-unit CubeSat that aimed to perform the first electric solar wind sail experiment. The attitude control system was designed to provide enough centrifugal force by spinning up the satellite to deploy a 10 m long tether. The required spin rate was a minimum of one rotation per second. The actuators used were three electromagnetic coils, each able to produce a magnetic moment of up to 0.1 A m^2. In this paper, we describe the design of the attitude control system, implementation of the spin controller and the in-orbit performance of the system. In addition we describe the effect that a residual magnetic moment had on the attitude control of the satellite and the measures taken to overcome this issue. During testing of the satellite, ESTCube-1 achieved the highest known spin rate of 841°/s for small scale satellites. The satellite ended its operations on the 19th of May, 2015 after 2 years in orbit.

1. Introduction

Magnetic satellite spin and spin-axis control has been extensively analysed in the literature for specific missions and as theoretical studies [1–6]. On nano- and microsatellites magnetic attitude control has been researched, or used for different applications, such as detumbling [7], Sun-pointing [8], nadir-pointing [9], alignment with the geomagnetic field [10] and spin-stabilisation [11]. Nanosatellites and picosatellites are often influenced by residual magnetic moments that reduce the ability to perform attitude control manoeuvres [12,13]. This problem has been analysed and a method for compensation has been developed previously [14]. Problems with a residual magnetic moment were also encountered on ESTCube-1. However, for ESTCube-1 the residual magnetic moment is similar in magnitude to the magnetic torquers and therefore it is not possible to compensate for it fully.

Although attitude control using magnetic torquers on nanosatellites has a long history, to the best knowledge of the authors, in-orbit performance of magnetic spin control for nanosatellites at high spin rates (in the order of 100°/s and more) has not been presented. In this paper, we present the flight results of the ESTCube-1 attitude control system (ACS) which was designed to achieve an angular velocity of 360°/s. The large angular velocity was needed for the centrifugal deployment of the tether to be used for the electric solar wind sail (E-sail) mission [15].

During preparations for tether deployment a significant residual magnetic moment was identified on the satellite that had a detrimental effect on attitude control capabilities and aligned the satellite with the Earth's magnetic field vector.

This problem was approached by characterising the residual magnetic moment, developing a coil correction function that would alter the coil output to counter the disturbing moment and by modifying the original spin controller to allow spinning up the satellite around an arbitrary axis. Fortunately, the uncontrolled spin axis that is influenced by the inertia tensor and the residual magnetic moment was still perpendicular to the direction of tether deployment so it was not seen as a major issue.

The strong residual magnetic moment of the satellite also made it impossible to perfectly realign the spin axis with the Earth's polar axis and maintain the alignment without continuously running the spin controller. Because it was not safe to actively control the satellite's attitude during the experiment, the spin axis alignment was not used while performing the spin-up for the tether deployment experiment.

The spin controller was originally described in [16] and studied

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http://dx.doi.org/10.1016/j.actaastro.2016.07.032
0094-5765/

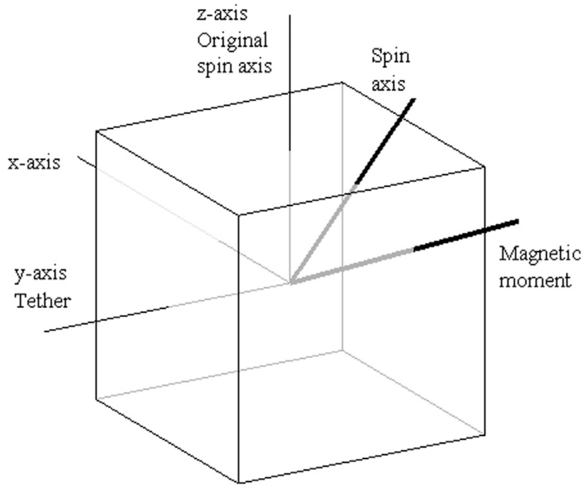

Fig. 1. Illustration of the satellite's spin axes and tether deployment direction [20].

for ESTCube-1 in [17]. However, that research did not include such a severe case of internal magnetic disturbances. In addition to the disturbances further alterations had to be made to the controller to account for a new magnetic coil activation timing algorithm (described in [18]). Due to these changes and the updates to the satellite's inertia matrix the simulation results presented in [17] differ significantly from the in-orbit results.

The ESTCube-1 ACS was capable of spinning up the satellite around an axis that runs across the cube between opposite edges (Fig. 1) to an angular velocity of 841°/s. Such a high speed was used in an attempt to loosen the reel locking mechanism by exerting larger centrifugal forces on it.

2. System design

The ESTCube-1 ACS was designed with the aim to perform a controlled spin-up to high angular velocities that would provide enough centrifugal force to deploy an up to 10 m long tether. Tether deployment set a series of requirements for the attitude determination and control system (ADCS) of the satellite [17].

Initial requirements for tether deployment.

- Spin up the satellite to at least 360°/s to provide enough centrifugal force for the deployment of 10 m of tether.
- The satellite spin axis must be perpendicular to the tether deployment direction. The axis precession must be kept as small as possible. The deviation of the spin axis must not exceed 10° at any time. This is required to avoid the tether rubbing against the satellite structure when it is reeled out. The tether deployment direction is illustrated in Fig. 1.
- Align the satellite spin axis with the Earth's polar axis with a pointing error of less than 3° to minimise the Lorentz force acting on a charged tether.

The requirement to align the spin axis was relaxed because of the electrical power needed to keep continuously aligning the spin axis and because it is not possible to control the spin axis during the experiment phase after tether deployment. It is still possible to measure the E-sail effect without inertial alignment, but the results need more thorough analysis for the verification of the force acting on the tether.

The tether on ESTCube-1 was manufactured so that the first 3 m of the tether was less likely to break. Because of this the experiment plan was changed and a minimum of 115° angular velocity was set as a new requirement. This would provide enough tether tension to reel out the first 3 m of tether. The 3 m of the tether were reinforced and was more likely to survive the vibrations during launch. For additional testing we also wanted to spin up the satellite to very high angular velocities. This is further described in Section 5.

The ESTCube-1 ACS uses magnetic torquers as its only actuators. These are three flat magnetic coils with no core, each capable of producing a maximum magnetic moment of roughly 0.1 A m^2. The three coils are placed on the insides of three orthogonal sidepanels of the satellite and are aligned with the satellite body axes. The coils were built in-house to comply with the requirements and structure of ESTCube-1 [19].

Each of the coils consumes up to 0.4 W of power. The electrical power system was originally designed to produce up to 2 W of power with its solar panels. This power is used to power the coils, the on-board computer and other electronics. Unfortunately, by the time the satellite was deemed ready for the experiment (16 months after launch) the power production had decreased to roughly 1 W [20].

This meant that the experiment could still be done, but it needed longer breaks to recharge the batteries. That waiting time was reduced by implementing subsystem sleep modes in the electrical power system software and therefore reducing the power consumption for the rest of the satellite [21].

The attitude determination system was designed to calculate the attitude at high spin rates, which meant that sensors had to be chosen according to how frequently it would be possible to obtain attitude. For this reason we chose sensors with high measurement rate to be used in the design. The satellite uses six sun sensors, two magnetometers and two gyroscopic sensors to calculate and predict attitude information. Originally the system had four gyroscopic sensors, but one of them failed in the early stages of the mission, which also rendered a second one inoperational due to a simplification in the design of the low-level measurement filter.

The attitude determination accuracy for ESTCube-1 is better than the required 2° [18]. The magnetic field vector is separately provided by magnetometers which have an uncertainty of 3.2°. The uncertainty for the Sun sensors is 2.5° [19]. The uncertainty that was achieved by the gyroscopes after in-orbit calibration was approximately 0.5°/s [18]. All uncertainties are given as expanded uncertainties at approximate confidence level of 95%, coverage factor $k=2$.

3. Spin controller

The spin controller algorithm was mostly based on the well known Euler's equation of rigid body dynamics (Eq. (1)),

$$\vec{T_d} = I\cdot\vec{\dot{\omega}_d} + \vec{\omega_S} \times (I\cdot\vec{\omega_S})\cdot k_{precession} \tag{1}$$

where $\vec{T_d}$ is the desired output torque vector, I the 3×3 inertia matrix, $\vec{\dot{\omega}_d}$ the desired angular acceleration vector, $\vec{\omega_S}$ the current angular velocity vector and $k_{precession}$ the precession gain (not part of the original Euler's equation).

The precession gain was added for testing purposes to enable or disable the precession component, but it could also be used for scaling. Scaling is necessary when a large angular acceleration demand saturates the actuators and the output signal is scaled down to the actuator limits. To avoid the precession component being scaled down to minute levels, $k_{precession}$ should be set greater than 1.

The desired angular acceleration for spin-up and realignment is calculated using Eq. (2). This equation was derived from the equation given in [16].