Acta Astronautica 116 (2015) 254–270

Contents lists available at ScienceDirect

Acta Astronautica

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

Fault-tolerant attitude control of magneto-Coulombic satellites

Dipak Kumar Giri [a], Manoranjan Sinha [a,*], Krishna D. Kumar [b]

[a] Department of Aerospace Engineering, IIT Kharagpur 721302, India
[b] Department of Aerospace Engineering, Ryerson University, Canada

ARTICLE INFO

Article history:
Received 27 January 2015
Received in revised form
17 May 2015
Accepted 21 June 2015
Available online 2 July 2015

Keywords:
Fault-tolerant
Reconfiguration
Attitude
Magneto-Coulombic
Actuator
Iso-inertial

ABSTRACT

A fault-tolerant magneto-Coulombic satellite attitude control using statically charged shells is proposed. Two pairs of statically charged shells are used for the three axes attitude stabilization of a satellite in case one pair of them along any body axis fails. Equation of the motion for the failed system is presented. Equation for the charge required to produce desired torque post-failure is derived. This is used to find available torque post-failure, which is used to propagate states of the system. Controllability of the failed system for very high angular velocity is proved. It is shown that the torque available before and after the failure of one pair of the charged shells along any of the body axes remains the same. It is shown that even an iso-inertial magneto-Coulombic satellite can be stabilized using time invariant feedback control after the failure, which is not possible even using time variant conventional control for other systems. The global stability of the failed magneto-Coulombic system is proved for a proportional–differential control input. Moreover, it is proved that the failed system is locally exponentially stable. Simulation results are presented to show the efficacy of the proposed fault-tolerant magneto-Coulombic attitude control system. Simulation shows that power consumption before and after the failure remains almost the same.

1. Introduction

It is advantageous to use the spurious charges generated on the surface of a satellite due to the interaction of high energy photons and charged particles for the attitude or orbit management rather than dumping. If required, these charges can be further augmented by charges generated using electron or ion emitters which draw ions from a plasma chamber [1–4]. The first effort to use the charged particles (Coulomb force) for the orbit control of a formation of satellites was reported in [5,6]. Later, this concept was extensively treated in [7–9]. Even before these studies were carried out, an effort was made for the passive attitude stabilization of a satellite using charge particles in the geomagnetic field [10]. Much later, a preliminary work on the linearized pitch axis dynamics and control of a pendulum shaped satellite using charges in the geomagnetic field was reported in [11]. It requires to mention that efforts were also made to use purely Coulomb force for the attitude control of a non-spherical satellite [12,13].

A comprehensive study on the three axes active nonlinear attitude control of a satellite using charges or magneto-Coulombic actuators in combination with a proportional–differential (PD) controller was reported in [14]. Magneto-Coulombic actuators are nothing but the Coulomb-shells or charged surfaces. It was proved that such a system can be controlled on an average for a wide range of angular velocities ($\tilde{\omega} < \infty$) if the magneto-Coulombic actuators along the orthogonal body axes remain active all the times. A preliminary study on the two axes attitude control of a magnetically

* Corresponding author: Department of Aerospace Engineering, IIT Kharagpur 721302, India. Tel.: +91 3222283024.
E-mail address: ms.aissq@gmail.com (M. Sinha).

http://dx.doi.org/10.1016/j.actaastro.2015.06.020
0094-5765/

Nomenclature

A	direction cosine matrix that transforms from the orbital frame to the body frame
$\tilde{A}_1, \tilde{A}_2$	two mutually orthogonal vectors in a plane A
$\tilde{b}_0, \tilde{b}$	unit vectors along the Earth's magnetic field in the orbital and the body frames
$\tilde{B}_0, \tilde{B}$	Earth's magnetic field vector in the orbital and the body frames
$\tilde{e}^b_x, \tilde{e}^b_y, \tilde{e}^b_z$	first, second, and third columns of the direction cosine matrix
I	inertia matrix of the satellite (kg m^2)
k_p, k_v	proportional and derivative gains
$\tilde{M}$	charge moment with components in the body frame (C m)
$\tilde{q}$	satellite attitude quaternion vector with respect to the orbital reference frame
Q_{lim}	cut-off limit of charges (C)
$Q_{f_{lim}}$	cut-off limit of charges for the failed case (C)
Q_x, Q_y, Q_z	charges along the x, y, and z body axes (C)
r_x, r_y, r_z	distances between charges along the x, y, and z body axes (m)
$S(\cdot)$	skew matrix of size 3 × 3
$\tilde{T}_{coul}$	magneto-Coulombic torque vector (N m)
$\tilde{T}_{dist}$	disturbance torque vector (N m)
$\tilde{T}_{gg}$	gravity gradient torque vector (N m)
$\tilde{u}$	desired control torque vector (N m)
$\tilde{v}$	velocity of the satellite along the body axes (m/s)
$\tilde{v}_0$	velocity of the satellite along the orbital axes (m/s)
$x\,y\,z$	body reference frame
$X\,Y\,Z$	Earth centered inertial reference frame
$x_0\,y_0\,z_0$	orbital reference frame
ε	small arbitrary positive constant
$\tilde{\Gamma}_2, \tilde{\Gamma}_3$	control matrices for the failed and intact systems
$\overline{\Gamma}_2, \overline{\Gamma}_3$	time average of the control matrices $\tilde{\Gamma}_2(\cdot), \tilde{\Gamma}_3(\cdot)$
Γ_b, Γ_0	control matrices in the body and the orbital reference frames
$\lambda_{min}, \lambda_{max}$	minimum and the maximum eigenvalues of the inertia matrix
$\Im$	unit matrix of size 3 ×3
$\tilde{\omega}$	angular velocity of the satellite in the inertial reference frame (rad/s)
$\tilde{\omega}_r$	relative angular velocity of the satellite with respect to the orbital reference frame (rad/s)
$\tilde{\omega}_0$	orbital angular velocity (orbital rate) of the satellite in the inertial reference frame (rad/s)
$\tilde{\Omega}(t), \tilde{\Omega}_0(t)$	unit vectors in the direction of $\tilde{\nu} \times \tilde{B}$ and $\tilde{\nu}_0 \times \tilde{B}_0$

actuated satellite was reported in [15]. The controllability and stability issues of a partially failed magneto-Coulombic satellite system have not been addressed either for short or wide range of angular velocities ($\tilde{\omega} < \infty$). Thus, it is imperative to investigate the issue of two axes attitude control of magneto-Coulombic satellite system over a wide range of angular velocity.

The three axes controllability issue [16] of a satellite was treated extensively in the last three decades. A general three axes attitude control using momentum exchange devices is not possible with fewer than three independent actuators [16]. In fact, two independent actuators cannot even locally asymptotically stabilize a rigid spacecraft using a time-invariant static or dynamic feedback [17], but an exponential convergence is possible with time varying feedback [18]. However, even the time varying feedback fails to control an iso-inertial satellite putting a constraint on the use of momentum exchange devices in case one of them fails. On the other hand, a three axes magnetically actuated satellite, which is an under actuated system, can be controlled and stabilized by a continuous time-invariant state feedback in a periodically varying magnetic field [19,20]. It was shown in [19] that for a mutually linearly independent magnetic field and its time derivative at every instant of time the attitude dynamics of a three axes magnetically actuated satellite is strongly accessible. Further, for a periodically varying magnetic field the attitude dynamics of a satellite is fully controllable [19]. Later it was proved in [14] that the magnetically actuated satellite system is controllable and stable over a wide range of angular velocity ($\tilde{\omega} < \infty$) for a proportional–differential controller. However, the controllability and stability issue of a partially failed (two axes actuation) magneto-Coulombic system over a wide range of angular velocity ($\tilde{\omega} < \infty$) has not been addressed. Therefore, a comprehensive study addressing the controllability and global stability of a magneto-Coulombic system is required in case one pair of the Coulomb shells along any of the body axes fails.

In the present paper, fault-tolerant control of a magneto-Coulombic satellite system using Lorentz force in the post-failure situation is addressed. Obviously, this requires addressing the issues of two-axes attitude control and global stability of a satellite using Lorentz force. As mentioned earlier, the actuators consist of electrostatically charged shells or Coulomb shells which interact with the time varying earth's magnetic field to produce the actuating torque. It needs to be mentioned that at any instant the available actuating torque is confined to the plane containing the magnetic field vector and the satellite velocity vector, rendering the three axes actuated magneto-Coulombic satellite system to an under actuated one. In fact, this system is more constrained than a magnetically actuated satellite because the actuating torque vanishes whenever either the magnetic field vector gets aligned along the velocity vector or the Lorentz force becomes parallel to the charge moment (defined later). However, this occurs only for some countable number of points along the orbit making this under actuated system three axes controllable on an average [14]. Charge management can be carried out using various devices such as plasma chamber [21,22]. Charge management system is already