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Three-axis active magnetic attitude control asymptotical study

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ABSTRACT

Active magnetic attitude control system providing given inertial attitude is considered. Control algorithm is constructed on the basis of a planar motion model. It decreases attitude discrepancy. Alternative approach is based on the PD-controller design. System behavior is analyzed for specific motion cases and sometimes for specific inertia tensor (axisymmetrical satellite) using averaging technique. Overall satellite angular motion is covered. Necessary attitude is found to be accessible for some control parameters. Stability is proven and optimal algorithm parameters are obtained. Floquet-based analysis is performed to verify and broaden analytical results.

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1. Introduction

A three-axis active magnetic attitude control system and related algorithms are of great interest and importance for small satellites. Magnetorquers are low-cost, reliable and small and, therefore, especially attractive for such kind of satellites. The trade-off is the underactuation problem. Magnetorquers may be complemented with other actuators. These actuators better be compact, lightweight, fuel-independent. Fluid rings [1] can be noted among novel actuators. Control may be based on optimal or boundary value problem solutions [2], however this approach is hardly available for small satellite onboard computer.

Present paper overcomes the underactuation issue without additional actuators and using rather simple control algorithm. We can outline one paper with comprehensive analytical approach to this problem [3]. Three-axis attitude is achievable with magnetorquers only but the control scheme is hard to implement on a spacecraft. Restrictive assumption (spherically-symmetrical satellite) was made in [4]. The analysis is not valid for a three-axial satellite and has limited technical importance. Numerical analysis of the problem is covered better. We can outline interesting works [5] and [6]. Probably the most important paper on the three-axis magnetic control apart from [3] is [7]. Performance of the three-axis magnetic attitude control system of the Gurwin-Techsat small satellite is present. Only the necessary attitude maintenance is shown. Nevertheless, the work shows the engineering possibility to overcome the underactuation issue.

This paper deals with underactuation issue analytically. The control is based on a PD-controller. This is the common way to construct three-axis magnetic control algorithm. Another intuitive control construction scheme is discussed. The control is studied analytically in order to prove asymptotical stability of the necessary attitude. Optimal control parameters (in terms of the maximum degree of stability) are obtained. Analytical results are improved and complemented using the Floquet theory. Control limitations are briefly discussed.

2. Problem statement

2.1. Geomagnetic field model

We use the averaged (simplified direct dipole) geomagnetic field model following our previous studies [8,9]. The

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Nomenclature

Θ	Averaged geomagnetic field model cone half-angle
$L,\rho,\sigma,$ φ,ψ,θ	Osculating variables
$\mathbf{Q},\mathbf{A},\mathbf{D}$	Direction cosine matrices
q_{ij},a_{ij},d_{ij}	Direction cosine matrices elements
$\boldsymbol{\omega}$	Angular velocity
$\mathbf{S}$	Attitude error vector
$\boldsymbol{\Omega},\mathbf{w}$	Dimensionless angular velocity
$\mathbf{J}$	Inertia tensor
A,B,C	Inertia tensor components
$\mathbf{M}$	Torque
$\overline{\mathbf{M}}_L$	Dimensionless torque
i	Orbit inclination
α,β,γ	Attitude angles
$\mathbf{W}$	Kinematics matrix
$\mathbf{m}$	Satellite dipole moment
$k_a,k_\omega;k'_a,k'_\omega;$ K_a,K_ω	Control gains
ξ	Degree of stability
V	Lyapunov function (candidate)
$\mathbf{B}$	Geomagnetic induction vector
B_i	Unit geomagnetic induction vector components
B_0	Geomagnetic induction vector magnitude
ω_0	Orbital angular velocity
L_0	Initial angular momentum
l	Dimensionless angular momentum
$\varepsilon_1,\varepsilon_2$	Small parameters
κ	Small parameters relation
χ	Control gains relation
θ_1,θ_2	Satellite and orbit properties-based parameters

geomagnetic induction vector moves uniformly on the cone side with the doubled orbital angular speed. To introduce this model we need to notify a reference frame $O_aY_1Y_2Y_3$ where O_a is the Earth center, O_aY_3 axis is directed along Earth's axis, O_aY_1 lies in Earth's equatorial plane and is directed to the ascending node of the orbit, the O_aY_2 axis is directed so the system is right-handed. If the magnetic induction vector source point is translated to O_a then the cone is tangent to the O_aY_3 axis, its axis lies in the $O_aY_2Y_3$ plane. The cone half-angle Θ is given [10] by

$$\tan\,\Theta=\frac{3\,\sin\,2i}{2\left(1-3\sin^2 i+\sqrt{1+3\sin^2 i}\right)}$$

where i is the orbit inclination. This model allows the most compact and simple, though rather accurate geomagnetic field model approximation. Geomagnetic induction vector may deviate by as many as 18° from “real” one according to [10] where detailed model behavior can be found. This model can hardly be used to assess attitude accuracy. Here it is implemented to prove necessary attitude stability using averaged technique while accuracy problem is not covered.

2.2. Reference frames and equations of motion

Let us introduce all necessary reference frames.

$O_aZ_1Z_2Z_3$ is the inertial frame, obtained from $O_aY_1Y_2Y_3$ turning by angle Θ about O_aY_1 axis.

$OL_1L_2L_3$ is the frame associated with the angular momentum of the satellite. O is satellite's center of mass, OL_3 axis is directed along the angular momentum, OL_2 axis is perpendicular to OL_3 and lies in a plane parallel to the $O_aZ_1Z_2$ plane and containing O, OL_1 is directed such that the reference frame is right-handed.

$Ox_1x_2x_3$ is the bound frame; its axes are directed along the principal axes of inertia of the satellite.

Reference frames' mutual orientation is described with the direction cosine matrices $\mathbf{Q},\mathbf{A},\mathbf{D}$ expressed in tables

	L_1	L_2	L_3
Z_1	q_{11}	q_{12}	q_{13}
Z_2	q_{21}	q_{22}	q_{23}
Z_3	q_{31}	q_{32}	q_{33}

,

	x_1	x_2	x_3
L_1	a_{11}	a_{12}	a_{13}
L_2	a_{21}	a_{22}	a_{23}
L_3	a_{31}	a_{32}	a_{33}

,

	x_1	x_2	x_3
Z_1	d_{11}	d_{12}	d_{13}
Z_2	d_{21}	d_{22}	d_{23}
Z_3	d_{31}	d_{32}	d_{33}

.

We introduce subscripts Z,L,x to denote the vector components in frames $O_aZ_1Z_2Z_3$, $OL_1L_2L_3$ and $Ox_1x_2x_3$ respectively. For example, the first component of a torque $\mathbf{M}$ in these frames is M_{1Z},M_{1L},M_{1x}.

We use osculating variables and Euler angles to represent satellite motion. Osculating variables are $L,\rho,\sigma,\varphi,\psi,\theta$ [11] where L is the angular momentum magnitude, angles ρ,σ represent its attitude with respect to $O_aZ_1Z_2Z_3$ frame (Fig. 1). Attitude of $Ox_1x_2x_3$ with respect to $OL_1L_2L_3$ is described using Euler angles φ,ψ,θ.

Direction cosine matrices $\mathbf{Q}$ and $\mathbf{A}$ are

$$\mathbf{Q}=\begin{pmatrix}\cos\,\rho\,\cos\,\sigma & -\,\sin\,\sigma & \sin\,\rho\,\cos\,\sigma\\ \cos\,\rho\,\sin\,\sigma & \cos\,\sigma & \sin\,\rho\,\sin\,\sigma\\ -\,\sin\,\rho & 0 & \cos\,\rho\end{pmatrix}, \tag{1}$$

$$\mathbf{A}=\begin{pmatrix}\cos\,\varphi\,\cos\,\psi-\,\cos\,\theta\,\sin\,\varphi\,\sin\,\psi & -\,\sin\,\varphi\,\cos\,\psi-\,\cos\,\theta\,\cos\,\varphi\,\sin\,\psi & \sin\,\theta\,\sin\,\psi\\ \cos\,\varphi\,\sin\,\psi+\,\cos\,\theta\,\sin\,\varphi\,\cos\,\psi & -\,\sin\,\varphi\,\sin\,\psi+\,\cos\,\theta\,\cos\,\varphi\,\cos\,\psi & -\,\sin\,\theta\,\cos\,\psi\\ \sin\,\theta\,\sin\,\varphi & \sin\,\theta\,\cos\,\varphi & \cos\,\theta\end{pmatrix}. \tag{2}$$

Inertia tensor of the satellite is $\mathbf{J}_x=diag(A,A,C)$; the satellite is considered axisymmetrical one when osculating variables equations are used. This restriction facilitates

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