AN ACTIVE FORCE CONTROL (AFC) BASED CONTROL MOMEN GYROS FOR ATTITUDE CONTROL OF SMALL SATELLITE

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by

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LIST OF ABBRREVIATIONS

ADCS	Attitude Determination and Control System
AFC	Active Force Control
AFCCA	Active Force Control Crude Approximation
AFCCAIL	Active Force Control Crude and Iterative Learning
ASCMG	Adaptive-Skew Control Moment Gyroscope
CEACS	Combined Energy and Attitude Control System
CMG	Control Moment Gyroscope
CMG-RW	Control Moment Gyroscope-Reaction Wheel
COTS	Commercially of The Self
DGCMG	Double Gimbal Control Moment Gyroscope
IGRF	International Geomagnetic Reference Field
IPACS	Integrated Power and Attitude Control System
ISS	International Space Station
LEO	Low Earth Orbit
LQ	Linear Quadratic
LVLH	Local Vertical Local Horizontal
MED	Momentum Exchange Device
MP	Moore-Penrose
MTGAC	Magnetic Torque Gimbal Angle Compensation
PD	Proportional-Derivative
PD+AFC	Proportional-Derivative+Active Force Control
PD+AFC+MTGAC	Proportional-Derivative+Active Force Control+ Magnetic Torque Gimbal Angle Compensation

PI	Proportional-Integral
PID	Proportional-Integral-Derivative
rpm	Rotation per minute
RW	Reaction Wheel
SGCMG	Single Gimbal Control Moment Gyroscope
SR	Singularity Robust
SSTL	Surrey Satellite Technology Ltd
SVD	Single Value Decomposition
TPM	Torque Product Minimization
VPDRF	Variable Periodic Disturbance Rejection Filter
VSCMG	Variable Speed Control Moment Gyroscope

LIST OF SYMBOLS

α	Orbit angle measure from the ascending node
β	Pyramid skew angle/Angular momentum precession angle
$\dot{\gamma}$	Gimbal angle rate of VSCMG
Δ	Differences between two values
$\boldsymbol{\delta}$	Gimbal angles vector of SGCMGs
$\boldsymbol{\delta}_{\mathbf{init}}$	Initial gimbal angles vector
$\boldsymbol{\delta}_{\mathbf{final}}$	Final gimbal angles vector
$\boldsymbol{\delta}^*$	Preferred gimbal angles vector
δ_e	Maximum gimbal angle error
$\delta_{e_{avg}}$	Average value of maximum gimbal angle error
$\dot{\boldsymbol{\delta}}$	Gimbal angle rates vector
$\dot{\boldsymbol{\delta}}_{\mathbf{e}}$	Gimbal angle error rates vector
$\dot{\delta}$	Gimbal angle rate
$\dot{\delta}_i$	Gimbal angle rate of i^{th} VSCMG
$\dot{\delta}_{max}$	Gimbal angle rates limit
ζ	Damping ratio
η_m	Phase angle
ϑ	True anomaly
θ	Pitch angle
θ_s	Attitude angle of the satellite
$\dot{\theta}_s$	Angular rate of the satellite
$\dot{\theta}_s^{max}$	Maximum angular rate of the satellite

$\ddot{\boldsymbol{\theta}}'$	Measured acceleration of the dynamic system
$\ddot{\boldsymbol{\theta}}_{\mathbf{s}}$	Satellite angular acceleration vector
$\ddot{\theta}_s$	Angular acceleration of the satellite
λ	Singularity robust (SR) inverse steering law constant
$\mu_{\oplus}$	Earth gravitational constant (398600 km^3/s^2)
ξ_m	Instantaneous inclination
ρ	Atmospheric density
ϕ	Roll angle
ψ	Yaw angle
$\boldsymbol{\omega}$	Satellite angular velocity vector
$\boldsymbol{\omega}_{\mathbf{I/B}}$	Inertially referenced satellite's angular velocity relative to inertial coordinate system
ω	Argument of perigee
ω_{E}	Earth's orbital frequency
ω_n	Natural frequency
ω_0	Orbital frequency
$\dot{\boldsymbol{\omega}}$	Satellite angular acceleration vector
$\dot{\boldsymbol{\omega}}_{\mathbf{I/B}}$	Inertially referenced satellite's angular acceleration relative to inertial coordinate system
ω_{CMG}	Angular velocity of the CMG's flywheel
$\boldsymbol{\Omega}$	Non-constant rotational speed of VSCMG's flywheel
$\boldsymbol{\Omega}(\boldsymbol{\omega})$	4×4 Skew symmetric matrix
Φ	Euler rotation angle
♈	Vernal equinox

$\mathbf{A}(\boldsymbol{\delta})$	Jacobian matrix
$\mathbf{A}^{+}$	Pseudoinverse of Jacobian matrix
$\mathbf{A}^{\mathrm{T}}$	Transposed of Jacobian matrix
$\mathbf{A}^{\#}$	Singularity robust inverse
$\mathbf{A_s}$	Satellite's exposed area
$[\mathbf{A}(\mathbf{q})]$	Direction cosine matrix expressed in quaternion
a	Orbit semimajor axis
$\mathbf{B}$	Geomagnetic field vector
B	Magnitude of the geomagnetic field vector
$\mathbf{C_D}$	Drag coefficient
$\mathbf{C_g}$	Centre of gravity
C_s	Solar radiation constant ($1358\ \mathrm{W/m^2}$)
$\mathbf{C_{sp}}$	Centre of solar pressure
c	Speed of light ($3.0 \times 10^8\ \mathrm{m/s}$)
D	Residual magnetic dipole moment
$\mathbf{e}$	Eigenvector of rotation, $\mathbf{e} = [e_1\ e_2\ e_3]^{\mathrm{T}}$
F	Solar force
$\hat{\mathbf{g}}_\mathbf{s}, \hat{\mathbf{g}}_\mathbf{g}, \hat{\mathbf{g}}_\mathbf{t}$	Spin, gimbal and torque axes unit vectors
$\mathbf{H}$	Total angular momentum of the system
$\dot{\mathbf{H}}_\mathbf{B}$	Rate of change of satellite's angular momentum in satellite's body frame
$\dot{\mathbf{H}}_\mathbf{I}$	Rate of change of satellite's angular momentum in inertial coordinate system
$\mathbf{h}$	CMG system angular momentum vector
h	Orbital altitude/angular momentum of flywheel

h_i	Angular momentum of i^{th} VSCMG
h_0	Angular momentum magnitude of SGCMG
h_x, h_y, h_z	Angular momentum along satellite's body axes
h'	Rotated angular momentum of flywheel
$\dot{\mathbf{h}}$	Generated CMG torque vector
$\dot{h}_x, \dot{h}_y, \dot{h}_z$	Generated CMG torque along satellite's body axes
$\dot{h}_{CMG}$	Generated CMG torque
$\dot{h}_{CMG}^{req}$	Required CMG torque
$\mathbf{I}$	Satellite's moment of inertia tensor/Principle moment of inertia
I_x, I_y, I_z	Principle moment of inertia along satellite's body frame
$\mathbf{I}'$	Estimated inertia vector of the dynamic system
I_{CMG}	Moment of inertia of the CMG
i	Orbit inclination
i_s	Incidence angle
J_i	Moment of inertia of i^{th} VSCMG
$\mathbf{K_d}$	Derivative attitude control gain
$\mathbf{K_p}$	Proportional attitude control gain
$\mathbf{M}$	Magnetic dipole moment generated by the magnetic torquers
$\mathbf{M_{limit}}$	Moment acting on the satellite's body/Magnetic dipole moment saturation of the magnetic torquers
M	AFC gain
M_e	Earth's magnetic dipole, (7.9×10^{15} Wbm)

m	Singularity index
m_s	Satellite total mass
m_{CMG}	CMG system total mass
O_ζ, O_η, O_ξ	Axes of the gimbal ring
O_x, O_y, O_z	Axes of the reference frame
$\mathbf{q}$	Quaternion vector
$\mathbf{q_c}$	Commanded quaternion vector
$\mathbf{q_e}$	Quaternion error vector
$\mathbf{q_o}$	Output quaternion vector
$q_{i=1,2,3}$	Vector elements of the quaternion
q_4	Scalar which gives the magnitude of the rotation angle
q_r	Reflectivity factor
$\mathbf{q}^*$	Complex conjugate quaternion
$\mathbf{q_{norm}}$	Normalized quaternion
$\|\mathbf{q}\|$	Quaternion norm
R	Distance from the centre of the Earth
R_e	Radius of the Earth $R_e = 6370$ km
R_o	Orbital radius of the satellite
$\mathbf{RPY_{init}}$	Initial satellite attitude (R – roll along X_B axis, P – pitch along Y_B axis and Y – yaw along Z_B axis)
$\mathbf{RPY_{ref}}$	Reference/desired satellite attitude (R – roll along X_B axis, P – pitch along Y_B axis and Y – yaw along Z_B axis)
$\mathbf{S}(\boldsymbol{\omega})$	3×3 Skew symmetric matrix
$\mathbf{s_i}$	Spin axis vector

T	Orbital period
$\mathbf{T_{aero}}$	Aerodynamic torque vector
$\mathrm{T_{aero}}$	Aerodynamic torque
$\mathrm{T_{aero,constant}}$	Constant component of aerodynamic torque
$\mathrm{T_{aero,harmonic}}$	Harmonic component of aerodynamic torque
$\mathrm{T_{aero,max}}$	Maximum aerodynamic torque
$\mathbf{T_c}$	Required magnetic torque vector
$\mathbf{T_d}$	External disturbance torque vector
T_{dx}, T_{dy}, T_{dz}	External disturbance torques exerted on the satellite body
$\mathbf{T_{gg}}$	Gravity-gradient torque vector
$\mathbf{T_{ext}}$	External torque vector
$\mathbf{T_{magnetic}}$	Magnetic disturbance torque vector
$\mathbf{T_M}$	Magnetic torque vector
$\mathbf{T_O}$	Output torque of VCMG
$\mathbf{T_{sp}}$	Solar radiation torque vector
$\mathrm{T_{solar,constant}}$	Constant component of solar radiation torque
$\mathrm{T_{solar,harmonic}}$	Harmonic component of solar radiation torque
$\mathrm{T_{solar,max}}$	Maximum solar radiation torque
$\mathbf{T'_{cmg}}$	Measured actuator torque vector
$\mathbf{T'_d}$	Estimated disturbance torque vector
t	Time
t_c	Gimbal angle converging time
$\mathbf{t_i}$	Torque axis vector

u	Internal control torque generated by the CMG system
V	Satellite's velocity
W(s)	Weighting function
(X_I, Y_I, Z_I)	Inertia frame coordinate system
(X_O, Y_O, Z_O)	Orbit reference frame coordinate system
(X_B, Y_B, Z_B)	Satellite's body frame coordinate system
$\otimes$	Quaternion multiplication operator

GIROSKOP KAWALAN MOMEN BERASASKAN KAWALAN DAYA AKTIF (AFC) UNTUK KAWALAN ATITUD SATELIT KECIL

ABSTRAK

Sistem giroskop kawalan momen (CMG) adalah pilihan yang sesuai untuk bagi rekabentuk sistem kawalan atitud (ACS) satelit kecil bagi misi berprestasi tinggi kerana ia memiliki amplifikasi kilasan yang tinggi. Namun, kebolehan sistem ini adalah terhad dengan kehadiran unsur gangguan kerana limitasi pengawal atitud piawai untuk menolak gangguan tersebut secara teguh selain sistem CMG yang berdepan degan masalah sudut gimbal tersesar. Dalam kajian ini, kawalan daya aktif (AFC) dicadangkan dan diintegrasikan bersama pengawal berkadaran-terbitan bagi mengarah sistem CMG menjana kilasan kawalan bagi misi yang ditetapkan manakala sistem pampasan sudut gimbal kilasan magnetik (MTGAC) diintegrasikan ke dalam ACS untuk memampas gimbal tersesar sudut. Kesemua model matematik dibina dan dilaksanakan dalam perisian Matlab®-Simulink™. Berdasarkan simulasi, skema AFC yang dicadangkan sangat mempengaruhi prestasi manuver atitud dan tudingan atitud satelit. Dengan memilih parameter AFC yang sesuai, manuver atitud yang dikehendaki dapat dicapai dan ralat atitud dapat dikurangkan dengan ketara lebih dari 60%. Manakala, sistem MTGAC berjaya mengekalkan gimbal-gimbal GKM pada sudut yang dikehendaki lantas meletakkan sistem CMG jauh dari ketunggalan. Tambahan itu, sistem MTGAC juga memberi darjah kebebasan tambahan kepada kawalan tudingan atitud apabila ia menambahbaik ketepatan atitud sebanyak 75% tanpa mempengaruhi prestasi mavuver atitud satelite. Penemuan kajian ini telah pertama kalinya mendemonstrasikan keandalan skema AFC and MTGAC bagi satelit kecil dengan sistem CMG yang sebelum ini belum pernah dikaji.