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Control torque generation of a CMG-based small satellite with MTGAC system: a trade-off study

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Abstract. In this paper, the gimbal angle compensation method using magnetic control law has been adopted for a small satellite operating in low earth orbit under disturbance toques influence. Three light weight magnetic torquers have been used to generate the magnetic compensation torque to bring diverge gimbals at preferable angle. The magnetic control torque required to compensate the gimbal angle is based on the gimbal error rate which depends on the gimbal angle converging time. A simulation study has been performed without and with the MTGAC system to investigate the amount of generated control torque as a trade-off between the power consumption, attitude control performance and CMG dynamic performance. Numerical simulations show that the satellite with the MTGAC system generates more control torques which leads to the additional power requirement but in return results in a favorable attitude control performance and gimbal angle management.

1. Introduction

Control moment gyroscope (CMG) is a momentum exchange device that controls satellite attitude based on the conservation of angular momentum of the satellite system [1]. It has a torque amplification characteristic which makes it as a perfect actuator for fast slew maneuver and precise attitude pointing control over other actuators such as momentum wheels and reaction wheels. These features increase the operational envelop of the satellites and subsequently increase the return of mission data and reduce payload complexity [2,3]. Control torque is generated by rotating the CMG's gimbal at certain gimbal angle rate. This causes the direction of the flywheel's angular momentum vector to change and results in a generation of control torque, orthogonal to both flywheel's spin and gimbal axes [4]. There are three types of CMG i.e. single gimbal CMG (SGCMG), double gimbal CMG (DGCMG) and variable speed CMG (VSCMG). Among these three, SGCMG is less complex and cheaper than VSCMG and it has more significant torque amplification over DGCMG [5-7]. However, SGCMG has drawback in term of singularity where at certain gimbal angle orientations, the control torque cannot be generated by the CMG cluster thus resulting in a loss of satellite attitude controllability. The singularity problems have lead towards the development of singularity avoidance or steering laws that can avoid or escape the CMG cluster from singular states [8-12].

Another concern about the CMG system is the gimbal angle offset due to disturbance torques. The constant disturbance torques cause the gimbals to drift away from preferred or reference angles. This situation reduces the repeatability of slew maneuvers and can also drive the CMG cluster into saturation singularity state which most of the steering laws fail to avoid or escape. Since the CMG

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system lacks ability to compensate the drifted gimbals, an auxiliary controller to maintain the CMG gimbal at preferable angle is required. In principle, another external control torque is applied on the satellite to counteract the disturbance torques.

Magnetic control torque offers simple, cheap and more sustainable option to counter this problem. Therefore, it is more preferable for small satellite application, especially for low Earth orbit (LEO) missions. The technique utilizes the coupling action between the geomagnetic field and the magnetic dipole moment induced either by three or two magnetic torquers on-board the satellite. McElvain [13] and Stickler and Alfriend [14] proposed a control equation which was later became the standard for wheel unloading control law that uses magnetic control torque. The momentum unloading strategy was designed such that the produced counter torque is a function of the excess momentum to be removed. Meanwhile, Camillo and Markley [15] derived analytical formulae based on the bang-bang and linear controllers in order to optimize the performance of the reaction wheel angular momentum unloading after considering the limitations of using magnetic torquers. Then, an optimal magnetic momentum control for inertially pointing spacecraft with reaction wheel was studied by Lovera [16]. The optimal approaches based on periodic linear quadratic (LQ) and H_∞ control were proposed and their effectiveness was compared with the classical control law. The simulation results showed that the periodic control was more efficient than the classical control algorithm in achieving the desired momentum unloading performances. Suhadis and Varatharajoo [17] studied the active magnetic control technique to unload the excess wheel angular momentum of a small biased-momentum satellite in a nominal operation. They adopted the proportional-integral (PI) controller to keep the wheel's angular momentum within the bias value. Two cases were considered where two and three magnetic torquers were considered for each case, respectively. The results from the numerical studies showed that the momentum unloading performance with three magnetic torquers was better than with two magnetic torquers where a faster unloading control can be achieved.

On the other hand, the implementation of magnetic control torque to compensate drifted CMG gimbals can be found from Lappas et al. work [18]. The control strategy was designed such that the required magnetic control torque generated by the magnetic torquers proportional to the gimbal angle error rate. A controller gain known as gimbal angle converging time was introduced which need to be properly selected in order to obtain sufficient compensation torque. In the numerical study, three magnetic torquers aligned with the satellite's principle axis were considered to compensate the drifted gimbal of 4-SGCMGs system in the conventional pyramid configuration. It was found that, the proposed magnetic torque controller was able to bring back the drifted gimbals to the preferred angles within acceptable error band. However, the effect of the gimbal angle compensation controller on generated control torques and attitude control performances were not covered in their study.

In this paper, the gimbal angle compensation system coined as magnetic torque gimbal angle compensation (MTGAC) system is adopted to compensate the gimbal angle of a 4-SGCMGs cluster. The system is implemented onboard a small satellite platform operating in low earth orbit (LEO) under disturbances torques. This magnetic torque controller is cooperated with the standard PD (proportional-derivative) controller that controls the satellite attitude. Meanwhile, the Singularity Robust (SR) inverse steering law is utilized as the singularity avoidance law for the CMG cluster. The study compares the generated control torques during attitude pointing mode without and with the MTGAC system and then discuss in terms of trade-off between power consumption, CMG dynamics and attitude control performance. All presented algorithms are numerically treated for simulation studies via simulation tools.

2. Satellite attitude control structure

2.1 Satellite dynamics and kinematics

The MTGAC system onboard a CMG-based controlled small satellite uses three magnetic torquer coils to generate magnetic compensation torque. These magnetic torquers are placed along the satellite's body-fixed axes (X_B, Y_B, Z_B) where the Z_B axis points toward the earth, the Y_B axis is normal to the orbital plane and the X_B axis points toward the satellite's orbital motion and complete

the right-hand orthogonal system. In addition, a cluster of 4-SGCMGs is also configured such that the axes of the system are along the satellite's body-fixed axes, respectively. Figure 1 shows the configuration of the MTGAC magnetic torquers as well as 4-SGCMGs system.

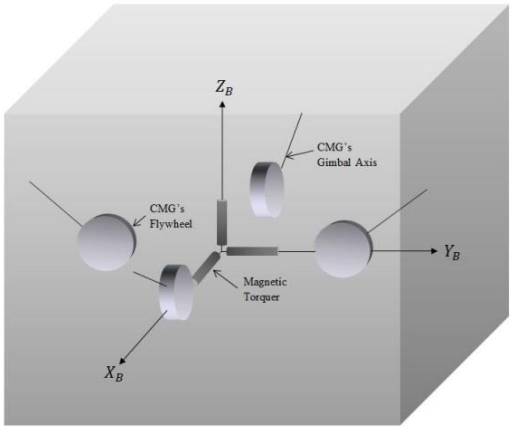

Figure 1. Satellite configuration with four SGCMGs and three magnetic torquers.

Based on the figure 1, the equation of motion of a satellite with a CMG cluster and three magnetic torquers is governed by the following equation of motion [7]

$$\dot{\mathbf{H}}_\mathbf{s} + \boldsymbol{\omega} \times \mathbf{H}_\mathbf{s} = \mathbf{T}_\mathbf{ext} \tag{1}$$

where $\mathbf{H}_\mathbf{s}$ is the angular momentum vector of the total system expressed in the spacecraft body-fixed control axes, $\boldsymbol{\omega}$ is the satellite angular velocity vector, and $\mathbf{T}_\mathbf{ext}$ is the external torques vector. The external torque, $\mathbf{T}_\mathbf{ext}$ is the disturbance torque from the environment $\mathbf{T}_\mathbf{d}$ (i.e. aerodynamic torque, magnetic torque and solar radiation torque) for case without the MTGAC system whereas for case with the MTGAC system it is the total of disturbance torque and magnetic control torque from the gimbal angle compensation system, $\mathbf{T}_\mathbf{ext} = \mathbf{T}_\mathbf{d} + \mathbf{T}_\mathbf{M}$.

The total angular momentum vector of the system consists of the angular momentum of the satellite and the CMG cluster and it is given as

$$\mathbf{H}_\mathbf{s} = \mathbf{I}\boldsymbol{\omega} + \mathbf{h} \tag{2}$$

Substituting equation (2) into equation (1) gives

$$\left(\mathbf{I}\dot{\boldsymbol{\omega}} + \dot{\mathbf{h}}\right) + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega} + \mathbf{h}) = \mathbf{T}_\mathbf{ext} \tag{3}$$

and by introducing the internal control torque vector, $\mathbf{u}$ generated by the CMG system, equation (3) can be written as

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega} = \mathbf{u} + \mathbf{T}_\mathbf{ext} \tag{4}$$

$$\dot{\mathbf{h}} + \boldsymbol{\omega} \times \mathbf{h} = -\mathbf{u} \tag{5}$$

where $\mathbf{I}$ is the moment of inertia of the satellite and $\mathbf{h}$ is the angular momentum vector of the CMG cluster expressed in the satellite body-fixed axes. For the commanded control torque input, $\mathbf{u}$ the CMG torque command is chosen as

$$\dot{\mathbf{h}} = -\mathbf{u} - \boldsymbol{\omega} \times \mathbf{h} \tag{6}$$

in which equation (6) is incorporated with the steering law to determine the gimbal angle rate command.

2.2 CMG dynamics

In this study, a cluster of four identical SGCMGs in pyramid configuration is selected to be employed onboard small satellite as the attitude controller. The configuration has a skew angle of $\beta = 54.73$ degree and it is commonly considered due to uniformity of the momentum envelop and minimum redundancy [7]. The control torque generated by the CMG cluster is the time derivative of the CMG angular momentum. Based on the SGCMGs configuration it can be obtained as follow

$$\dot{\mathbf{h}} = \mathbf{A}(\delta)\dot{\boldsymbol{\delta}} \tag{7}$$

where $\mathbf{A}(\delta)$ is the Jacobian matrix defined as

$$\mathbf{A}(\delta) = \frac{\partial \mathbf{h}}{\partial \boldsymbol{\delta}} = h_0 \begin{bmatrix} -cos\beta \cos\delta_1 & \sin\delta_2 & cos\beta \cos\delta_3 & -\sin\delta_4 \\ -\sin\delta_1 & -cos\beta \cos\delta_2 & \sin\delta_3 & cos\beta \cos\delta_4 \\ sin\beta \cos\delta_1 & sin\beta \cos\delta_2 & sin\beta \cos\delta_3 & sin\beta \cos\delta_4 \end{bmatrix} \tag{8}$$

where h_0 is the magnitude of flywheel's angular momentum. From equation (7), the gimbal angle rate is determined by considering the pseudoinverse steering law given by

$$\dot{\boldsymbol{\delta}} = \mathbf{A}^{+}\dot{\mathbf{h}} = \mathbf{A}^{\mathbf{T}}(\mathbf{A}\mathbf{A}^{\mathbf{T}})\dot{\mathbf{h}} \tag{9}$$

Since singularity is the drawback of SGCMG, the Singularity Robust (SR) inverse steering law has been used in this study due to its simplicity to aid the CMG system avoiding or escaping singular states [8]. Thus, the gimbal angle rate command becomes $\dot{\boldsymbol{\delta}} = \mathbf{A}^{\mathrm{T}}(\mathbf{A}\mathbf{A}^{\mathrm{T}} + \lambda\mathbf{I})^{-1}\dot{\mathbf{h}}$ where λ is the SR invers steering law constant that need to be properly selected. A singularity index $m = \det(\mathbf{A}\mathbf{A}^{\mathbf{T}})$ is used to indicate the state of the CMG system where for $m = 0$ it indicates that the CMG system is in singularity state. It is worthwhile to mention that, the SR steering inverse does not always avoid or escape the CMG system from singular states, especially saturation singularity.

2.3 Attitude Controller

The attitude of the satellite is controlled based on the required control torque commanded by the attitude controller. For a real time implementation, the standard PD (proportional-derivative) controller is adopted. The quaternion error and angular rate vectors are fed to quaternion feedback controller and it is modelled as [19]

$$\mathbf{u} = -\mathbf{K_p}\mathbf{q_e} - \mathbf{K_d}\boldsymbol{\omega} \tag{10}$$

where $\mathbf{q_e} = [q_{1e} \quad q_{2e} \quad q_{3e}]^{\mathrm{T}}$ is the attitude quaternion error vector. By considering the one-to-one equivalence between the direction cosine matrix elements and the quaternion vector elements, the required command control torque can be expressed as [20]

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} -K_{p_x} q_{1e} q_{4e} - K_{d_x}\omega_x \\ -K_{p_y} q_{2e} q_{4e} - K_{d_y}\omega_y \\ -K_{p_z} q_{3e} q_{4e} - K_{d_z}\omega_z \end{bmatrix} \tag{11}$$

The proportional and derivative gains are given as $\mathbf{K_p} = 2{\omega_n}^2[\mathbf{I}]$ and $\mathbf{K_d} = 2\zeta\omega_n[\mathbf{I}]$ respectively, where ζ is the damping ratio and ω_n is the natural frequency. For better attitude performance, the gains need to be properly selected by chosen suitable value of damping ratio and natural frequency.

3. Magnetic torque gimbal angle compensation (MTGAC) system

The gimbal angle offset due to disturbance torques is compensated using magnetic control torque. This torque is generated when the generated magnetic dipole moment of the magnetic torquers inside the satellite couples with the Earth's magnetic field vector [21]. This interaction can be described as [20]

$$\mathbf{T_M} = \mathbf{M} \times \mathbf{B} \tag{12}$$

where $\mathbf{T_M}$ is the generated magnetic torque vector, $\mathbf{M}$ is the magnetic dipole moment vector generated by the magnetic torquers inside the satellite and $\mathbf{B}$ is the Earth's magnetic field vector.

The Earth's magnetic field or geomagnetic field is mathematically expressed by a spherical harmonic model known as Complex Geomagnetic Field Model (CGFM). In this study, however, the Simplified Geomagnetic Field Model (SGFM) is considered to reduce computational burden and it is modelled in the local vertical and local horizontal (LVLH) coordinate system as [22]

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}_{LVLH} = \frac{M_e}{a^3} \begin{bmatrix} \sin i \cos(\omega_0 t) \\ -\cos i \\ 2\sin(\omega_0 t)\sin i \end{bmatrix} \tag{13}$$

where $M_e = 7.9 \times 10^{15}\mathrm{Wbm}^{-1}$ is the Earth's magnetic strength of the dipole vector, a is the orbit's semi-major axis, ω_0 is the orbital frequency and t is the time measured from $t = 0$ s at the ascending node of the geomagnetic equator. Based on equation (13), it is obvious that the geomagnetic field experienced by the satellite is depends by the orbit inclination and semi-major axis or altitude of the satellite. Satellite orbiting at high orbit inclination with low altitude will experience more geomagnetic than satellite at low orbit inclination of the same altitude.

By having the variation of geomagnetic field along the satellite's orbit, the magnetic dipole moment, $\mathbf{M}$ need to be induced by the magnetic torquers can be obtained from the cross product of the commanded magnetic torque and the geomagnetic field, $\mathbf{B}$ and it is given as [23]

$$\mathbf{M} = \frac{\mathbf{B} \times \mathbf{T_c}}{B^2} \tag{14}$$

where $B = \|\mathbf{B}\|$ is the magnitude of the geomagnetic field and $\mathbf{T_c}$ is the magnetic torque required to compensate the gimbals angle offset. The required magnetic torque is designed to be dependent on the gimbal angle error rate and it is defined as [19]

$$\mathbf{T_c} = -\mathbf{A}(\delta)\frac{\boldsymbol{\delta}^* - \boldsymbol{\delta}}{t_c} \tag{15}$$

where $\mathbf{A}(\boldsymbol{\delta})$ is the Jacobian matrix, $\boldsymbol{\delta}^*$ is the preferred gimbals angle vector, $\boldsymbol{\delta}$ is the nominal gimbals angle vector and $\boldsymbol{t_c}$ is the time for the current gimbal angles to converge to the preferred gimbal angles. By substituting equation (14) and (15) into equation (12), the magnetic control torque generated by the magnetic torquers is expressed as follow

$$\mathbf{T_M} = -\frac{\mathbf{B} \times \mathbf{A}(\delta)\frac{\boldsymbol{\delta}^* - \boldsymbol{\delta}}{t_c}}{B^2} \times \mathbf{B} \tag{16}$$

The expression in equation (16) tells that the gimbal angle converging time t_c influences the amount of magnetic torque that needs to be generated and the required magnetic torque can be achieved whenever the magnetic dipole moment vector is perpendicular to the geomagnetic field vector.

4. Simulation studies

All mathematical models in the previous chapters were made amenable for numerical simulations in the Matlab®-Simulink™. The mission of the satellite was to perform attitude pointing mode i.e. roll (R) = 30°, pitch (P) = 0° and yaw (Y) = 0° for 25 orbital cycles. First, the simulation was performed without the MTGAC system (Case I). Then, it was followed by a simulation with the MTGAC system (Case II) at orbit inclination of 65°. All simulation parameters used in this study are summarized in table 1. The PD-controller gains are obtained through fine tuning using heuristic method whereas the value of t_c was selected to be 100s for optimal gimbal angle compensation performance [24].

Table 1. Simulation Parameters.

Parameter	Value
Orbital Parameters	
Altitude, h	500 km
Orbit inclination, i	65 deg
Orbital frequency, ω_0	0.0011 rad/s
Orbital cycle	10 orbits
Disturbance Torques	
T_{dx}	$8 \times 10^{-5} \sin(\omega_o t)$ Nm
T_{dy}	$8 \times 10^{-6} + 5 \times 10^{-5} \cos(\omega_o t) + 8 \times 10^{-5} \sin(\omega_o t)$ Nm
T_{dz}	$8 \times 10^{-6} + 5 \times 10^{-5} \cos(\omega_o t)$ Nm
Satellite Parameters	
Satellite's moment of inertia, $\mathbf{I}$	$\begin{bmatrix} 4.5 & 0 & 0 \\ 0 & 4.5 & 0 \\ 0 & 0 & 4.5 \end{bmatrix}$ kgm^2
Initial attitude, $\mathbf{RPY}_{\text{initial}}$	$[0 \quad 0 \quad 0]^{\mathrm{T}}$ deg
Desired attitude, $\mathbf{RPY}_{\text{desired}}$	$[30 \quad 0 \quad 0]^{\mathrm{T}}$ deg
Initial gimbal angle, $\boldsymbol{\delta}_{\text{initial}}$	$[0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}}$ deg
Preferred gimbal angle, $\boldsymbol{\delta}^*$	$[0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}}$ deg
Maximum gimbal angle rate, $\dot{\boldsymbol{\delta}}_{\mathbf{max}}$	$\pm[10 \quad 10 \quad 10 \quad 10]^{\mathrm{T}}$ deg/s
Flywheel angular momentum, h_0	0.47 Nms
Gimbal angle converging time, t_c	100 s
Magnetic dipole moment limit, $\mathbf{M}_{\mathbf{limit}}$	$\pm[12 \quad 12 \quad 12]^{\mathrm{T}}$ Am^2
Proportional gain, $\mathbf{K}_{\mathbf{p}}$	$[3.86 \quad 3.86 \quad 3.86]^{\mathrm{T}}$ Nm/rad
Derivative gain, $\mathbf{K}_{\mathbf{d}}$	$[5.84 \quad 5.84 \quad 5.84]^{\mathrm{T}}$ Nms/rad
SR-inverse steering law constant, λ	0.01

The generated CMG torques without and with the MTGAC system during attitude pointing mode are shown in figure 2. For Case I, the maximum control torque along the x-axis is 8.5×10^{-5} Nm in positive direction and -8.5×10^{-5} Nm in negative direction. Along the y-axis, the maximum control torque is 1.1×10^{-4} Nm in positive direction and -9.0×10^{-5} Nm in negative direction. Meanwhile, along the z-axis the maximum control torque generated by the CMG system is 6.0×10^{-5} Nm in positive direction and -4.5×10^{-5} Nm in negative direction. On the other hand, for Case II, the

maximum control torque along the x-axis is 5.0×10^{-5} Nm in positive direction and -8.5×10^{-5} Nm in negative direction, 3.5×10^{-5} Nm in positive direction and -4.5×10^{-5} Nm in negative direction along the y-axis whereas along the z-axis the maximum control torque is 7.5×10^{-5} Nm in positive direction and -6.5×10^{-5} Nm in negative direction. By comparing the torques between these two cases, the CMG system generates more attitude control torque in total for Case I since it needs to counter for constant disturbance torques that act on the satellite during attitude pointing mode. In contrast, for Case II the constant disturbance torques that caused the gimbal to drift from its preferred angle are countered by the magnetic control torque from the MTGAC system.

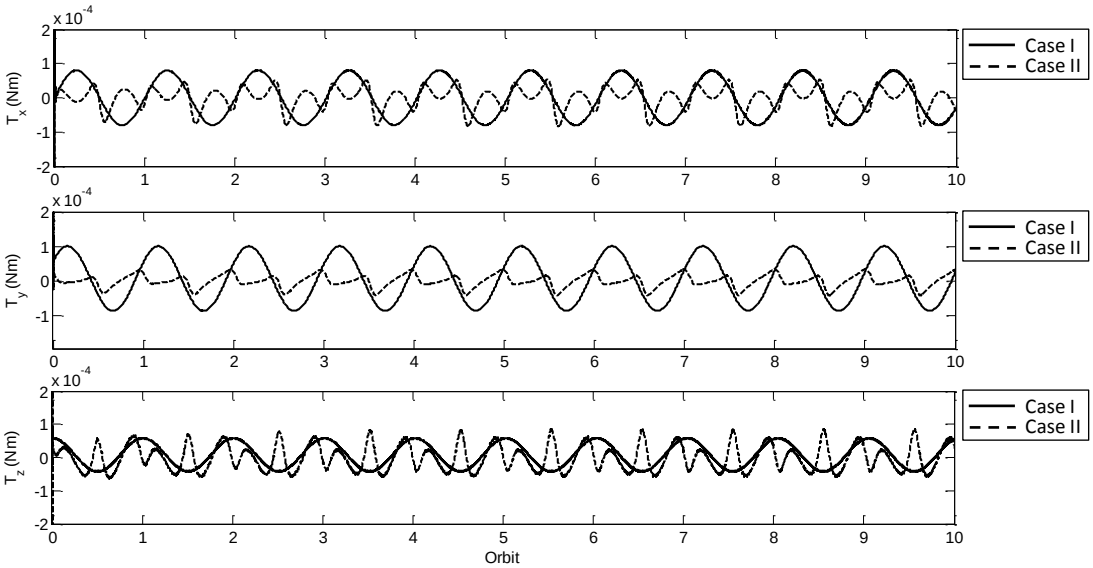

Figure 2. CMG torque during attitude pointing mode.

Figure 3 shows the magnetic control torques generated by the MTGAC system. The maximum magnetic torque along the x-axis is 1.0×10^{-4} Nm and -1.0×10^{-4} Nm in positive and negative direction, respectively. Along the y-axis, the maximum magnetic torque is 1.1×10^{-4} Nm in positive direction and -8.0×10^{-5} Nm in negative direction whereas along the z-axis the maximum magnetic torque is 1.1×10^{-4} Nm in positive direction and -1.3×10^{-4} Nm in negative direction. Summing the generated torques tor each cases, the total control torque for Case II is in fact larger than for the Case I. Total control torque for Case I is found to be 2.3×10^{-4} Nm and -2.2×10^{-4} Nm, in positive and negative direction, respectively whereas for Case II, the total control torque is 4.8×10^{-4} Nm in positive direction and -5.1×10^{-4} Nm in negative direction. Since the total generated control torque has direct influence to the amount of power consumption, the implementation of the MTGAC system to compensate gimbal angle offset leads to additional power requirement for the CMG-based controlled satellite. For small satellite platform where power is one of the main design constraints, this seems to be less favorable. However, the implementation of gimbal angle management system is crucial since the CMG system requires auxiliary control torque to compensate drift gimbals in which if not properly treated can lead to saturation singularity where sometime singularity avoidance law fails to avoid or escape.

The advantages of utilizing the MTGAC system are depicted in figure 4 and figure 5 respectively where a similar simulation is performed for 20 orbital cycles. Based on figure 4, the satellite fails to maintain at the desired attitude through the simulation time for Case I whereas the attitude of the satellite is successfully maintained about the desired attitude with certain accuracies for Case II. The loss in the attitude control of satellite for Case I is due to the gimbal angle offset where the gimbal for all SGCMGs gradually diverge from the preferred angle, as shown in figure 5. In fact, the #2 SGCMG

suddenly diverges towards unfavorable negative angle after 18th orbital cycle which causes the satellite to loss its attitude controllability. In contrast, for Case II the gimbals are successfully compensated about the preferred angle thus allowing the satellite to fulfil the attitude pointing mission.

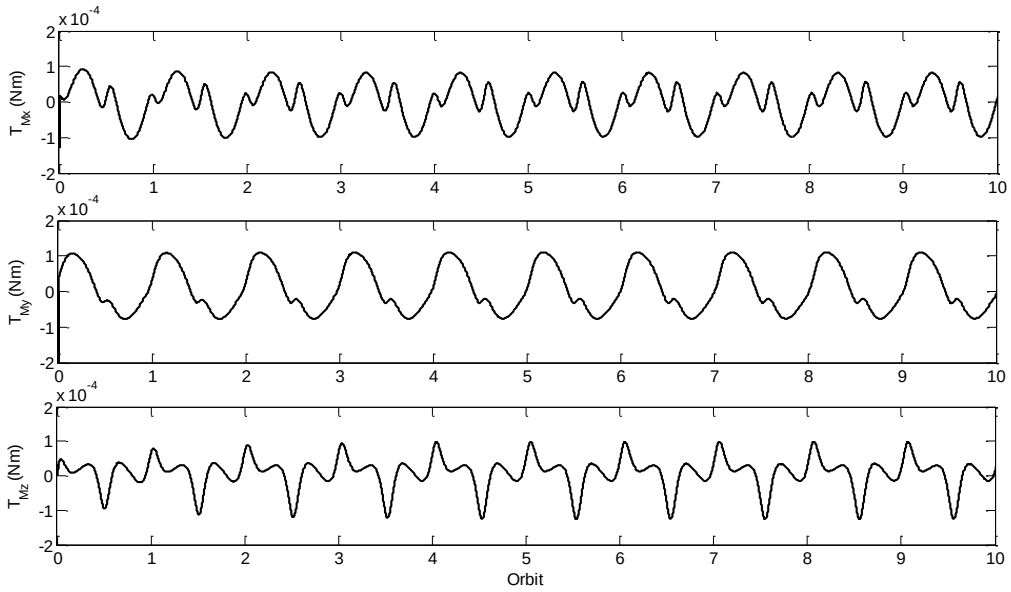

Figure 3. Magnetic torque generated by the MTGAC system during attitude pointing mode.

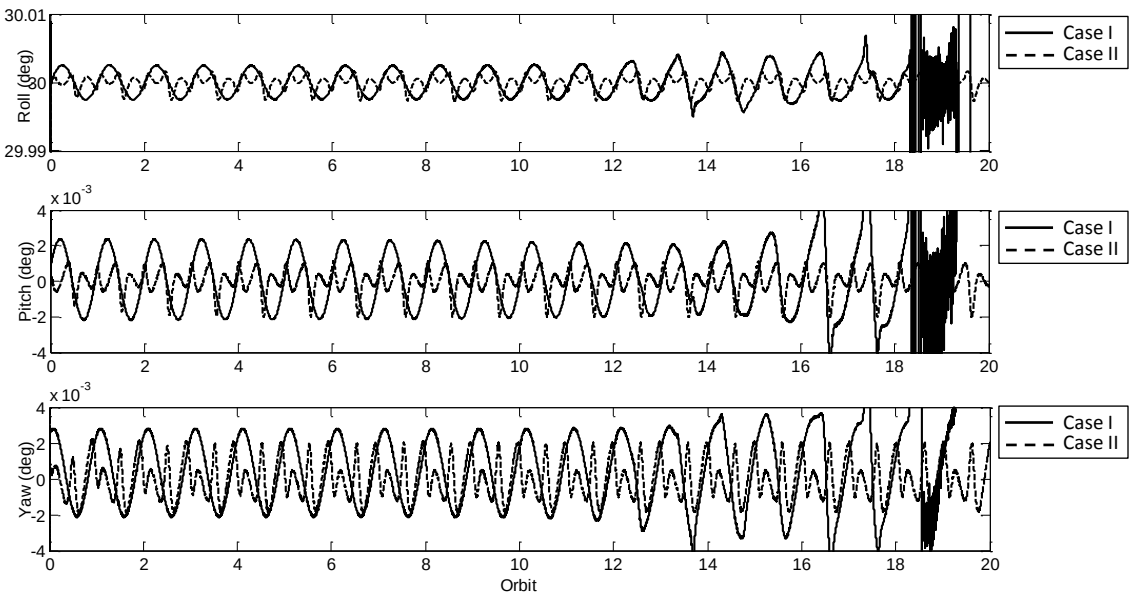

Figure 4. Satellite attitude during attitude pointing mode for 20 orbits.

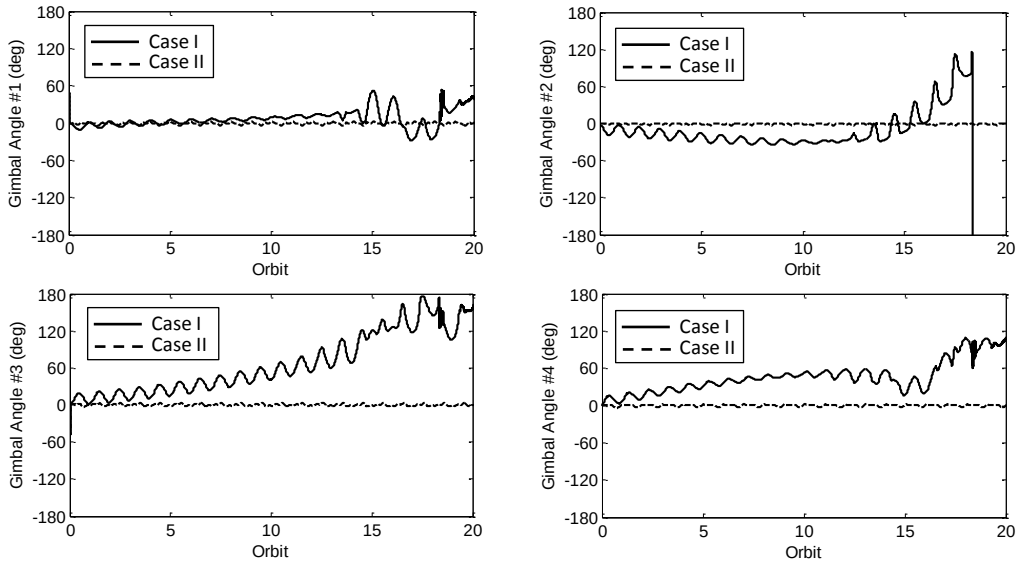

Figure 5. Gimbal angle of the CMG system during attitude pointing mode for 20 orbits.

5. Conclusion

In this paper, the control torques generated by CMG-based small satellite without and with the MTGAC system has been studied. The MTGAC system which is meant to compensate gimbal angle offset is cooperated with the PD-based attitude controller. All algorithms were implanted on MATLAB®-SIMULINK™ for simulation studies where the generated control torques are discussed as a trade-off between power consumption, attitude control performance and CMG dynamics. Results from the simulations show that the implementation of MTGAC system leads to additional power consumption due to addition of generated magnetic control torque. However, this addition leads to a better attitude control of the satellite as well as gimbal angle management of the CMG system which allows the satellite to fulfil its mission. The optimal power consumption of the satellite with the MTGAC system can be achieved if the software and hardware of system is carefully designed.

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