Control Moment Gyroscopes: a new opportunity in small satellites for enhancing satellite services, profitability and enabling new optical communication

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Abstract— **The growing market for small satellites requires agile, efficient, and compact attitude control systems (ACS) to improve mission performance, enable satellite quantum communications and data observation, and increase precision and agility in control. Reaction Wheels (RW), control moment gyroscopes (CMGs), and magnetorquers are used for satellite attitude correction. Variable Speed CMG (VSCMG) devices can combine the advantages of both RWs and CMGs. A novel VSCMG linear array is proposed. Comparison results between diverse CMG configurations are provided to show the future capabilities of this linear VSCMG array for applications in small satellites.**

Keywords—ADCS, CMG, RW, VSCMG, satellite, optical quantum communications, earth observation

I. Introduction

RWs are the most used momentum exchange devices for satellite ACS due to their advantages of high angular momentum and reduced footprint despite their low maximum torque, which seriously limits satellite agility. CMGs generate torque by changing the direction of their angular momentum vector. CMGs are also far more power efficient; for a few hundred watts and about 100 kg of mass, large CMGs can generate thousands of Nm of torque. A reaction wheel of similar capability would require megawatts of power. [1]

However, due to size and weight constraints, other performance parameters, such as moment-to-weight ratio and moment-to-volume ratio, are required in microsatellites. Satellite operators and manufacturers must choose between performance and size. Another problem is the complexity of satellite control devices with many degrees of freedom. However, Onboard Computers (OBCs) are powerful enough to handle more complex control routines for complex ADCSs.

II. CMG Design varieties.

A. *Single gimbal CMGs*

When the CMG gimbal rotates, the change in the rotor's angular momentum´s direction generates torque that reacts onto the body to which the CMG is mounted; this type of CMG exchanges angular momentum in such a way it requires very little power, allowing them to apply very large torque with minimal electrical input.

B. *Dual gimbal CMGs*

This CMG has two gimbals on perpendicular axes each. This design can orient the rotor's angular momentum vector in any direction. However, the movement of one gimbal requires the second gimbal to counter-react the torque generated by the first gimbal, which can lead to a higher power requirement for a given torque than a single-gimbal CMG. If the objective is to efficiently store angular momentum, as seen in the case of the International Space Station, dual-gimbal CMGs are an excellent choice. On the other hand, if a spacecraft needs to generate significant output torque while minimising power consumption, single-gimbal CMGs are better suited.

C. *Variable Speed CMGs*

The primary practical benefit of VSCMGs, compared to conventional CMGs, is the additional degree of freedom by changing the CMG wheel´s angular momentum as RWs do. This can be harnessed for continuous CMG singularity avoidance and VSCMG cluster reorientation. Research has shown that the flywheel rotor torques required for these purposes are very small and within the capability of conventional CMG rotor motors [2]. Thus, the practical benefits of VSCMGs are readily available when using conventional CMGs, such as replacing their flywheel motors, along with modifications to CMG cluster steering and control laws for CMG rotor motors, demonstrating the adaptability of existing technology. The VSCMGs can also be used as a mechanical battery to store the electric energy of the flywheels as kinetic energy.

III. CMG Geometrical Configurations.

A. *Pyramidal configuration.*

For any CMG configuration, the actuator torque $T_{cmg} \in \mathbb{R}^3$ contribution is [3]:

$$T_{cmg} = \dot{h} + \omega \times h$$

The total angular momentum vector $h = \sum h_i$ of the CMG cluster equals the summation of individual N CMGs, usually four, angular momentum vectors, $h_i \in \mathrm{R}^3$, $i = 1, \ldots, N$.

The angular momentum of the CMG cluster, with the assumption that each CMG generates a unity magnitude of angular momentum in the case of the CMG pyramid configuration under consideration, may be computed in the spacecraft body frame as a matrix A that depends on δ_i which is the i-th gimbal angle, β is the skew angle (inclination of the pyramid faces within the horizontal plane), c_β is $\cos(\beta)$, s_β is $\sin(\beta)$, c_i is $\cos(\delta_i)$ and s_i is $\sin(\delta_i)$. The angular momentum derivative $\dot{h}$ of the CMG cluster can, then, be determined as follows:

$$\dot{h} = A \begin{bmatrix} \dot{\delta}_1 \\ \dot{\delta}_2 \\ \dot{\delta}_3 \\ \dot{\delta}_4 \end{bmatrix} = T_{cmg} - \omega \times h$$

B. Linear configuration.

The desired CMG gimbal rates are computed by knowing the satellite attitude, satellite desired attitude and CMG gimbal angles. To calculate the different $\dot{\delta}_i$ values, the A matrix must be inverted by doing the $A^T * \left((A * A^T) + (\lambda * I^{3x3})\right)^{-1}$ pseudo-inverse, where λ is a constant factor.

Moreover, while a pyramidal array can deliver 3.2 times the angular momentum of one CMG on any axis igual to 53.13°), the linear array can deliver 4 times the angular momentum of one CMG on a single axis, while the other axes are limited to 2. However, the X-axis on most satellites is expected to get more angular momentum than the other axes.

Note that the pyramidal layout uses 2.14 times the volume of the proposed linear layout (when the beta is igual at 53.13° [4,5], and the length of each CMG is double its diameter).

Note that any CMG torque direction is perpendicular to both the gimbal direction and the angular momentum direction. So, by replacing the CMG flywheel motors with larger ones, each CMG can be converted to a VSCMG and generate more torque on the VSCMG angular momentum axis.

On a linear VSCMG, the total generated torque is:

$$T_{vscmg} = T_{cmg} + T_{rw}$$

$$T_{rw} = -B * \begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \\ \dot{h}_3 \\ \dot{h}_4 \end{bmatrix}$$

Where B is the VSCMG array angular momentum direction matrix, $\dot{h}_i$ which is the i -th flywheel angular momentum derivative, assuming every VSCMG on the array is identical. Note when the modulus of each row of the A matrix gets close to zero, the same row on the B matrix gets higher modulus. By comparing the modulus on each row, it is possible to decide whether to change the gimbal angle or the angular momentum from each wheel when a torque command is obtained. Note that this torque command is computed according to the desired satellite attitude compared to the actual satellite attitude.

IV. Simulation results

A series of ACS performance simulations are showing considering:

$$J_{sat} = diag([0.3083, 0.1233, 0.3083])\ [kg * m^2]$$
$$[\phi_0, \theta_0, \psi_0] = [60,30,0]\ [deg]$$
$$[\hat{\phi}, \hat{\theta}, \hat{\psi}] = [60,30,0]\ [deg]$$
$$h_{min} = 16.4\ [mNms]$$
$$h_{max} = 38.9\ [mNms]$$
$$\dot{h}_{max} = 16.3\ [mNm]$$
$$\dot{\delta}_{max} = 30 * \left(\frac{\pi}{30}\right)\ [rad * s^{-1}]$$
$$\lambda = 10^{-5}$$

Where J_{sat} is the satellite inertia tensor, $[\phi_0, \theta_0, \psi_0]$ and $[\hat{\phi}, \hat{\theta}, \hat{\psi}]$ are the satellite initial and desired attitude respectively, h_{min} and h_{max} is the minimal and maximum angular momentum being stored on each VSCMG respectively, $\dot{h}_{max}$ is the maximum torque each VSCMG can deliver and $\dot{\delta}_{max}$ is the maximum gimbal rate each VSCMG can achieve. For CMG simulation results, it is considered each one is storing an amount of angular momentum equal to h_{max}.

TABLE I. ACS control on X axis simulation results with standard deviation in parenthesis

ACS type \ Performance parameter	Rise time [s]	Overshoot [%]	Root-mean-square error [deg]
Linear CMG	12,77 (0,00001)	0,00780 (0,00550)	0,00330 (0,00280)
Linear VSCMG	11,81 (0,00004)	0,00071 (0,00022)	0,00021 (0,00004)
Pyramidal CMG	10,72 (0,00001)	0,00083 (0,00018)	0,00018 (0,00003)

TABLE II. ACS control on Y axis simulation results with standard deviation in parenthesis

ACS type \ Performance parameter	Rise time [s]	Overshoot [%]	Root-mean-square error [deg]
Linear CMG	12,90 (0.00001)	0,05530 (0,03120)	0,00880 (0,00580)
Linear VSCMG	11,21 (0,00001)	0,00053 (0,00014)	0,00008 (0,00001)
Pyramidal CMG	10,78 (0.00001)	0,00110 (0,00032)	0,00016 (0,00003)

TABLE III. ACS control on Z axis simulation results with standard deviation in parenthesis

ACS type \ Performance parameter	Root-mean-square error [deg]
Linear CMG	0,00610 (0,00570)
Linear VSCMG	0,00011 (0,00002)
Pyramidal CMG	0,00017 (0,00005)

In conclusion, the behavior of a linear VSCMG array on the satellite X axis can achieve very good performance results when compared to pyramidal CMGs by considering both devices generating the same angular momentum and having the same gimbal rate and by having a much lower footprint. Despite the lower available angular momentum to the other satellite axes, these axes do not require as much angular momentum as the required to the satellite X axis.

References

[1] R Votel, D Sinclair. "Comparison of control moment gyros and reaction wheels for small Earth-observing satellites." 26th Annual AIAA/USU Conference on Small Satellites. August 2012

[2] H. Schaub, J Junkins. "Singularity Avoidance Using Null Motion and Variable-Speed Control Moment Gyros". Journal of Guidance, Control, and Dynamics. 23 (1): 11–16. January 2000.

[3] B. Wie, Space vehicle dynamics and control (American Institute of Aeronautics and Astronautics. 2008

[4] L. Haoxiang, et al., ¨Selecting Initial Gimbal Angles of Roof-type CMG System for Avoiding Singularities in Spacecraft Attitude Maneuver¨ Trans. Japan Soc. Aero. Space Sci. Vol. 65, No. 3, pp. 123–133, 2022

[5] H. Kurokawa, ¨Theory and Steering Laws of Single-Gimbal Control Moment Gyros, J. Guid. Control Dynam., 30 , pp.1331–1340, 2007.