Experimental Testing of a CMG Cluster for Agile Microsatellites

V.J. Lappas, WH Steyn, C.I. Underwood

***Abstract*— This paper presents experimental results on the performance of a Control Moment Gyroscope (CMG) cluster. The goal is to design a CMG cluster for 3-axis control for agile microsatellites. The experimental data are compared with simulation (theoretical) results and both are used to verify the principles, benefits and performance specifications of the CMG cluster. The main aims are:**

1. To practically confirm the theoretical work (simulations) performed in previous CMG studies

2. To validate the viability of using CMG's as actuators on a microsatellite in a practical way

3. To confirm the agility and power efficiency that CMGs can potentially provide to microsatellites

CMG systems are considered to be in the literature more efficient devices from an electrical power point of view, than current actuators such as reaction/momentum wheels (RW/MW). Thus it becomes important to measure the electrical power consumption of a CMG system. These measurements are presented in this paper and then compared to two of SSTL's RWs. These RWs are currently operational and in orbit: SSTL's minisatellite UoSAT-12 RW and Tsinghua University's Tsinghua-1 microsatellite RW. CMGs are shown to have a potential performance advantage over RW/MW, for spacecraft with agile requirements.

***Index Terms*—Attitude Control, Control Moment Gyros, Microsatellites, Reaction Wheels**

I. Introduction

A Single Gimbal CMG (SGCMG) is a CMG with a constant speed momentum wheel, gimbaled in one axis only. For full three-axis control of a spacecraft, a cluster of four CMGs is normally used. CMGs, due to their inherit gyroscopic properties can potentially generate large torque and angular momentum outputs, in a more efficient way than current technologies such as reaction or momentum wheels. The type and number of CMGs that can be used in an ACS is a trade off between performance, cost, mechanical and algorithm complexity. SGCMGs and Variable Speed CMGs (VSCMG) are the most powerful (from the torque point of view) of all, but SGCMGs require a minimum of four units for full 3-axis control in order to avoid singularities. SGCMGs have been thoroughly studied in the past and have been baselined to be used in future space missions [1, 10, 11, 13]. CMGs can potentially change the way in which we will develop and operate the small satellites of the future. Agility besides increasing the operational envelope of the spacecraft, will also enable such spacecraft to collect more earth and space science data than before whilst using the same or even less resources. This in practice means a direct increase in the commercial and scientific value of these spacecraft. Small satellites are bound to face some challenging missions in the future that will require a high degree of agility (high slew rates). CMGs are ideal candidates for these missions and this paper investigates, in a practical way, the use of such sophisticated actuators for small satellites. The work following is structured as follows: First the CMGs are sized for a SSTL microsatellite platform, then the design of the CMGs is presented. Section IV details the CMG experiments and a discussion is followed on the results and on the sources of experimental error. Section V briefly describes a comparison of electrical power consumption between RWs and CMGs.

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II. CMG Sizing for Microsatellites

The 4-CMG cluster in pyramid configuration discussed throughout many CMG studies is used as the basis for an ACS system for a microsatellite [1,13]. From analyses conducted it was concluded that a torque of 52.25 mNm is required to perform a 30° maneuver in 10s [1]. This requirement is used to size a CMG for a microsatellite (Eq. 1):

$$\mathbf{N}_{\mathbf{CMG}} = \mathbf{h} \times \dot{\boldsymbol{\delta}} \tag{1}$$

Sizing the angular momentum of the CMG h and the maximum gimbal angles rate $\dot{\delta}_{\max}$ (same for all four CMGs) is a trade-off between performance (torque), size and singularity avoidance. One would want to keep the angular momentum as small as possible, since it depends on the inertia of the spinning wheel as well as the speed of rotation of the wheel. This implies that with a larger angular momentum, a larger DC motor will be required, with a heavier disc. On the other hand, the larger the gimbal rate, the larger the δ angle excursions, thus the greater the probability that the CMGs will enter into a singularity. Thus it becomes important to optimise h and $\dot{\delta}$ given the mechanical constraints of a practical system. The attitude control model designed in previous studies is used to perform and evaluate this trade and to select the optimum values to be used in a CMG system [1]. From simulations, it has been decided to use a $\dot{\delta}_{max}$ of 7.5°/s (or 0.13 rad/s). This value slightly exceeds the maximum slew rate needed in order to perform a 30° maneuver in 10s. This selection for $\dot{\delta}_{max}$ ensures that torque amplification is feasible throughout a commanded maneuver. Normally, one can calculate the angular momentum h, by using Equation 1 (and get h_0 of each CMG) but this will not enable us to properly size a CMG for a single axis maneuver. This can be explained by analysing the 4-CMG cluster trying to do a maneuver about its x-axis:

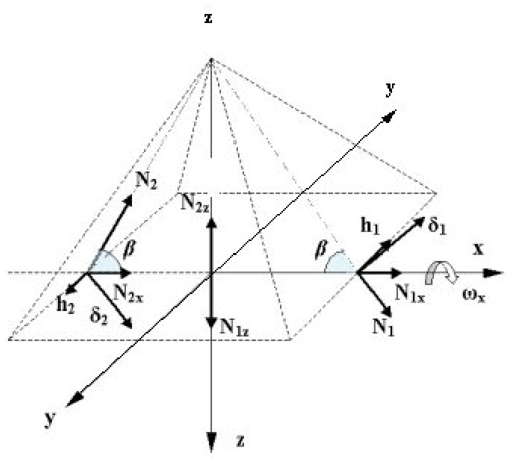

Figure 1: CMG Cluster for an x-axis Maneuvre

The torque generated will be:

$$\mathbf{h_1} = h_0 \begin{bmatrix} -sin\delta_1\, cos\beta \\ cos\delta_1 \\ sin\delta_1\, sin\beta \end{bmatrix} \text{ and } \dot{\boldsymbol{\delta}}_1 = \begin{bmatrix} \dot{\delta}_1 \sin\beta \\ 0 \\ \dot{\delta}_1 \cos\beta \end{bmatrix},$$

$$N_{1x} = h_0\, \dot{\delta}_1\, \cos\beta cos\delta_1$$

$$\mathbf{h_2} = h_0 \begin{bmatrix} sin\delta_2\, cos\beta \\ -\,cos\delta_2 \\ sin\delta_2\, sin\beta \end{bmatrix} \text{ and } \dot{\boldsymbol{\delta}}_2 = \begin{bmatrix} \dot{\delta}_2 \sin\beta \\ 0 \\ -\,\dot{\delta}_2 \cos\beta \end{bmatrix},$$

$$N_{2x} = h_0\, \dot{\delta}_2\, \cos\beta cos\delta_2$$

Due to symmetric rotation $\delta_1 = \delta_2$ and $\dot{\delta}_1 = \dot{\delta}_2 = \dot{\delta}$:

$$N_x = 2h_0\, \dot{\delta}\, \cos\beta cos\delta \qquad (2)$$

Thus, for N_z = 52.25 mNm, $\dot{\delta}_{max}$ = 0.13 rad/s and $\delta = 0^\circ$, h_0 = 0.347 Nms

A value of 0.35 Nms is used to size the disc of the spinning wheel:

$$h_0 = I_{CMG}\omega \qquad (3)$$

The DC motor chosen to be used to spin the disc has a maximum speed of rotation of 20,000 rpm. Thus, a disc with an inertia of 1.7 x 10^{-4} kg-m^2 is needed. A more detailed analysis on the CMG sizing and performance analysis can be found in References [1, 13]. The derived CMG parameters are listed in Table 1.

TABLE 1
CMG MK.II CHARACTERISTICS

Parameter	Value
DC motor mass [Faulhaber 1525E]	30 g
Momentum Wheel	150 g
Gimbal motor mass [P10]	9 g
Gimbal Motor Gear box [R10]	6 g
Potentiometer [Sector]	10 g
Couplers (2)	10 g
CMG cluster Power (Min.-Max.)	TBD
Voltage	5-12 V
CMG Mass	200 g
CMG Ang. Mom. h_0 (ω_w ~ 11,200 rpm)	0.23 Nms
CMG avionics	50 g
CMG Total Mass	~ 1170 g
CMG Output Torque	52.5 mNm

III. DESIGN OF A CLUSTER OF CMGS

The testing of a pre-prototype CMG (CMG Mk.I) lead to the design of another enhanced CMG as part of a 4-CMG cluster, the CMG Mk.II [1]. The CMG Mk.II utilizes:

- A different and more powerful BLDC motor with integrated electronics (Faulhaber 1525 BRE)
- A larger flywheel (angular momentum), properly sized to generate the required torque on the Mk.II CMG (I_{CMG} = 1.7 x 10^{-4} kg-m^2)
- The same stepper/gimbal motor (Escap P010/R10) as in the Mk.I
- New electronics based on a C515 Microcontroller

The Mk.II version focuses on resembling as much as possible a future CMG ACS system for a 50 kg SSTL microsatellite. In this context the CMG electronics are designed based on the architecture used on SSTL's small satellite designs. A C515 microcontroller is used to 'translate' via a Control Area Network CAN bus various telecommands, which enable the gimbal motors to operate. A PC is used to send telecommands and receive telemetry to the CMG cluster. Different gimbal rates can also be produced resulting to different gimbal angle excursions, thus different torque outputs. An improved and more robust mechanical design is also implemented in the CMG Mk.II design.

IV. CMG MK.II CLUSTER EXPERIMENTS AND RESULTS

A. Introduction to Air-Bearing and Experimental Hardware

Having designed the electronics to control the DC motor and stepper motors, the CMG is put on an air bearing table.

An air-bearing table provides the capability of rotation without significant friction.

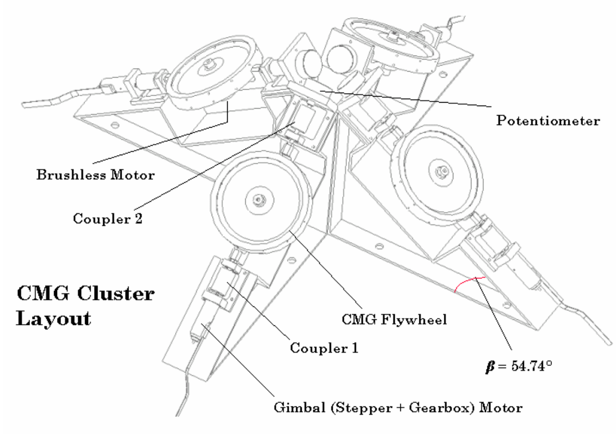

Figure 3: CMG MK.II Cluster Layout

It is frequently used to test the dynamic characteristics and performance of a model satellite control system during the pre-launch experimental testing campaign on the ground. It is suspended by air, which allows nearly frictionless rotation. The rotational freedom depends on the mechanical structure. The air bearing table used is a single degree of freedom air bearing mounted around a semi-sphere which provides air suspension via 6 holes placed 120° apart in two different levels, which propel air under pressure to slightly lift the rotating part of the table from the stationary part. The resulting lack of contact between the rotating and stationary part offers significant advantages such as:

- Low friction
- High degree accuracy of motion
- Zero wear

Balancing masses are used to properly balance the air-bearing platform. In order to test the CMG cluster, the air-bearing test facility is used again. An Inertial Measurement Unit (IMU), which comprises three gyroscopes, one per axis, is used to record angular rate measurements of the rotating platform. The experiments involves performing a single axis maneuver where two CMGs are used. An analysis of such a maneuvre was performed in Reference [2].

The experimental set-up of the CMG cluster is depicted in Figure 5.

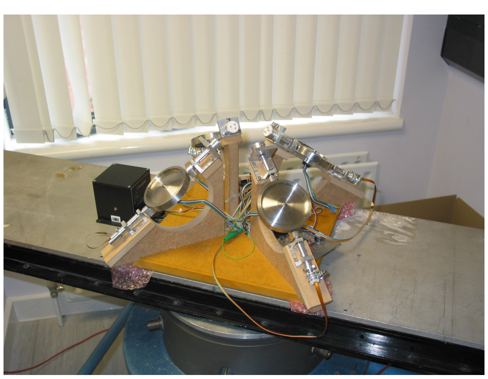

Figure 5: CMG Mk.II Cluster Experimental Set-Up

The experiments are conducted in the University of Surrey's AODCS Lab located in the lower level of the Surrey Space Centre. Although the environment is not ideal for experiments that require the absence of aerodynamic friction, it is better suited due to the medium grade environment (compared to normal laboratories) existent due to the propulsion requirements for which the laboratory was built for.

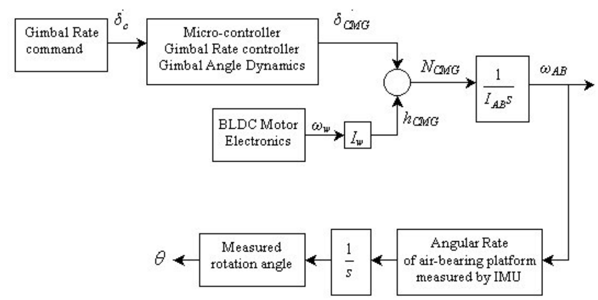

Figure 4: Block Diagram of the CMG Cluster Experiments on the Air-Bearing Platform

The CMGs used in the experiment are all identical, placed in the apyramid geometrical configuration with a skew angle of 54.7°. The CMG electronics are positioned together with the CMG hardware and the only wires attached are the CAN bus, IMU serial link and power cables. Figure 4 indicates a block diagram of the experiment performed.

B. *Single-Axis Maneuver with Two CMGs*

1) *Dynamics of Air-Bearing*

The theoretical values for CMG Torque are measured using Equation 2 in a CMG based attitude control model simulated in MATLAB©/SIMULINK© [1]. The experimental values are measured via the relationship derived from the dynamics of the rotation table:

$$N_{CMG} + N_d = -I_{AB}\,\dot{\omega}_{AB} \tag{3}$$

where,

ω_{AB} is the angular speed of the air-bearing rotating platform
ω_w is the angular speed of the CMG flywheel
N_d is the external disturbance torque

For $N_d = 0$ (due to the air-bearing table) and by knowing the moment of inertia of the air-bearing table I_{AB} (4.1 kg-m^2) the experimental measurements of the angular rate ω_z can be used to calculate the experimental torque of the CMG cluster as seen in the block diagram of Figure 4.

2) *Experimental Results and Discussion*

Due to the noise caused from the gyro measurements, the angular rate measurements need to be filtered in order to reduce the noise. In this case a Kalman Filter is used [9, 10]. Details on the mathematical description of the simple filter can be found in References [1, 13]. Figure 6a indicates the theoretical and experimental CMG torques. There are three profiles: The theoretical CMG torque is marked as a solid line, the raw measurement (or unfiltered) torque as a bar line and the filtered torque as a bar-dot line. The unfiltered torque clearly is very noisy, mainly due to the more pronounce effect of angular rate noise, especially after the differentiation of the angular rate which is needed to calculate the torque. The theoretical values are generated from CMG simulations modeled in MATLAB©/SIMULINK© which do not take under consideration the wheel and gimbal motor dynamics, or any other internal disturbances. Figure 6b presents more clearly the theoretical and the filtered experimental torques. It can be observed that the torque generated by the two CMGs reaches a maximum and minimum value of ± 36 mNm with maximum variations (error) of 0.008 mNm and this is mainly due to the disturbances that affect the CMG cluster on the air-bearing (air-bearing bias, friction) and also due to mechanical reasons (CMG stepper motor backlash, micro vibrations, wheel imbalances and small wheel speed variations). The most dominating sources of error are those caused by aerodynamic friction and due to air-bearing biases. For the mechanical errors, although they are high bandwidth disturbances they can potentially cause small errors in measurement. The IMU sampling is of the order of 0.1 s. Figure 6c illustrates the torque noise (caused by the gyro noise differentiated).

Figure 6d presents the angular rates (raw measured, filtered and simulation values) with a maximum angular rate of 3.27º/s (experimental) and a maximum theoretical value of 3.4º/s. Multiple measurements were made and the average set was used. The measurements were taken using small sampling rates due to the high angular rates of the rotating platform. The small errors between theoretical and experimental values can be explained from the disturbances mentioned. These errors are within a band of ±0.27 º/s. Figure 6e illustrates the values for the angle θ, the rotation angle of the rotating air-bearing platform caused by the CMG gimbaling. The CMGs rotate the air-bearing platform to an angle of approximately 37.89°. This, compared to the theoretical simulations indicated an error in attitude (yaw) of 2.11° or 5.275 %. Considering that the maneuver performed is an open-loop maneuver and coupling the disturbance effects of the air-bearing this result is within an acceptable error band of 2.11º. This error in angle θ is expected to significantly decrease if the experiments where to be performed in a more ideal environment (clean room or in vacuum). However, even with the mentioned disturbances and expected small error in the rotation angle θ, the experiments demonstrate the CMG performance for a 4.1 kg-m^2 platform along with the significant torque capability of the CMGs. Figure 6f presents the gimbal rate of ±7.75º/s used as well as the maximum gimbal angle excursions of ±77.5.

C. *Sources of Experimental Errors*

The above experiments have indicated that there are three main sources of error causing variations between the theoretical and experimental results. These are:

- Aerodynamics friction
- Air-bearing biases
- High frequency disturbances caused due to mechanical reasons

Another important source of error is the noise that exists from the gyro measurements made using the IMU.

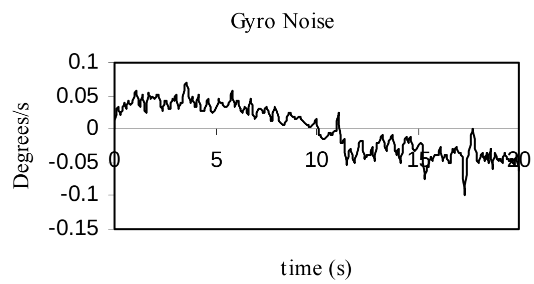

Figure 5: Angular Rate ω_z Gyro Noise

Figure 5 indicates the gyro noise produced by the IMU during the 40º maneuvre with the 2 CMGs.

V. CMG Electrical Power Consumption

Electrical power is an issue critical in small satellite development and operations. Although some sources in the literature such as [1, 2, 9-11, 13], mention that CMGs require less electrical power than other actuators such as reaction/momentum wheels, there is no theoretical or practical support to this claim. The development of the CMGs in this thesis as well as the information available on the reaction wheels developed at the Surrey Space Centre can provide though an indicative means of comparing the two different actuators. The CMG Mk.II was designed to be capable of producing a torque of 52.25 mNm, which is sufficient to generate an average slew rate of 3º/s for the microsatellite platform analysed in this paper. Due to the restricted space available, a brief overview on the comparison of RW and CMG electrical power consumption is provided. For more detailed consideration the reader is directed to References [1,13]

A. *CMG Electrical Power Consumption*

In this Section a comparison is made based on using the CMG cluster conducting a single-axis yaw maneuver on the air-bearing table where 2 CMGs are operated. This CMG operation is then compared to two single RW in-orbit performances, one using the minisatellite UoSAT-12 RW and another microsatellite RW from the Tsinghua-1 microsatellite. The basis of the electrical power comparison of the actuators (CMG vs. RW) is completing the same single-axis maneuvre of 40º, with one RW per case (minisatellite and microsatellite RWs) and two CMGs (as in Section IV). The electrical power is measured by measuring the current used by the stepper motors and BDC motors, in vacuum. A vacuum jar is used to simulate the space environment as close as possible, by using a pump to generate a pressure of 20 mBar (0.0194 atm) [13].

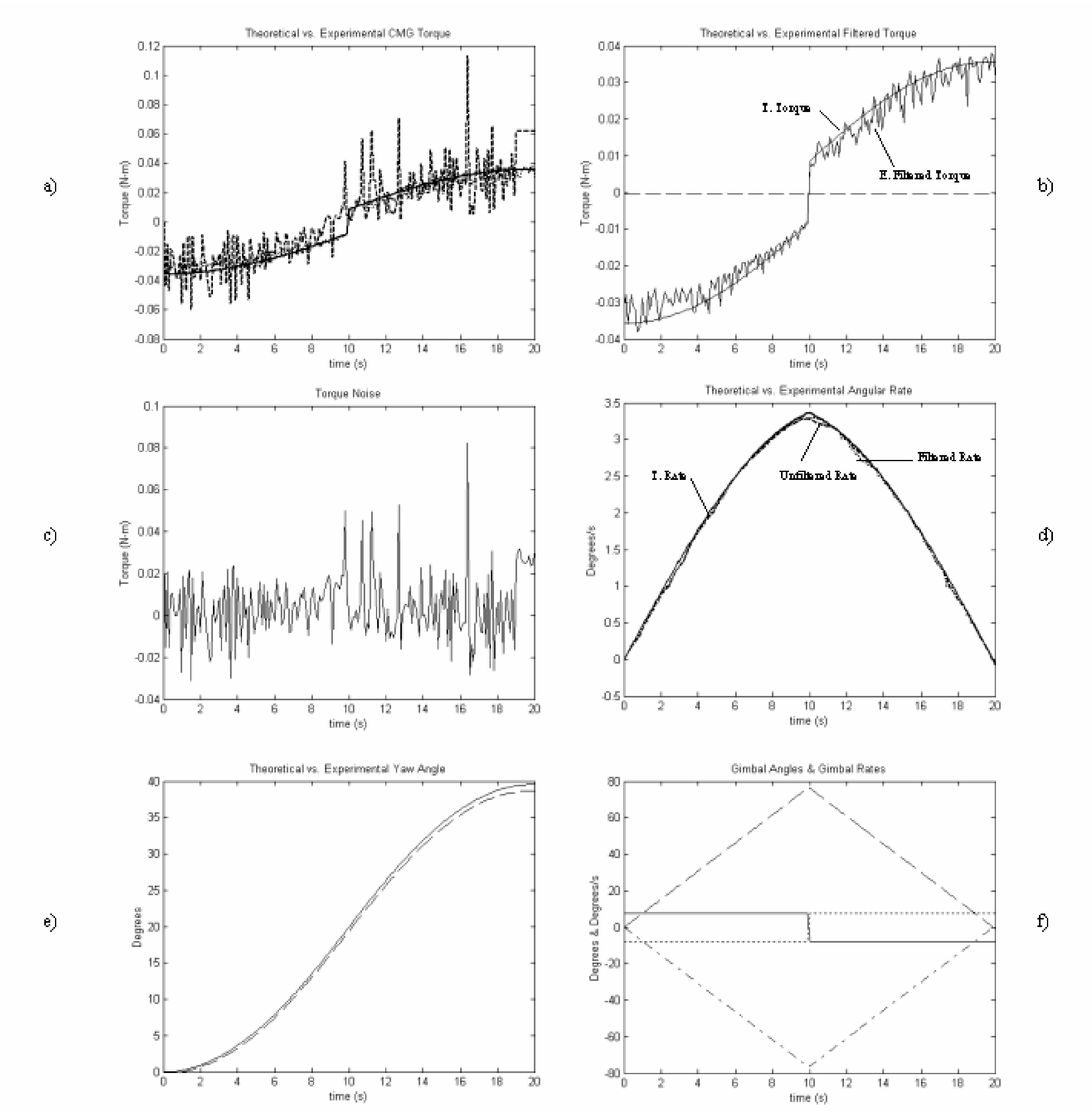

Figure 6: a) Theoretical vs. Experimental CMG Torque b) Theoretical vs. Filtered Experimental CMG Torque c) CMG Torque Noise d) Theoretical vs. Experimental Angular Rate ω_z (Yaw) e) Theoretical vs. Experimental Angle (Yaw) f) Gimbal Angles and Gimbal rates (Theoretical)

Space is considered to have a pressure of approximately 10^{-7} Torr, which is 1.35 x 10^{-4} Bar (1.31 x 10^{-4} atm) [12]. Figure 7 presents the total CMG electrical power for the 2 CMGs used to perform a single-axis 40º maneuvre. The maximum power required is 1.617 W with an average power of 1.6145 W.

B. *RW Electrical Power Consumption*

Next, two cases of RW based manoeuvres of different size (microsatellite and minisatellite) are presented. Experiments were made to measure the electrical power consumption of the Tsinghua-1 and UoSAT-12 RWs. A 40° pitch maneuvers are commanded to be completed, as with the case of the CMG in the previous Section. Results of the experiments including the times to complete the commanded maneuvers, avaerage electrical power values and torques are listed in Table 2. Although this comparison is not exact due to the unavailability of a RW that can produce a 52.25 mNm torque as the CMGs can produce, the results attained from the experiments provide useful information towards proving that

CMGs are more efficient from an electrical power consumption point of view than RW systems.

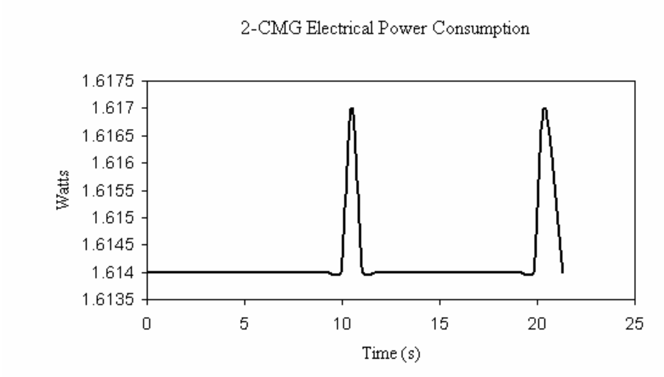

Figure 7: CMG Cluster Electrical Power Consumption

TABLE 2
ELECTRICAL POWER CONSUMPTION EXPERIMENTAL DATA

Parameter	UoSAT-12	Tsinghua-1	CMG
MOI (kg-m^2)	40	2.5	4.1
Time (s)	200	150	20
Torque (mN-m)	20	10	52.25
Mass (kg)	3.2	1	0.585[1]
Avg. Power (W)	2	0.45	1.61
Scaled Power (W-kg-m^2)	0.05	0.16	0.39
Scaled Energy (J/kg-m^2)	10	27	7.85

Form Table 2, it can be observed that clearly the CMGs rotate the air-bearing platform (4.1 kg-m^2) rapidly, in 20s. In order to compare the actuators in an equal way, an energy index is introduced. The index reflects the energy accumulated during a maneuvre on a normalized 1 kg-m^2 MOI platform. This index takes into account the slew rate (thus torque) capability of the actuators, the power required to perform the same single axis 40° maneuvre for all actuators 'using' the same platform (normalised 1 kg-m^2). From Table 2 the CMGs prove to be the least power consuming actuator with an energy index of 7.85. This is 21.5 % more efficient than the UoSAT-12 RW power consumption and 70.9 % more efficient than the Tsinghua-1 RW.

VI. CONCLUSION

Practical work confirms the theoretical findings on the advantageous use and performance of CMGs for agile small satellites. A cluster of 4-CMGs in pyramid arrangement is used to demonstrate full 3-axis control. Using an air-bearing platform ground experiments were performed in order to evaluate the performance of the designed CMGs as well as to practically confirm the theoretical findings of previous CMG work. A pre-prototype of a CMG, CMG Mk.I, was used as a precursor towards developing a more powerful CMG, the CMG Mk.II, which would be able to generate the required torque of 52.25 mNm in order to provide an average slew rate of 3º/s for the microsatellite platform analysed in this thesis. The CMG Mk.II was tested , in a cluster form with a pyramid configuration, using the same method as with CMG Mk.I. A single axis maneuver was reproduced on ground experiments, in order to replicate a *x*-axis maneuver using two CMGs for a spacecraft equipped with CMGs. Due to disturbances such as aerodynamic friction it was expected that the CMGs would not be able to achieve their full torque capability on ground tests in a room environment. However the experiments indicated their large torque capability of approximately 36 mNm for the two CMG maneuver. Furthermore experiments indicate the superior electrical power efficiency when utilizing a CMG cluster when compared to a RW system. Specifically the CMG Mk.II maximum and average powers were found to be 1.614 W and 1.617 W respectively. Specifically the CMGs are shown to be more power efficient by at least 21.5 % from reaction wheels, with a mass saving of 41.5 % to the smallest (Tsinghua-1) RW.

Having a total mass of about 1.17 kg (including all electronics), CMGs were shown in a practical way to potentially be an efficient and highly capable means of controlling agile microsatellites.

[1] Mass for two CMGs, unpackaged

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