CONTROL MOMENT GYRO CMG 15-45 S :
A compact CMG product for agile satellites in the one ton class

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Abstract

This paper describes the small Control Momentum Gyro developed by Astrium and Teldix for small agile satellites. This product is based on a small wheel developed by Teldix to deliver 15 Nms in a minimal volume and to sustain a very high output torque over more than one million of manoeuvres. Thanks to a very high amplification ratio, the CMG 15-45 S delivers up to 45 Nm and can be used to set a satellite of one ton at 3 degrees per second in less than 2 seconds.

The CMG 15-45 S is based on an innovative architecture, patented by EADS Astrium, which minimises the mechanism size and mass and simplifies its mechanical interfaces. This small equipment fits easily in a small satellite of one ton or below. The reduction of the mechanism size improves also its pointing performances and minimises its disturbances. The performances of the CMG 15-45 S have been tested in an AOCS closed loop to verify that they are compatible with an earth observation mission working at sub-metric resolution.

1. A small CMG delivering a very high output torque

The demand for agile satellites has increased considerably over the last few years, be it for commercial or military applications, Earth observation, astronomy, optical instruments or radar payloads. Earth observation at high resolution calls in particular for high line-of-sight mobility to compensate for the reduction in ground swath. Agile scenarios in Earth observation include multi-strip mosaics or dense successions of images, with combined roll (across-track coverage), pitch (along-track motion) and yaw (image strips orientation) manoeuvres.

When it comes to providing a high output torque (above a few tenths of Nm typically) at reasonable cost (mass and power consumption), reaction wheels are no match for small Control Moment Gyroscopes (CMGs). CMGs rely on gyroscopic effects to produce very important output torques by rotating the spin axis of a momentum wheel. If $\dot{\sigma}$ denotes the gimbal rate and h the wheel momentum, the output torque is $T = h \times \dot{\sigma}$. The CMG 15-45 S presented in this paper offers an outstanding amplification ratio: it delivers up to 45 Nm with a wheel of 15 Nms only.

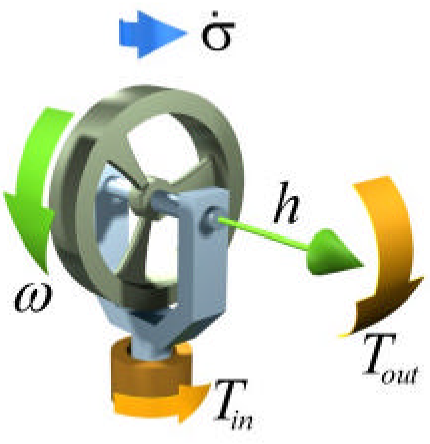

Figure 1: A CMG generates a high gyroscopic torque by rotating the spin axis of a momentum wheel.

2. Minimising the wheel size

Minimising the momentum demand for a given class of satellite is a key issue in the product optimisation, since a low momentum decreases the mechanism size and complexity and improves its performances.

The reason why CMGs are usually oversized with respect to the strict agility demand lies in the way they used to be controlled. Unlike standard 3-axis attitude control with three reaction wheels, the management of a cluster of CMGs needs some amount of pre-processing before issuing commands to the actuators. The aim is to find a suitable set of gimbal rates that produce the proper output torque. Depending on the combination of gimbal angles σ, the system may become singular and no solution is found that satisfies the torque demand. The standard solution to eliminate singularities is to oversize the momentums by a factor 3. If the wheel momentum is three times higher than the nominal requirement, the system can indeed operate inside a small region of the momentum envelope where no singular states are encountered.

Recent developments in guidance algorithms now mean that the full capacity of the CMG cluster can be exploited, minimizing the momentum demand for each CMG. With four CMGs of only 15 Nms, it is now possible to set a satellite in the one ton class at more than three degrees per second in less than two seconds. Such a small momentum offers many advantages through snowball effects:

- The size, mass and power consumption of the wheel is minimised: it minimises the size, mass and power consumption of the gimbal mechanism;
- The balancing of the wheel is more precise and the microdynamics disturbances are therefore minimised;
- The low mass supported by the gimbal mechanism minimises the preload and the friction in the bearings and the pointing performances are improved;
- The gyroscopic torque to be delivered by the gimbal mechanism to control the orientation of the wheel momentum during the satellite rotation is minimised. The motor capacity is minimised, its power consumption is reduced and its pointing performances are improved;
- The gyroscopic amplification of the gimbal mechanism pointing errors is minimised since it its proportional to the wheel size;
- Proven technologies can finally be used and no new components have to be developed and qualified.

3. A compact architecture with simple interfaces

The architecture of the CMG 15-45 S has been conceived around four key requirements: minimal volume (< 35 x 27 cm), minimal mass (< 16 kg), high stiffness (> 120 Hz) and simple interfaces to integrate easily into small satellites.

The wheel is the key element of the mechanism architecture since the sphere occupied by the wheel when it rotates around the gimbal axis determines largely the overall volume. We have optimized an existing small wheel to provide a maximum momentum in a minimal volume and to withstand a very high output torque. The gimbal is designed to stay within the diameter of the sphere defined by the wheel rotation to minimize the overall height.

Figure 2: CMG 15-45 S Architecture (patented)

Additional care was also given to interface simplicity for easy integration in the host satellite. All the gimbal assembly is located under the wheel, whereas in many classical designs, the gimbal components are distributed on both sides (e.g. motor on one side of the wheel and sensors on the other side). The CMG can therefore be mounted on a single base plate with a minimal footprint (20 cm) and no additional hardware is required to install the equipment. Three standard connectors for signals & power are implemented on the same side around the base plate for easy access during integration.

4. A product based on proven technologies

The CMG has been designed in the view of series productions: the wheel is based on Teldix core technologies and the gimbal mechanism uses standard components from European manufacturers qualified by CNES and ESA.

A particular aspect of the CMG application is that the mechanism must withstand a very high number of dynamic cycles under a high output torque. A satellite manoeuvre is made of two displacements at CMG level, the first displacement being used to accelerate the satellite and the second one for deceleration. Theoretical computation show that the non-failure lifetime (L_{nf}) exceeds two millions of displacements with an average torque of around 20 Nm, with comfortable margins on the wheel (> 100 %) and even greater margins on the gimbal mechanism

Figure 3: CMG momentum wheel under lifetime tests at Teldix

To consolidate this theoretical analysis, Teldix has performed a lifetime test campaign on a telecom wheel. Figure 3 illustrates the test bench where the wheel is installed on a rotating table simulating the gimbal mechanism. The test has been interrupted after 2.4 millions of displacements (i.e. 1.2 millions of manoeuvres at satellite level) with no evolution of the wheel behaviour, no performance losses on either the wheel friction or its static and dynamic unbalances.

A life test has also been performed on the slip ring used to transfer the wheel signal through the gimbal mechanism. The test has been performed in an ultra vacuum chamber at CNES. The cycles were representative of CMG applications with an inversion of the rotation at each displacement and a random distribution of amplitudes. The test has been interrupted after 5millions of displacements (i.e. 2.5 millions of manoeuvres at satellite level) without any evolution in the friction performances and electrical behaviour. The friction remains very low, below the specified ± 13 mNm at End Of Life.

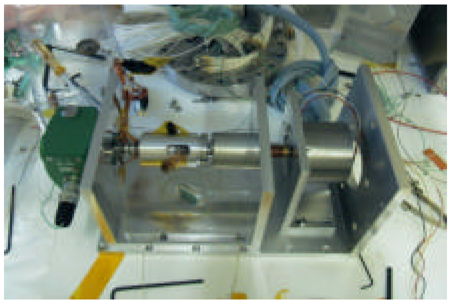

Figure 4: CMG Slip ring under lifetime tests at CNES

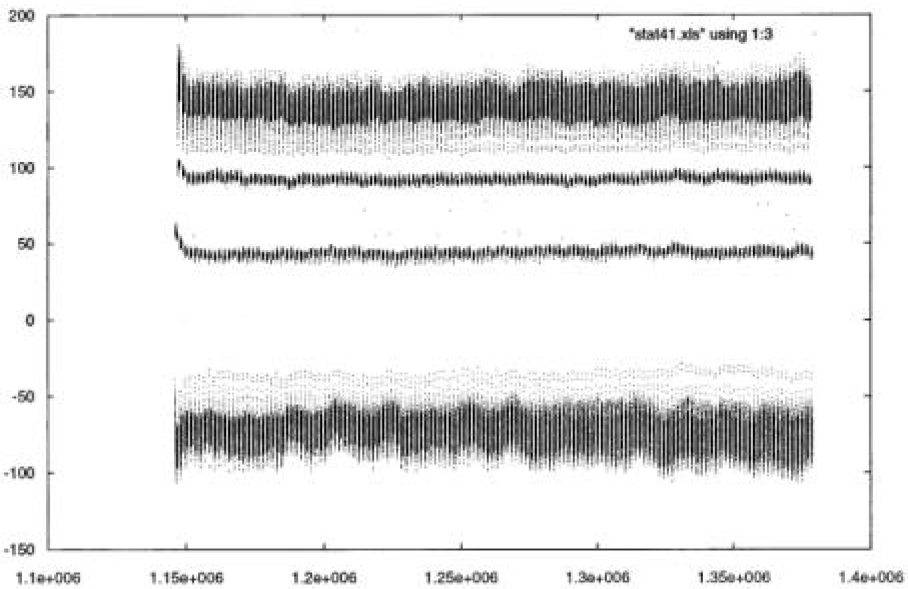

Figure 5: Slip ring friction torque over lifetime
Scale: X in millions of displacements; Y in gcm (1 gcm = 0.1 mNm) with a zero offset

5. A high performance actuator validated in AOCS closed loop

We have developed an Elegant Breadboard of the CMG to validate its main performances and consolidate its design.

CMG Elegant Breadboard

The test bench controlling the CMG in closed-loop is illustrated on figure 6. The functional software is prototyped on a real time test bench driving the CMG and measuring its delivered torque.

Performances have been validated on realistic manoeuvres extracted from a scenario of an earth observation mission. Figure 7 illustrates one of the tested profiles, where the manoeuvre lasts 10 seconds and the imaging sequence lasts 10 seconds. It can be seen that the satellite maximum rate is reached in 2 seconds and that the braking phase lasts 2 seconds.

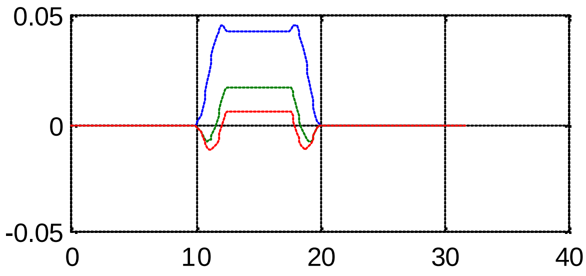

Figure 7: Typical satellite manoeuvre (rate in rad/sec versus time in seconds).

Several satellite manoeuvres have been tested in open loop to validate that the pointing error at equipment level never exceeds 10 mrad (0.57 deg) during manoeuvre phases and always stays below 2 mrad (0.12 degrees) in fine pointing phases. This very good accuracy in controlling the momentum orientation translates into an outstanding stability of the satellite attitude (a few micro-radians per seconds).

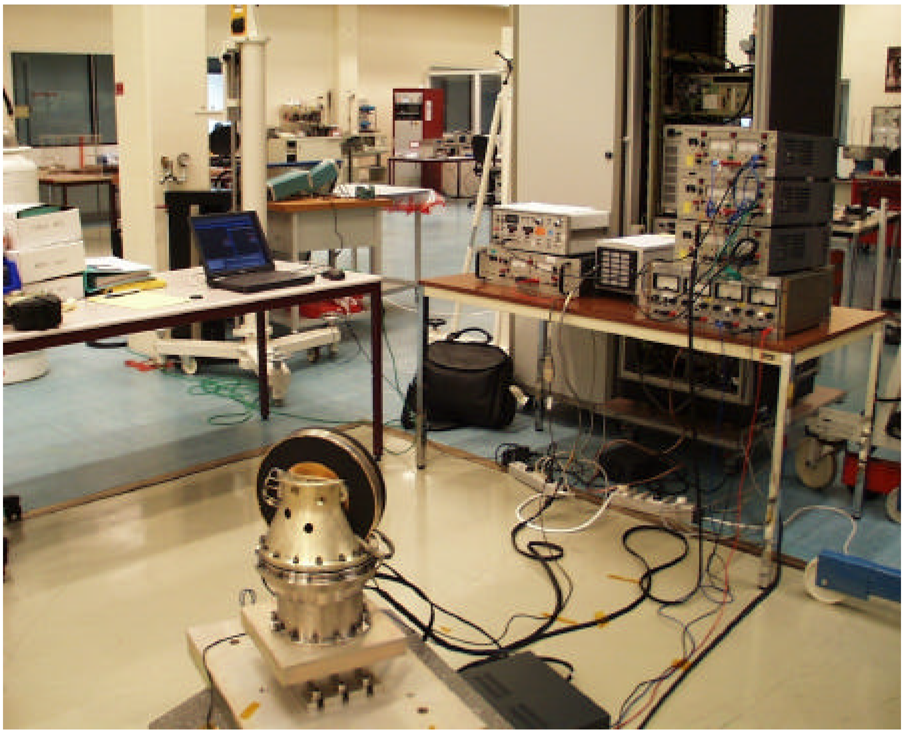

Figure 6: AOCS closed-loop test bench with the CMG in the loop

Figure 8 illustrates a typical test result, where the CMG pointing accuracy remains below 0.5 mrad (0.03 deg) during the imaging phase (starting at 22 seconds). Figure 9 illustrates the induced impact on the satellite pointing stability: the satellite rate error remains below 1.3 µrad/s during the imaging phase. The residual oscillations (known as hunting cycles) are due to the dry friction in the gimbal mechanism (bearings and slip ring). We have limited their impact to a negligible contribution at AOCS level thanks to an optimisation of the gimbal bearing design (where the frictions are lower than 50 mNm) associated to a high bandwidth controller (10 Hz) running at high frequency (2 kHz) in the CMG electronics and fed by a high resolution optical encoder (22 bits).

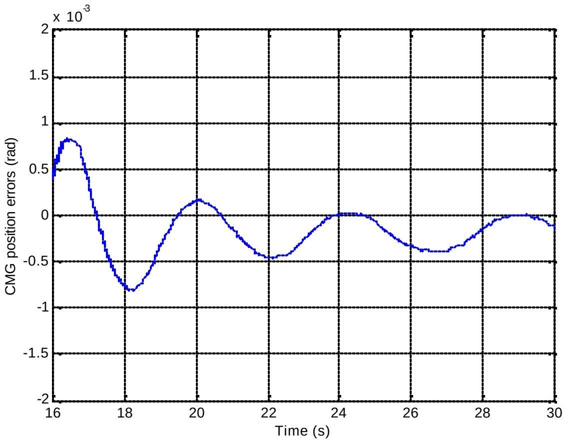

Figure 8: CMG pointing performance on a typical satellite manoeuvre.

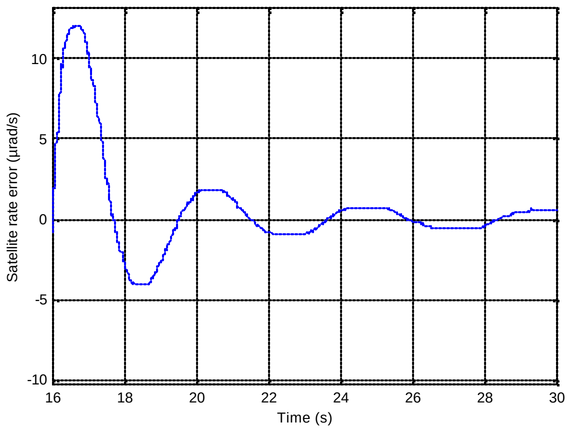

Figure 9: Illustration of the satellite rate errors induced by the CMG pointing error

6. Conclusion

We have designed a small CMG for series productions using only well proven technologies in the view of a production in small-series. The wheel is based on Teldix core technologies and the gimbal mechanism uses standard components from European manufacturers qualified by CNES and ESA.

The components are assembled in an optimized architecture that minimizes the volume and the mass. The CMG can be mounted on a single base plate with a minimal footprint and no additional hardware is required to install the equipment. The CMG 15-45 S integrates easily into small satellites of one ton or even less. This compact architecture, patented by Astrium, has also been retained for our mini and medium CMGs.

We have developed and tested an Elegant Breadboard to validate not only the CMG design but also the system performances. Engineering and Qualification Models are now under development for ESA and CNES.

7. Acknowledgements

The authors would like to acknowledge CNES and ESA for their joined supports on the development of the first European CMG.

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