DEVELOPMENT OF A CONTROL MOMENT GYROSCOPE FOR SMALL SATELLITES

Alexander Mayer (1), Lisa Hafemeister (1), Roy Bretfeld (1), Dr.-Ing. Christian Raschke (1),
Heiko Jahn (1), Dr.-Ing. Sebastian Scheiding (1)

(1) Astro- und Feinwerktechnik Adlershof GmbH, Albert- Einstein-Straße 12, 12489 Berlin,
Germany, info@astrofein.com

ABSTRACT

Nowadays, primarily conventional reaction wheels are used to control the attitude of spacecrafts. Nevertheless, some missions require the attitude control to be much more agile. Due to their functional principle Control Moment Gyroscope (CMG) based control systems provide a much higher agility and are thus getting more and more important.

Astro- und Feinwerktechnik Adlershof GmbH (Astrofein) is currently developing a CMG for Small Satellites supported by ESA GSTP-6. To make CMGs available for smaller satellites, a trade-off between volume and mass as well as power consumption and performance had to be made. The current design ensures a high target performance of 8Nms/14Nm with a dedicated mass of 8kg and a maximum power consumption of about 40W. An Engineering Qualification Model (EQM) was built and is currently undergoing an environmental test campaign, that includes different tests such as the Thermal-Vacuum and Micro Vibration test. The specification and the current status of the CMG as well as an insight on the test results with regards to the performance of the CMG within the environmental tests will be given in this paper.

1 DEVELOPMENT APPROACH

The project was based on a breadboard design that was developed to familiarize with the special setup of the Control Moment Gyroscope (CMG). Aim of the current activity was to develop the CMG to a higher maturity of Technology Readiness Level 5 (TRL5). Throughout the course of the project, the mechanics, as well as the electronics, and the software were reworked and adapted, resulting in building a full-scale Engineering Qualification Model (EQM). The EQM was then used to demonstrate its representative functions in an environmental test campaign.

The project subdivides into four phases. During the first phase requirements were consolidated and the breadboard design was reworked and adapted, which was followed by the Preliminary Design Review (PDR). Prior to the Critical Design Review, the mechanical and electrical parts were developed. The software was adapted to this new hardware as well. After the design passed the critical review, the parts were manufactured, assembled, and integrated. Furthermore, test specifications were created. Once the CMG EQM Manufacturing, Assembly, Integration (MAI) was finished, a Test Readiness Review (TRR) was held, confirming the readiness of the hardware for the environmental test campaign. The CMG EQM underwent the test and verification in project phase 4. This phase also included the assessment of the tests and the project documentation. The development approach is pictured in Fig 1.

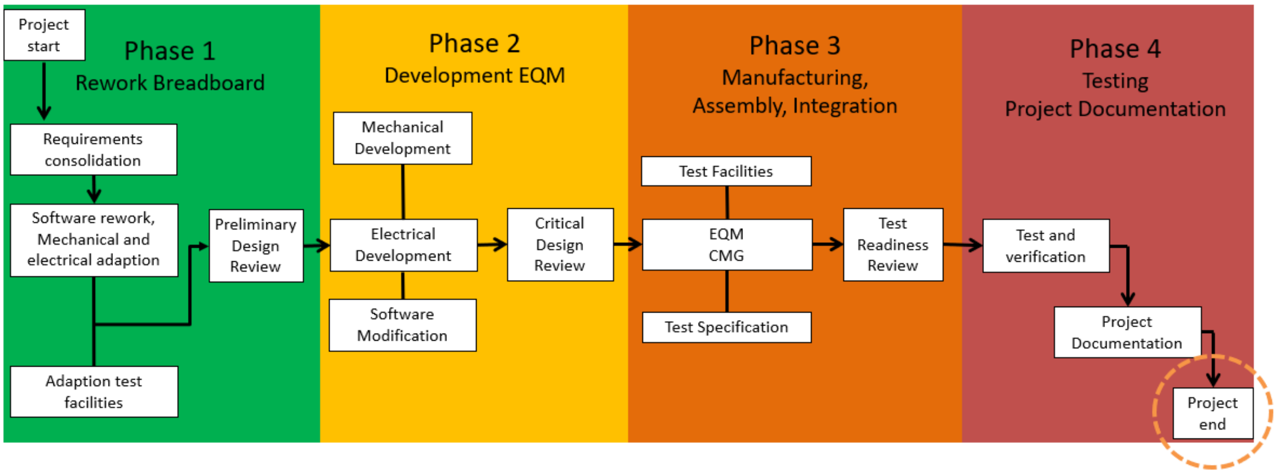

Figure 1. Project phases of EQM development

2 FUNCTIONAL PRINCIPLE

Contrary to reaction wheels (RW), that apply torque by changing their flywheel speed, the speed of the CMG flywheel remains constant. A gyroscopic output torque is created by rotating the CMGs gimbal axis. Fig 2. illustrates this principle.

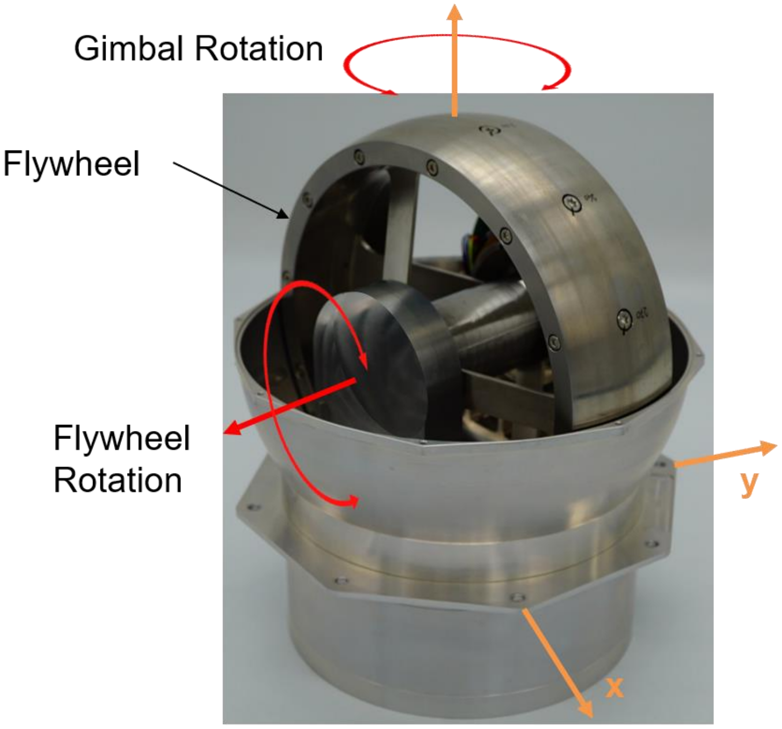

Figure 2. CMG principle

This principle results in two major benefits. On the one hand, CMGs ensure highly agile operations, e. g. Attitude Control Systems (ACS) for Earth Observation (EO) missions. On the other hand, CMGs are, compared to common RWs, far more power efficient, since the rotating mass (flywheel) maintains its rotation.

3 TECHNICAL SPECIFICATIONS

Fig. 3 shows the EQM of the CMG. Tab 1 provides an overview of its main parameters.

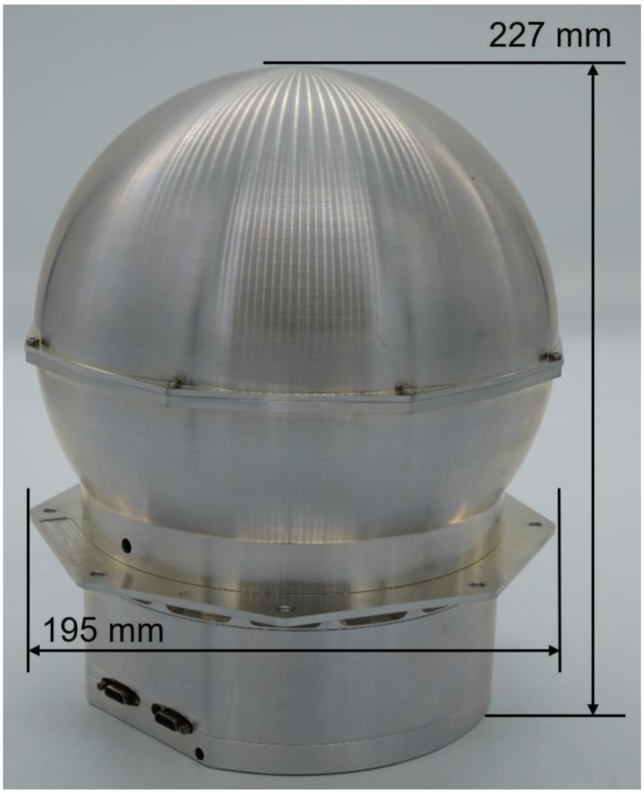

Figure 3. CMG EQM measures

Table 1: Technical specifications of the CMG EQM

Parameter	CMG EQM
Dimensions	
Height	227 mm
Width	195 mm (@ main flange)
Mass	6.5 kg
Angular Momentum (FW)	8 Nms
Maximum Output Torque	14 Nm
Operating temperature	-20°C to +50°C
Structure	
Material	Aluminium Alloy 7075
Surface Finish	Clear Chromated
Mounting Interface (I/F)	8 x M4

3.1 ELECTRONICS

Similar to the company’s reaction wheels, the EQM comprises an integrated Wheel Drive Electronic (WDE). The WDE is in line with the digital wheel development approach of Astrofein. Contrary to analogue commanded and controlled wheels, the digital wheel controller considers disturbances and compensates them to ensure that the commanded output is met. The interfaces (I/F) are pictured in Fig. 3. Tab. 2 gives an overview of the electronic specifications of the CMG EQM.

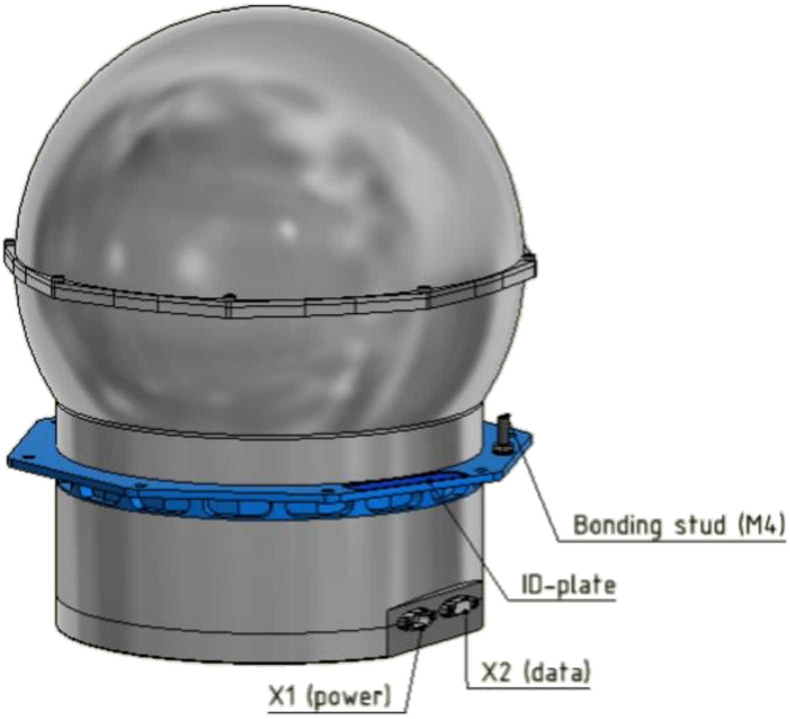

Figure 3. CMG EQM Interfaces

Table 2: Electronic specifications of the CMG EQM

Parameter	**CMG EQM**
Power	
Operating Voltage (redundant)	28 V (+10V/-6V)
@ FW Run-up	40W
@ Stand-by	≤ 4W
@ Maintaining Max. Angular Momentum	≤ 18W
@ Max. Output Torque	≤ 21W
Data I/F	
Physical	Micro-D15
Standard (redundant)	RS485
	RS422 (optional)
	CAN (optional)

4 INSIGHT ON TEST CAMPAIGN

After the MAI of the CMG EQM and the preparation of the test documents, a TRR was held to formally release the environmental test campaign. This campaign foresaw verifying the physical properties, short functional checks, vibration, and pyro testing, as well as thermal-vacuum (TV) tests and micro-vibration (MV). All tests were conducted at the premises of Astrofein. The campaign was closed by a Post Test Review (PTR). The test flow is illustrated in Fig. 4.

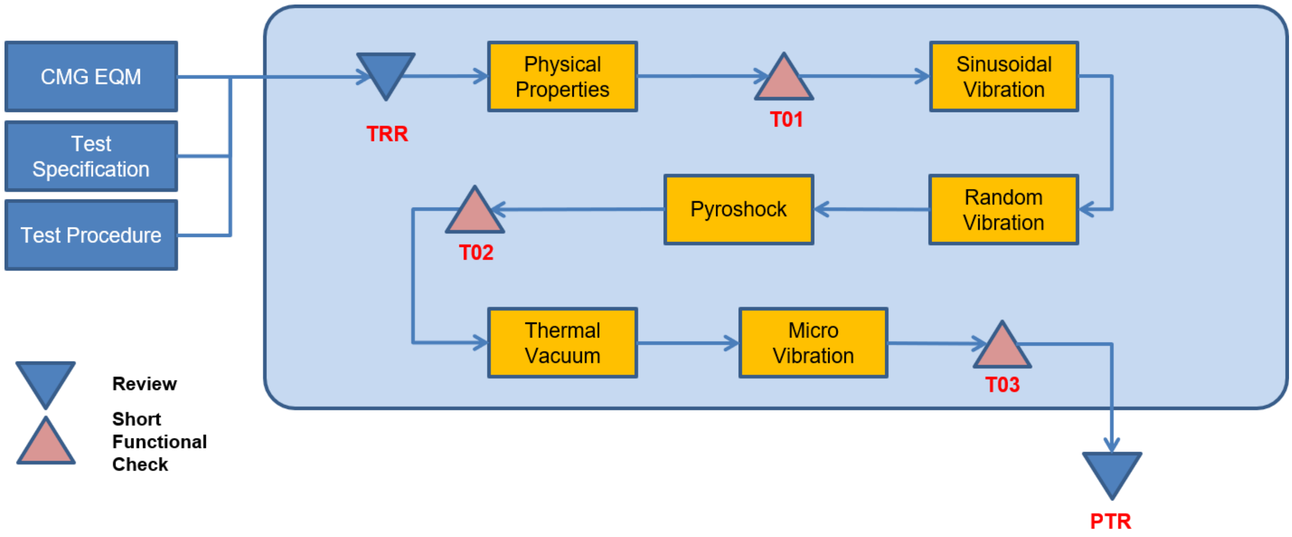

Figure 4. Qualification Test Flow

Vibration Test & Pyroshock

The vibration tests comprised sine and random vibration, as well as the corresponding resonance searches prior and after each axis. Subsequently, a pyroshock test was conducted. The tests were conducted in all three axes. The functional check that followed was conducted successfully. Thus, the mechanical test campaign is seen successful. Fig. 5 exemplarily shows the vibration test setup of the in-plane vibration tests (sine, random, resonance search). Fig. 6 illustrates the in-plane pyroshock test setup.

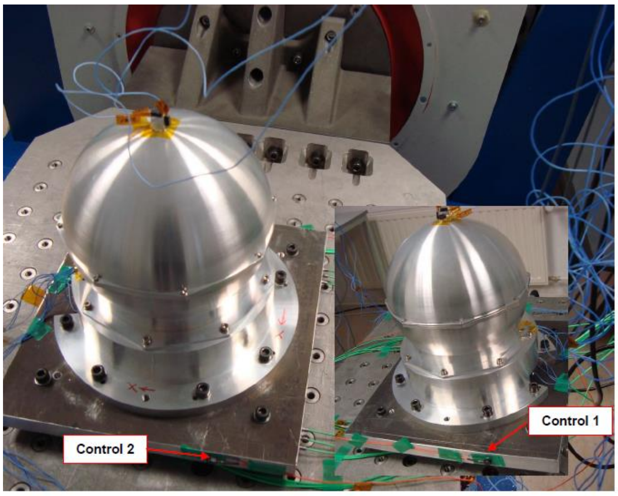

Figure 5. Vibration Test Setup

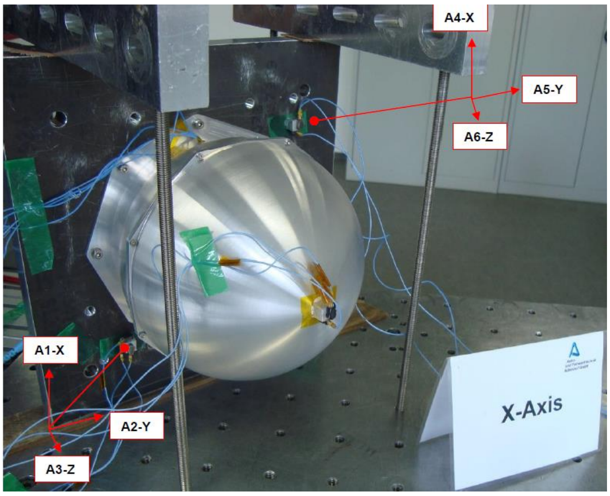

Figure 6. Pyroshock Test Setup

Thermal-Vacuum Test

The thermal-vacuum test was conducted in the small TV chamber of Astrofein, pictured in Fig. 7. Prior to starting the TVAC test, a short functional test was conducted before the chamber was air-evacuated, to ensure the CMG was properly working. Thereby, it was found that due constraints of the relatively small chamber and the high output torque of the CMG, the flywheel spin speed needed to be decreased from 3820 rpm to 1200 rpm, which decreased the output torque accordingly.

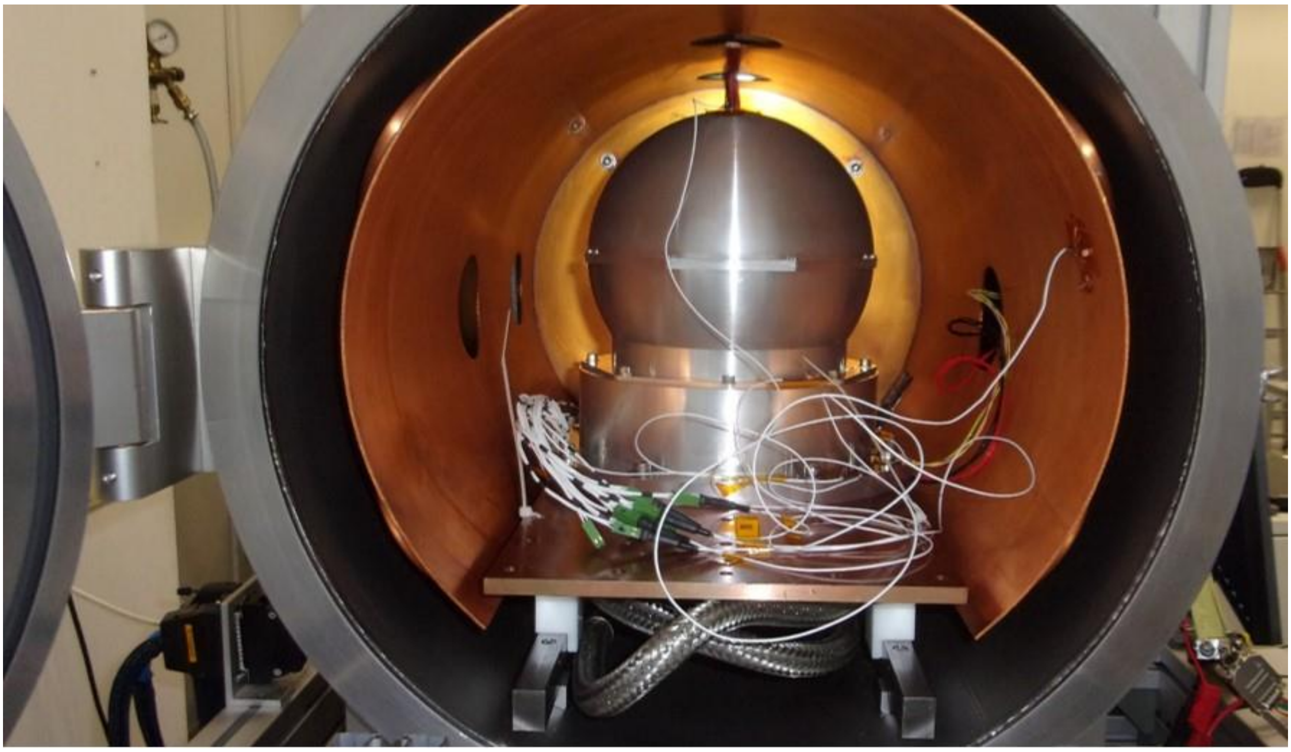

Figure 7. Small TVAC chamber at Astrofein

The TVAC test comprised eight cycles. Throughout the course of the first cycle, the non-operating min/max, as well as the min and max start-up temperatures were passed. Afterwards, six further cycles were performed. Before the last cycle, the chamber was programmed to come to a temperature hold (at ambient temperature), while remaining the low-vacuum-pressure environment. The flow is illustrated in Fig. 8 (not to scale). In addition to the short functional checks mentioned in Fig. 4, further functional checks were conducted during the TVAC campaign. The points in time during the campaign are highlighted with red dots in Fig. 8.

All functional tests were conducted successfully, with the exemption of the one performed at the last maximum operating temperature (*T_ops, max*). When commanding the CMG, commands would not be accepted. However, the telemetry was sending out valid values. Subsequent investigations showed that the temperature of one of the DC/DC converters exceeded its design parameters, effecting the telemetry. As a workaround it was decided to lower the operating temperature for the last cycle from 60°C to 50°C. When the latter was reached, the CMG accepted the commands again and passed the functional test.

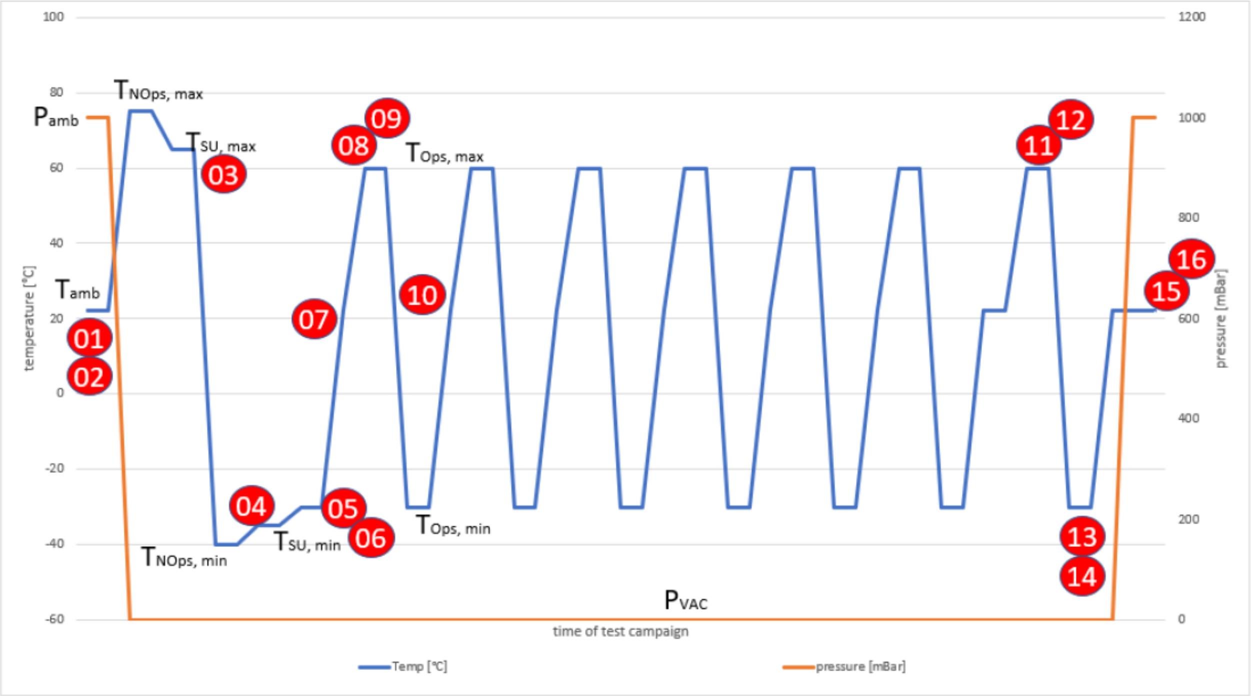

Figure 8. TVAC Test Flow

In general, the function of the CMG was shown under the relevant environment, with the performances deviating slightly.

For future projects, the electronics will be revised. Initially, the DC/DC converter was not explicitly designed to withstand an entire TVAC qualification test campaign at qualification test levels within the scope of the current project. Also, the internal linkage to the structure and heat transfer were not yet designed. However, the team decided to run the TVAC test and test the EQM accordingly. Thus, a revision of the WDE including its Electronic, Electrical, and Electromechanical (EEE) parts and the software is foreseen for a future project phase. Also, a delta qualification is to be performed in the next phase, comprising a test at nominal flywheel speed, possibly in a larger chamber.

Micro-Vibration Test

For the micro-vibration (MV) test that followed, three different use cases were defined to measure the micro-vibration characteristics of the EQM of the CMG, as well as to determine the real outputs and compare them to the design parameters. The use cases are:

- FW run-up, w/ fixed gimbal angle,
- FW steady state, 90° gimbal rotation, and
- FW steady state, gimbal constantly moving.

The test setup is shown in Fig. 9.

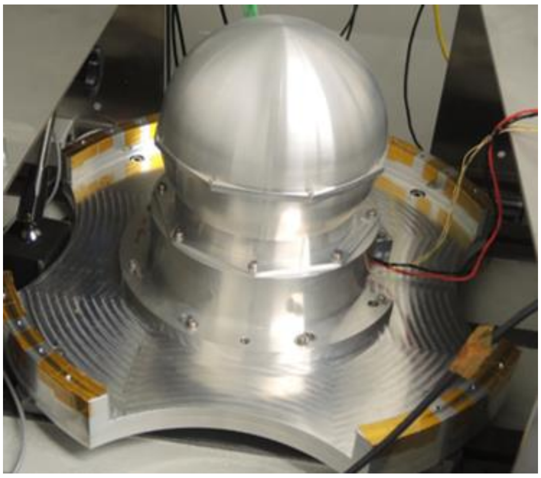

Figure 9. MV Test Setup

Assessing the test results, it was found, that the angular momentum of the EQM (illustrated in Fig. 10), as well as the torque (illustrated in Fig. 11) are in accordance with their design parameters of 8

Nms, respectively 14 Nm. The standard deviation of the (calculated) output torque is 0.26Nm (~1.9%). This performance was reached with the initial controller of the wheel.

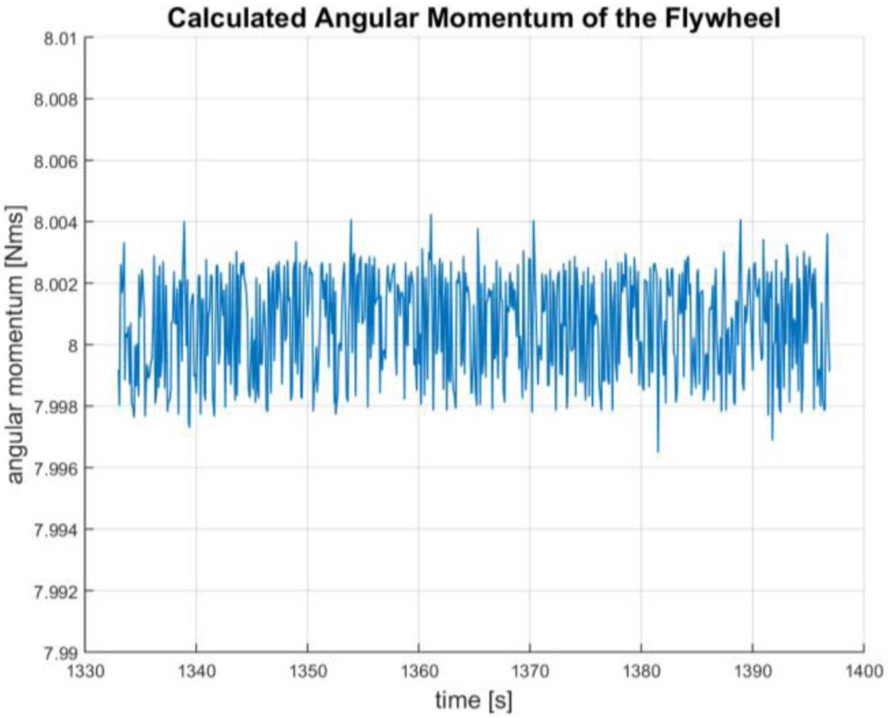

Figure 10. Angular Momentum (FW)*

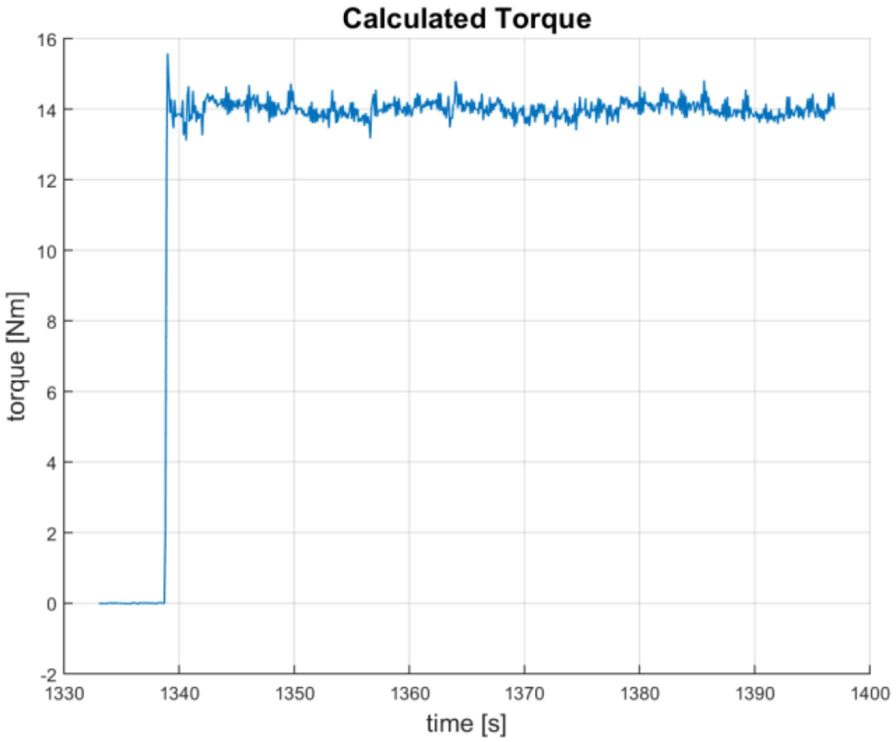

Figure 11. Torque*

(*) Calculated using measured values.

Further activities within future project phases will address the optimization of the gimbal controller. In order to ease the research on that, a new software was already designed and implemented, enabling the team to setup and modify controller parameters directly. Consequently, i. e. the trajectory can be optimized in order to improve the performance of the CMG.

5 FURTHER DEVELOPMENT GOALS [1]

For future project phases, further work packages were defined.

5.1 Mechanics

During the mechanical tests, valuable insights on the behaviour were gathered.

Bearing of the flywheel

As of now, the flywheel is mounted to two gimbal arms made of solid material (see Fig. 2 for details). During the vibration test campaign, shifts in frequencies and amplitudes have been noticed. Thus, research on the way of mounting the flywheel, respectively the design of the gimbal arms may be conducted. This way, the eigenfrequencies and the performance parameters may be optimized.

Bearing of the gimbal

Yet, no thermal correlation has been conducted. This should be done, especially in regards to the mount of the bearing, focusing on the compatibility of the bearing and the bearing seat during an extension of the material due to thermal influences.

Phenomenon of varying eigenfrequencies

During the vibration tests and their corresponding resonance searches it was noticed, that the Eigenfrequencies varied. It is possible, that structural joints may cause these changes, i. a. the gimbal bearing or the FW axis.

5.2 Electronics

During the function tests and the TVAC test, an issue with one of the DC/DC converters was noticed.

Thermal engineering

Current baseline of the electronics uses space-grade components with only minor usage of COTS parts. However, in the scope of the thermal-vacuum test it was noticed, that some EEE parts reach high temperatures. Thus, the electronics need to be modified focusing on the thermal control. Additionally, improving the thermal design of the CMG is foreseen for the next project phase.

Radiation Hardness

Not part of the current project phase was a radiation analysis or test. In order to reach a market maturity, the CMG needs to be revised focusing on the radiation hardness of its parts.

Components

Currently the gimbal encoder, as well as the slip ring are COTS parts. Both will need to be taken to another TRL before selling the CMG with them to customers. However, both did withstand the environmental test campaign including the qualification loads.

Data interface
Future electronics may include different types of data interfaces, i. a. RS422 or CAN.

Power
During the thermal-vacuum test campaign it was noticed, that the power requirements that were set for the development of the CMG were not met. During the next project phase, research is to be conducted on how the power values increase when operating the FW of the CMG with nominal rpm (reduced rpm was used this time), and possible reasons for the increase of the values are to be investigated. The latter includes i. a., the investigation on the bearings, how a thermal-cycling, and/or vibration testing affects the friction within the bearings.

5.3 Firmware

Also, during the qualification test campaign, improvements were identified, that are needed in order to reach a higher TRL, as well as to further optimize the performance of the CMG.

Control algorithm
The current version of the firmware allows to test different parameter sets, as well as setting different limits. This was done in order to be able to control and optimize the trajectory of the gimbal. This way, research on the performance can be conducted and the performance can be optimized.

5.4 TRL

Since the thermal-vacuum test was performed using a reduced flywheel rpm, a delta qualification is to be done subsequently. Though, the electronics and the mechanical parts did withstand the environmental test campaign and the CMGs EQM functionality was verified.

6 SUMMARY AND CONCLUSION

Within the scope of the current project phase, Astro- und Feinwerktechnik Adlershof GmbH (Astrofein) developed a CMG for Small Satellites supported by ESA GSTP-6. An existing breadboard design was the starting point. It was reworked and subsequently the design for a fully functional EQM was derived, resulting in its in-house manufacturing, assembly, and integration. Within the environmental test campaign, the functionality of the EQM was verified throughout the course of the entire campaign in a relevant environment. No radiation test has been conducted so far. Performance tests showed, that the as-designed output torque of 14 Nm is achieved, with a low standard deviation, although the initial version of the controller was used and not optimized yet.

In order to take the CMG to the next technology readiness level, the electronics and the mechanics need to be revised.

7 ACKNOWLEDGEMENT

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8 ABBREVIATIONS AND ACRONYMS

ACS	Attitude Control Systems
Astrofein	Astro- und Feinwerktechnik Adlershof GmbH
CMG	Control Moment Gyroscope
EEE	Electronic, Electrical, Electromechanical
EO	Earth Observation
ESA	European Space Agency
EQM	
FW	Engineering Qualification Model
GSTP	General Support Technology Programme
I/F	Interface
MAI	Manufacturing, Assembly, Integration
MV	Micro-Vibration
PDR	Preliminary Design Review
PTR	Post Test Review
RW	Reaction Wheel
TRL	Technology Readiness Level
TRR	Test Readiness Review
TV/TVAC	Thermal-Vacuum
WDE	Wheel Drive Electronic

9 REFERENCES

[1] Mayer A., Raschke C., Seiffert F., and Jahn H., *Final Report for µCMG*, EUROPEAN SPACE AGENCY CONTRACT REPORT (4000123641/18/NL/GLC/fk), Berlin, Germany, 2023.