Development of highly adaptive reaction wheels for geostationary and high agility satellites

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ABSTRACT

Astro und Feinwerktechnik Adlershof GmbH is one of the leading reaction wheel manufacturers. Like many small companies, the previous development of Astrofeins products was based on the optimal tailoring to specific tasks. While these products shared common elements and design approaches, they always differed in their core components. With an increasing variety of reaction wheels, a new design approach was implemented, the target was to keep particularly expensive components identical between different products. In the case of the High Line reaction wheel family, this is implemented for bearings, Wheel Drive Electronics (WDE) and motors. Mechanical components such as the flywheel and housing, still cannot be kept identical but benefit from similar design approaches and existing process/material qualifications. In addition, the new SmallSat wheels are discussed, those wheels do not fully implement this concept yet, but support exchangeable WDEs with different radiation resistances as well as the adaptation to a high torque variant without the need of modifying the WDE or mechanics.

It is also shown that the upscaling of the previous technologies, workflow and documentation structures reached their limits and had to be dealt with new solutions. However, the knowledge gained from this can be fully transferred to further developments.

1 INTRODURCTION

Astro- und Feinwerktechnik Adlershof GmbH (Astrofein) has been producing smart reaction wheels for over 20 years now, starting with the RW90, which was designed for the BIRD satellite and launched with it in 2001. The RW90 and the first following reaction wheels were designed for the smallest segment of Small satellites (<100kg) and CubeSats [1]. However, in recent years, there has been an increased demand for reaction wheels for larger SmallSats (>200kg), yet the missions linked to them often entailed higher design and quality requirements in comparison to those missions which could use the RW90. At the same time, the inquiries also included an increasing number of missions with high agility requirements, which therefore needed reaction wheels with above-average torque. In order to do justice to these market conditions, more radical developments were necessary. At the same time, Astrofein decided, on the basis of project initiatives, to work on their first "*High Line*" reaction wheel, which are particularly suitable for heavy geostationary satellites (>6000kg).

Instead of just building highly specialized reaction wheels again, the new developments were designed in such a way that the reaction wheels can be used more flexible and further subversions that are based on them could be derived more easily with less qualification tests.

In the following, the Astrofein smart reaction wheels will first be discussed in general, followed by a description of the new design approach and a presentation of the resulted reaction wheels. Finally, obstacles that arose from the new design approach are highlighted.

2 SMART REACTION WHEEL

Current analog reaction wheels are “only” electric motors with a flywheel mass. The control of these wheels are carried out by the satellite’s own processing architecture. Smart reaction wheels relieve the attitude control data processing unit and the satellite’s attitude control engineering team. They are performing tasks, which were part of the attitude control system of satellites, tasks that are related to controlling and monitoring the reaction wheel.
Astrofeins smart reaction wheels are characterized by the following attributes:

2.1 Digital Interface

Digital interfaces are essential for smart reactions wheels. They allow the easy integration of the wheels into a communication bus structure. The combination with a speed or acceleration controller is the first step towards a smart reaction wheel.
All types of Astrofeins reaction wheels are equipped with a serial digital interface. The interface can be adapted easily to the satellite’s requirements. Typical digital interfaces used in Astrofeins reaction wheels are (others can be realized on request):

- CAN 2.0
- RS485
- RS422

2.2 Model based controller

Besides digital interfaces model based controllers are an attribute of Astrofeins smart reaction wheels. With model based controllers Astrofeins smart reaction wheels reach higher accuracies and stabilities than standard reaction wheels [1]. In the event of disturbances, the controller reacts automatically and adjusts the torque so that the speed and location are maintained.

2.3 Monitoring and self-protection mechanisms

A further characteristic of Astrofeins smart reaction wheels are a variety of monitoring and protective mechanisms.
The monitoring and self-protection mechanisms can be divided into three branches:

- Temperature monitoring and protection against overheating
- Voltage and current monitoring and protection mechanisms
- Monitoring and protection mechanisms in the data processing system

Beside these main branches a limitation of the maximum commendable rotation, rate as well as torque are implemented.

The monitoring mechanisms will early indicate possible wheel failures, disturbances or wrong

handling by the operator. After any violation of the defined boundaries, the protective mechanisms reacts with an appropriate measure, e.g. switching into standby mode and waiting for clearing the raised failure flags. These measures should avoid self-damage or the propagation any occurred failure.

3 REACTION WHEEL FAMILY OVERVIEW and WDE types

To understand the design approach it should be explained which reaction wheel were already developed based on this approach and which will be based on those. Fig. 1 shows a general overview of all Astrofein reaction wheel. The underline of the different types has to be interpreted as follows:

- Red underline: already developed reaction wheel
- Blue underline : already developed based on new design approach described in the following chapter
- Orange underline: currently under development based on the new design approach

Based on that the main focus of the following chapter lies on the RW150, RW250 and RW6000 as well as the High Line in general.

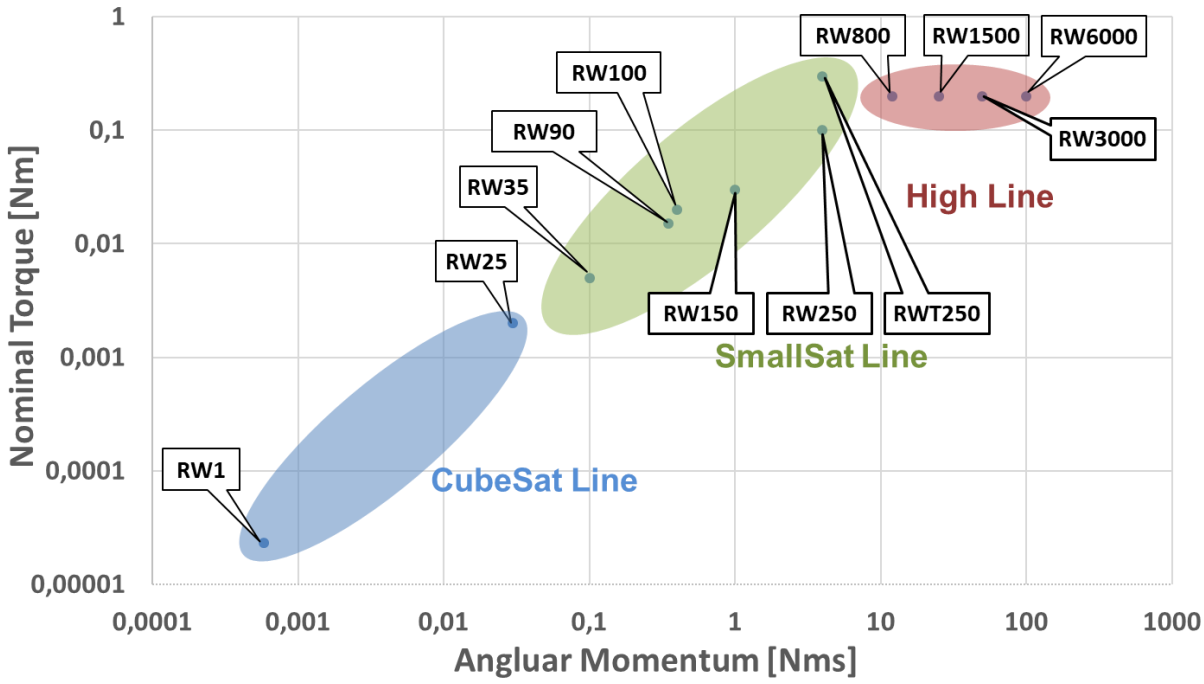

Figure 1. Astrofein reaction wheel overview

As can be seen from Fig. 1, reaction wheels with higher numbers are suited for the use in larger satellites. However, the respective reaction wheels of one size class can still be differentiated on the basis of the installed wheel drive electronics (WDE). Each WDE type is identified with a suffix which is placed at the end of the respective wheel type, e.g. RW250m or RW250s.
As described in the following chapter the usage of different WDEs for the same type of reaction

wheel was a major point of the new design approaches with the target of increasing the environmental adaptability of each reaction wheel type.

Astrofein provides the following four different WDE types.

- COTS WDE (c): WDE consist completely of COTS EEE parts.

- Mixed WDE (m): WDE mainly consisting of COTS parts (automotive grade) and some space grade parts. Additional test were performed for the qualification of automotive grade parts. A TID test on board level is done with each new batch of purchased EEE parts.

- Automotive grade WDE (a): WDE consisting only of COTS parts (automotive grade). In contrast to a mixed WDE, a complete screening campaign on part level is carried out with every new batch of procured EEE parts.

- Space grade WDE (s): WDE consisting completely of space grade parts

The automotive grade approach should be particularly emphasized here. This WDE can be fully used in harsh radiation environments and is also optimized for the long operating time in the geostationary orbits. However, due to the use of screened automotive grade EEE parts, the costs for this WDE are still much lower than the mixed WDE (m) approach and even much lower than the classic space grade WDE which is fully equipped with space qualified parts.

Table 1 shows an overview of the different wheel types and the possible WDE options. The green marked are already available, the orange ones are currently under development and the entries that are marked but not coloured are likely to be developed.

Table 1: Assignment of WDE types to RW types

Products	**WDE Type**			
	COTS	**Mixed**	**Space**	**Automotive**
RW1	X			
RW35	X			
RW90	X			
RW100	X			X
RW150	X	X		X
RW250		X	X	X
RWT250		X		
RW800		X	X	X
RW1500		X	X	X
RW3000		X	X	X
RW6000		X	X	X

4 DESIGN APPROACH

As previously mentioned, a new design approach has been used for the latest generation of Astrofein smart reaction wheels. This approach is based on the family concept, which has been used in the aviation industry for decades. This concept refers to an approach in which a series of related products or designs are developed based on a common platform or set of core components. In the context of aircraft manufacturing, it involves creating a family of aircraft models that share common design elements, systems, and components.

Despite their relatively lower system complexity (compared to whole aircrafts, cars etc.), reaction wheels, like other engineering systems, still consist of several sub-assemblies and critical parts, thus the corresponding concept can also be applied to reaction wheels. The following goals were formulated for the application of the concept:

- Increasing the cost efficiency of each reaction wheel
- Streamlined development of new reaction wheels of the same family
- Increasing adaptability of reaction wheel regarding different use cases

By adopting a family concept approach for reaction wheels, cost savings were archived through economies of scale. To understand the source of this savings in detail, the building blocks of the Astrofein reaction wheels must be viewed in detail. Each Astrofein reaction wheel consists of the same six building blocks; motor, bearing, encoder, housing, wheel drive electronics (WDE) and chassis (including the flywheel). The blocks are visualized in Fig. 2.

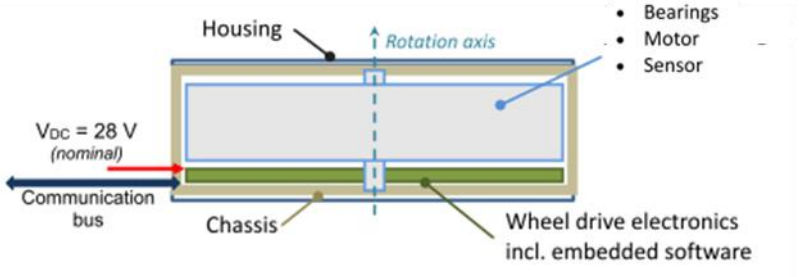

Figure 2. Schematic of building blocks

4.1 Application of the concept

With regard to chassis and housing, no major savings in production were achieved since the mechanical parts of different wheel sizes differ too much even within a family like the High Line reaction wheels. The optimization of size and mass of these building blocks is just too important to make cuts in order to save a bit on costs.

With regard to the design process of the chassis and housing the RW6000 had already benefited from Astrofeins experience with their former smaller reaction wheels, which already used similar structures, design principles and technical concepts. Nevertheless, the significantly larger structure of the RW6000 leaded to new obstacles during the development phase. The experience, gained with the RW6000, can be transferred to the entire highline now, resulting in a significant reduction in development effort for those projects, this is already the case for the RW3000. Although the parts of the chassis and flywheel assemblies of different RW types are not identical, the RW3000 development has already shown that components can still be kept in a similar style and the same material can be used. In addition to already mentioned lower design effort, this also ensures that assembly instructions only have to be slightly adapted and processes previously qualified for the RW6000 are fully applicable. Which further reduces the initial development costs.

In the case of the RW250, the primary objective of the new design was to employ the same mechanical structure for both the torque variant (RWT250) and the standard variant (RW250). A particular challenge in this context was the thermal behaviour. While the standard variant has a peak power consumption of 85W, the RWT250 variant hits 220W. Consequently, the chassis and flywheel needed to be optimized accordingly to ensure appropriate heat dissipation pathways, allowing for efficient transfer of heat to the interface without compromising the compact design of the reaction wheel.

Key points for scaling due to economies of scale are the motor, bearings and the WDE. The assemblies benefit from significant cost savings when purchased in larger quantities. At the same time, a safety stock can be built up from parts with much less risk, since it can be safely assumed that the stock can be used regularly for many different reaction wheels. In particular, the EEE part crisis of the last two years has made this point particularly important.
The current plan is to keep these three part types identical for the entire High Line. In the case of the RW6000, RW3000 and prototype developments of the RW800, this concept has already been implemented. It should be noted that these RW types, due to their field of application, are confronted with particularly demanding customer requirements. Therefore, the qualification that has already been carried out, the existing documentation and the already set purchasing specification ensure considerable savings in the further development process. Due to a smaller range of different documents and procedures, internal handling is also kept much simpler and less error-prone.
In case of the RW(T)250/RW150 this approach is limited to the WDE only. Motor and bearing are "*only*" identical for all RW250 variants (RW250m, RW250s and RWT250m) but are completely different compared to other smallSat wheels. The RW(T)250 was designed in such a way that it can be equipped with a space and mixed variant of the WDE. The mixed variant of this WDE, on the other hand, can also be integrated into the RW150 without any modification.

4.2 Development obstacles

The up scaling of the smallSat line to the High Line as well as the design approach itself posed several challenges, in following are a few illustrative examples.

The RW6000 was Astrofein's first larger wheel, building on the technological expertise of the smaller wheels. The assembly process, in particular, was confronted with entirely new obstacles. For instance, it was always necessary to perform manual adjustments of some parts to ensure precise distances between the components. Due to the sheer size and mass of the parts this become much more difficult than for the smallSat line, leading to the additional development of support equipment and additional process and ensure the desired level of accuracy could be achieved.
New processes also had to be implemented in the manufacturing workshop, in order to produce the large parts of the housing and flywheel in the same quality as the smaller reaction wheels.

Completely new problem areas also emerged in the test phase, with the significant increase in air drag at high speeds being particularly interesting. Under atmospheric conditions SmallSat wheels can easily be accelerated up to the maximum speed without reaching the power limits. In the case of the RW6000, however, air friction at higher speeds became so dominant that it was not possible to reach the maximum speed since the current protection mechanism had previously been triggered. The solution was a rather unconventional approach. The RW6000 can be equipped with vales allowing the flushing with helium, which reduces air friction to such an extent that full operation under atmospheric conditions is possible.

While it was stated in the previous section that family concept also entails a reduction in documentation, this advantage was not immediately used in its full extend. With the gradual growth of the different variants and types, the amount of documentation initially grew, since the existing development environment had not yet been adapted to this concept. Accordingly, after initial developments, a larger process had to be set up to summarize and standardize all documentation packages.

5 Reaction Wheel Characteristics

Finally, an overview of the reaction wheels which have been developed on the basis of the new design concept, should be given.

Wheel type:	**RW150**	**RW(T)250**	**RW6000**
Angular Momentum	1.0 Nms (@6000 rpm)	4.0 Nms (@5000 rpm)	100.0 Nms (@4200 rpm)
Moment of Intertia	$1.76 \cdot 10^{-3}$ kgm^2	$7.94 \cdot 10^{-3}$ kgm^2	$2.274 \cdot 10^{-1}$ kgm^2
Nominal Rotation Rate	6,000 rpm	5,000 rpm	4,200 rpm
Nominal Torque	0.03 Nm	0.1 Nm (standard) 0.3 Nm (torque version)	0.2 Nm
Mass	< 1.3 kg	< 2.75 kg	< 12 kg
Size	150 mm x 150 mm x 64.5 mm	180 mm x 180 mm x 80 mm	460 mm x 460 mm x 150 mm
Temperature Range	-25°C to 50°C	-25°C to 50°C	0°C to 62°C
Lifetime	7 years	7 years	15 years
Currently available WDE types	COTS WDE (c) Mixed WDE (m) (identical to RW250 WDE)	Mixed WDE (m) Space WDE (s)(only for standard version)	Automotive Grade WDE (a)

6 Summary & Outlook

In summary, Even though the first reaction of the high line and smallSat line were built based on the family approach, the full implementation of the concept is still in its early stages.The first experience with the scaling of existing wheels was gained with the RW6000 and will now be transferred to the RW3000 and RW800. The true measure of success for our new design approach will gradually reveal itself through the progression of those ongoing projects.
The RW250 and RW150 have already fully demonstrated the applicability of different WDEs to different wheel types and their benefits on supply chains, qualification and design processes. The interchangeable circuit boards with the resistant but much cheaper mixed and automotive grade WDE represent an innovative approach that Astrofein will continue to pursue for its reaction wheel families.
Based on the positive effects so far, the concept will in all probability be further expanded in order to be able to continue to provide cost-efficient reaction wheels despite demanding requirements.

7 REFERENCES

[1] Stoltz S., Raschke C., Courtois K., *RW 90, a smart reaction wheel – Progress from BIRD to TET-1*, 8th IAA Symposium on small satellites for earth observation", Berlin, Germany, 2011.