DEVELOPING, FLYING AND EVOLVING A CANADIAN MICROSATELLITE REACTION WHEEL – LESSONS LEARNED

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Abstract

Sinclair Interplanetary and The University of Toronto Space Flight Laboratory (SFL) collaborated to produce their first miniature reaction wheel in 2007. This design is novel in its custom-made motor and its lack of a sealed housing. The first 30 mNm-sec unit was launched on CanX-2 in April 2008 and continues to perform well.

The design can be easily modified. Variants as small as 10 mNm-sec, and as large as 60 mNm-sec, have been manufactured with a 1000 mNm-sec unit in the works. Different electronics boards support a host of different digital interfaces and power supply voltages. To date a total of 42 wheels of varying sizes have been delivered to customers.

The development effort has encountered some setbacks, and has overcome them. A seemingly innocuous manufacturing process change caused a batch of rotors to fail under severe vibration. More recently, high-energy proton testing of a 28 V electronics variant showed single-event burnout problems in the drive MOSFETs. Both of these problems were quickly understood and corrected, with units recalled from customers where necessary.

Now, three years after the initial prototypes were built, the reaction wheel is a mature family of products. Through vibration, thermal, radiation and lifetime tests on the ground, together with on-orbit heritage, the design is well-qualified for future missions.

Introduction

Reaction wheels and momentum wheels are commonly used by satellites to control their attitude. Canada has considerable expertise in this area, notably the Microsat Systems Canada Inc (formerly Dynacon) MW-200 and MW-1000 wheels and Bristol Aerospace's GyroWheel. Starting in 2007, Sinclair Interplanetary and the Space Flight Lab (SFL) developed a new series of reaction wheels suitable for very small satellites.

The initial impetus for this work was SFL's Generic Nanosatellite Bus (GNB) series of spacecraft. Each GNB is a 20 cm cube and requires three wheels. No commercially available wheel could meet this specification, so a new design was required. When the initial prototypes proved successful the wheel was also manifested on SFL's CanX-2 (a 10 x 10 x 30 cm nanosatellite) and launched in April 2008. The first GNB to be launched will be AISSAT-1, scheduled to fly in April 2010. Flight wheels have been delivered for four more GNB missions: CanX-3A (UniBRITE), CanX-3B (BRITE-Austria), CanX-4 and CanX-5.

A larger wheel with approximately twice the torque and momentum storage was developed for larger missions. This larger wheel has enjoyed considerable commercial success. Flight units have been delivered to CSA's M3MSAT, JAXA's SDS-3, and the joint CSA/JAXA JC2SAT mission.

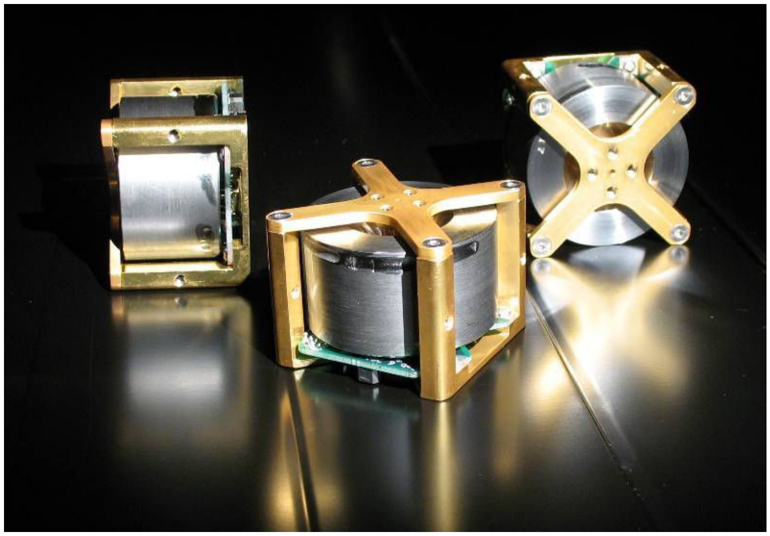

Figure 1 Three GNB Reaction Wheels

Wheel Design

The nuts-and-bolts design of the wheel has been described in previous papers[1]. In this section we will take a step back and look at the rational behind the major design choices.

A reaction wheel is made up of a number of parts: motor, rotor, bearings, electronics and structure. In the microsatellite market most wheels use a commercial brushless DC motor that has built-in bearings. This motor is then connected to an external rotor which provides the required inertia. It is also typical to use an enveloping structure that is hermetically sealed.

Our design is quite different. Instead of an integrated motor/bearing assembly with discrete rotor, we use an integrated motor/rotor assembly with discrete bearings. This is the standard for large satellite wheels, but has been uncommon in the microsatellite market. Making the motor and the rotor one piece realizes a number of benefits:

- The unit can be made much shorter. Instead of the traditional soup-can form factor we have a tuna-can. This saves space in the satellite and also reduces the cantilever mode under launch vibration.
- If the rotor is made from ferromagnetic material it can close the motor's magnetic circuit. The critical difference between this and the back-iron in a conventional brushless DC motor is that the rotor is spinning. In the reference frame of the rotor material the magnetic field is DC, whereas in a conventional motor there is an AC field. Thus, the integrated motor/rotor design has zero hysteresis and eddy-current drag.
- The motor magnets can be mounted out at the rim of the rotor where they contribute usefully to the inertia. In a conventional motor they are located close to the center where they do no good.
- The wide diameter of the motor facilitates a design with many magnetic poles. From an attitude standpoint, this increases the frequency of the torque ripple. Electrically, this increases the frequency of the current ripple. In both cases, higher frequencies are more easily mitigated. Having many poles also reduces the interference with spacecraft magnetometers.

Our second departure from the norm is our rejection of an enveloping enclosure. Most wheels use enclosures to maintain an atmosphere (or vacuum) that is compatible with their bearing lubricant, and to control the aerodynamic losses when operating on the ground. We are able to do without an enclosure for the following reasons:

- We carefully chose bearings that can operate equally well in air or vacuum, and are not affected by humidity. Silicon nitride balls roll on diamond-like-carbon races, lubricated with low vapour-pressure fluoropolymer grease. These dissimilar materials cannot gall in vacuum and cannot corrode in moist air.
- To a first approximation, the windage power loss is proportional to the 3^{rd} power of the wheel radius. A big spacecraft might have a wheel 50 cm in diameter, and the power required to spin that at 5000 RPM in an atmosphere would be prohibitive. In order to test the system outside a vacuum chamber the wheel must be sealed into an evacuated enclosure. By contrast, our wheel is 5 cm in diameter. The aerodynamic losses are 1,000x less. While the increased power consumption in an atmosphere is measureable it does not prohibit system testing.

Removing the sealed enclosure is a key simplification. It brings the following benefits:

- The diameter of the whole system is reduced. Or, conversely, a larger rotor can be used within a fixed unit footprint. Using the largest possible rotor is critical to achieving maximum momentum storage.
- Failure of the hermetic seal is no longer a concern. Seal failures are common on small reaction wheels, and are often catastrophic.
- No electrical feedthrough is required. Feedthroughs are bulky, unreliable, and they can constrain the electronics architecture.

Design Variants

The design is almost infinitely customizable, both mechanically and electrically. To keep the varieties manageable, four base models are supported as shown in **Error! Not a valid bookmark self-reference.**. The GNB wheel design is designated RW-0.03. Its power input is designed for compatibility with a single Li-ion cell, or with two series triple-junction GaAs cells. The digital interface is two 3.0 V CMOS logic level signals which can be configured for either an asynchronous serial link or an I2C link. A total of 24 flight units of this design have now been delivered.

Table 1: Existing Design Variants

Model	Momentum	Size	Mass	Voltage	Interface	Status
RW-0.01	10 mNm-sec @ 3410 RPM	5 x 5 x 3 cm	120 g	3.4 – 6.0 V	ASYNC, I2C	Prototypes built
RW-0.03	30 mNm-sec @ 5600 RPM	5 x 5 x 4 cm	185 g	3.5 – 6.0 V	ASYNC, I2C	On-orbit
RW-0.06	60 mNm-sec @ 6500 RPM	7.5 x 6.5 x 3.8 cm	225 g	7.5 – 35.0 V	RS485, ASYNC, SPI, I2C	Qualified, delivered, waiting for launch
RW-1.00	1.0 Nm-sec @ 6800 RPM	12 x 12 x 5.5 cm	1200 g	7.5 – 35.0 V	Redundant RS485, CAN	Detailed Design

The Canadian Space Agency required a slightly larger wheel for the JC2SAT program. This requirement led to the development of the RW-0.06 wheel. In addition to its size it has some electronics features suited for bigger satellites. Its power input will accept a standard 28 V avionics bus, though it will also operate down to 7.5 V. Its digital interface adds support for RS485 allowing greater separation between flight computer and reaction wheel as well as greater EMI tolerance. An SPI link is also supported. A total of 18 flight units of this design have now been delivered.

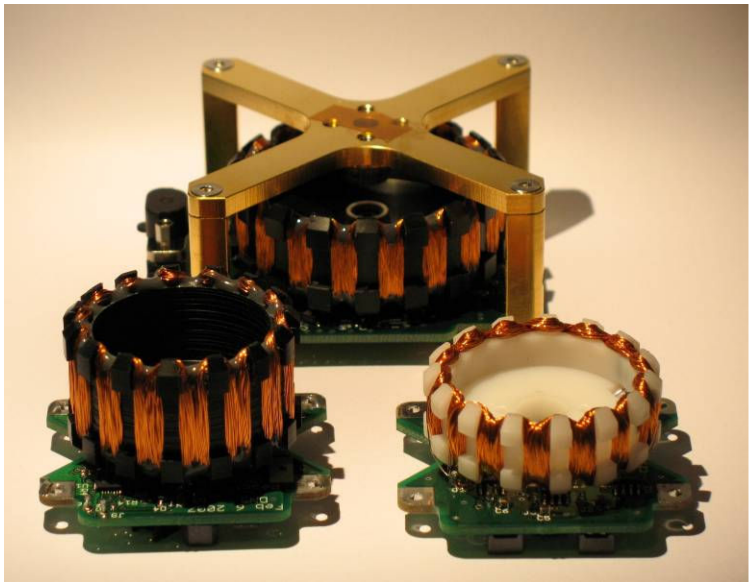

Figure 2: Electronics units from RW-0.03 (left), RW-0.01 (right) and RW-0.06 (rear)

Interest from CubeSat missions sparked the design of the RW-0.01 wheel. This very small wheel is available as individual components, or integrated as part of a three-axis actuator and sensor pack. So far there have been no sales of units this size, and development of even smaller devices will wait until there is a demonstrated market for them.

The final design variant is the much larger RW-1.00. The inertia of a wheel scales as the 4^{th} power of radius, so a wheel of twice the diameter of the RW-0.06 can store 16x the momentum at the same rotational speed. The electronics draw heritage from the RW-0.06, but the increased circuit board area allows a full fail-operational dual-string redundant configuration. This wheel has the size and reliability to be used on microsatellites in the 100-200 kg range.

Rotor Failures and Recovery

The first 16 RW-0.03 parts were built from two-piece rotors. A lathed wheel had a hole drilled through the center, and a precision-ground shaft pressed into it. This design was satisfactory, but it had two flaws. Due to the low aspect-ratio of the central hole it was hard to ensure that the shaft was exactly coaxial with the wheel. Misalignment lead to wheel imbalance and a visually unappealing wobble. More alarming, under severe vibration testing one of the press-fits loosened allowing the shaft to translate axially. While this latter failure would not have resulted in the loss of the unit, it would have caused increased power consumption and reduced the unit’s maximum speed.

When the RW-0.06 was designed a more sophisticated one-piece rotor was made. Precision machining allowed the wheel to be machined with a shaft protruding from each side. The one-piece wheel is guaranteed to have a coaxial shaft, and there is no danger of loosened press-fit. The design seemed superior in every way, and we were very surprised when a RW-0.06 failed catastrophically in vibration testing!

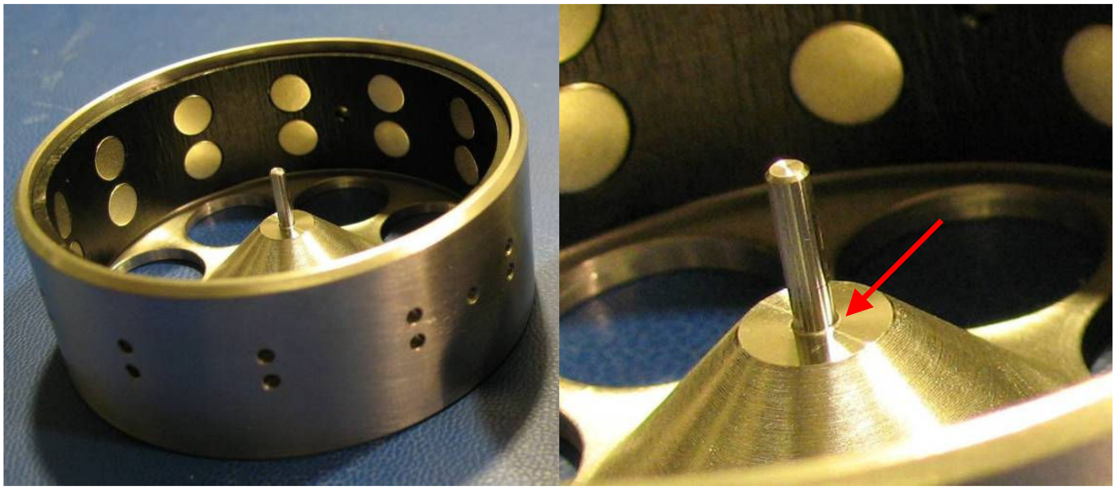

Figure 3: One-Piece Wheel, Showing Stress Concentration at Shaft Root

Inspection immediately showed that both shafts had snapped off the rotor at their roots. Subsequent analysis identified the cause of the failure as being fatigue. The reason that this design failed vibration while others had not was three-fold. First, the sharp corner at the intersection of the shaft and hub produced stress concentration significantly in excess of that experienced in the press-fitted shaft. While the RW-0.03 design did not contain a radius either, load transfer between the press-fitted shaft and the rotor differed in a way that reduced the mean stress in the shaft when compared to the integral-shaft design. Second, although it was not known during the design process, the press-fitted shaft had been made from a stronger alloy than the alloy used in the rotor (which was selected largely for its magnetic properties). Third and finally, the RW-0.06 was tested to a more severe random vibration spectrum than the RW-0.03 had been. Since fatigue failure is a very strong function of applied load, failure was simply more likely under the new spectrum.

A redesign was quickly implemented, using a one-piece rotor with generous radii instead of tight internal corners and a reduced length which was achieved by integrating other components directly into rotor itself. The radii prevent stress concentration, and also strengthen the root of the shaft. To validate the fix we performed and passed a vibration test with a duration of 30 minutes per axis (the original test that failed was only 2 minutes per axis), showing that we have large margins against fatigue.

The RW-0.01, RW-0.03 and RW-0.06 wheels are now all fabricated from one-piece radiused rotors. All of the wheels with defective rotors that had been delivered to customers have been recalled, had their rotors replaced, and have been re-tested.

Radiation Failures and Recovery

The high-voltage RW-0.06 electronics were radiation tested at the TRIUMF particle accelerator facility in Vancouver. Circuit boards were bombarded by a 105 MeV proton beam. The 34 V supply current was monitored, as well as the realtime digital telemetry from the units.

Two units were tested, and both experienced sudden and permanent failure. One reached a total ionizing dose of 17 krad, while the other failed at only 1.5 krad. [By comparison, an electronics unit in a LEO satellite might see ~1 krad / year.] This difference between the units suggests that the failure mechanism is a single-event-effect and not driven by total dose.

Inspection showed that the failed part was one of the six N-channel MOSFETs used to drive the motor. It appears to have failed due to single-event burnout (SEB). It is known that the SEB cross-section is related to the ratio of applied voltage to rated voltage. The part is rated to 60 Vds, and during testing was biased to a maximum of 34 V. The normal space derating rules call for the applied stress to be no more than 75%[2] or 80%[3] of the part rating. Based on these rules we had thought the design sound.

Further reading showed that this is not so. Those derating rules apply only when the using MOSFETs that have already been screened for radiation performance. Parts sold as "rad-hard" typically have no single-event burnout mode, and the single-event gate rupture cross-section is characterized. Commercial MOSFETs may experience single-event burnout at much lower applied voltages. The literature[4] mentions a part rated at 60 V that experience SEB at 22 V, and a number of 100 V rated parts that show SEB at 40 V. Of the 200 V parts mentioned, SEB was seen[5] at a minimum applied voltage of 50 V.

Based on this information the high-voltage electronics were redesigned using 200 V rated MOSFETs. Radiation tests were repeated, and this time two units reached 20 krad and 15 krad respectively without any evidence of SEB. The redesign has had the happy side-effect of making the unit more robust when performing high-torque slews at low temperature. Since the redesign we have never seen an electronics unit failure.

Life Testing

We are now confident that this reaction wheel design will meet the life requirements of typical microsatellite missions. This assurance comes from both on-orbit and ground-based testing.

CanX-2 has been on-orbit for two years, using its one RW-0.03 wheel for momentum bias stabilization. It has been running continually at ~2000 RPM, and remains operational with no evidence seen of any degradation. Another RW-0.03 has been running for the same time in ground-based testing. It is being spun at ~4000 RPM in an attempt to age the bearings faster. If bearing wear is assumed to be linear with speed, then this wheel has survived the equivalent of 4 years of nominal operation for a momentum wheel and considerably longer if the wheel is to be used as a reaction wheel with a speed bias closer to 0 RPM.

Another life test is ongoing with a RW-0.06 wheel. This part was subjected to a brutal 23 Grms vibration test, followed by continual operation at a mean speed of 3500 RPM. Testing began in November 2009, with no anomalies seen to date.

Conclusion

This project began as a high-risk experiment. I had built a lot of reaction wheels over the years, but never one with such a unique design. Magnetics design and bearing lubrication were two new skills that had to be learned through a combination of study and experiment. But the experiment paid off. One by one the identified risk items were retired, culminating in successful on-orbit operations.

The project has overcome a number of snags, and it is interesting to note that they were in areas that we had not identified as risks. We were comfortable with the one-piece rotor design as it was dimensionally equivalent to the two-piece design. We were happy with our transistor voltage derating because it seemed that we had plenty of margin. These failures have been learning exercises, and we have rapidly overcome them.

With 42 flight units sold we now have a significant share of the market. We hope to build on this success, supplying high-quality parts of existing designs while continuing to evolve and innovate new models.

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[1] Sinclair, D, et al, "Enabling Reaction Wheel Technology for High Performance Nanosatellite Attitude Control." 21st Annual AIAA/USU Conference on Small Satellites, Logan, Utah, 2007.
[2] "EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification and Derating", NASA/TP-2003-212242, NASA Goddard Space Flight Center, May 2003.
[3] "Space Product Assurance : Derating – EEE components", ECSS-Q-30-11A, ESA-ESTEC, April 2006.
[4] Coss, J.R., et al, "Compendium of Single Event Failures in Power MOSFETs", Nuclear & Space Radiation Effects Conference, 1998.
[5] Ibid.