DEVELOPMENT AND QUALIFICATION OF THE INTERNATIONAL SPACE STATION CENTRIFUGE SLIP RING ASSEMBLY

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ABSTRACT/RESUME

The Slip Ring Assembly (SRA) for the International Space Station (ISS) Centrifuge has been successfully qualified by Mecanex SA and delivered for inclusion in the Centrifuge Accommodation Module of the International Space Station.

The SRA is used to transfer electrical power between the ISS and the Centrifuge Rotor and electrical signals between the Centrifuge Stator and the Centrifuge Rotor either at rest or in rotation up to 65 RPM.

This paper focuses on the development process and the qualification campaign of the SRA, with special attention given to the life test. Emphasis is given to the lessons learned and the experiences gained during the work from the point of view of its use in the habitable space environment of the ISS.

Lessons learned from the SRA development with the technology studies and the EM tests have provided valuable experience in the field of SRAs with high demands on life time.

1. INTRODUCTION

The Slip Ring Assembly (SRA), shown in Figure 1, is 297 mm in length; the main body is 163 mm in diameter – 264 mm in diameter including the mounting flanges - and weighs 12 kg in production form. Four (4) electrical connectors on each the stator and the rotor portions provide for transmission of redundant power (120 VDC at 25 ADC maximum), redundant safety grounds rated for 25 ADC, three (3) IEEE-802.3 Ethernet signals of 100 ohms characteristic impedance, six (6) MIL-STD-1553B signals of 75 ohms characteristic impedance, six (6) analogue EIA-170 NTSC video signals of 75 ohms characteristic impedance, and five (5) spare signals. All signal circuits are rated at +/- 15 V and 1 A and are twisted shielded wire pairs except for the spares.

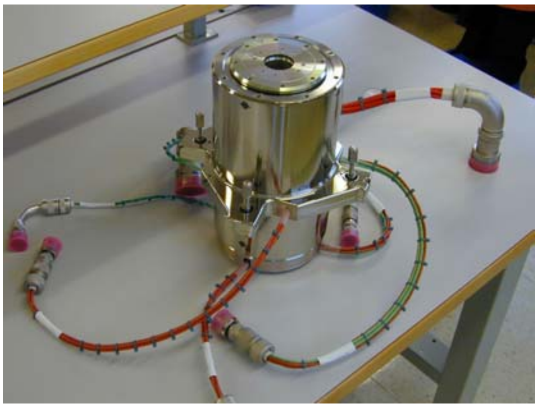

Figure 1 Slip Ring Assembly

The stationary part of this SRA – the stator - is the shaft with the contact rings. The rotating part – the rotor – is the housing with the sliding contact brushes encapsulated in a Nickel-plated casing.

The shaft stator contains 46 solid gold rings on a shaft of cruciform shape and is constrained in operation by provision on the stator of a slot to receive a slip-fit pin that is fixed to the customer's Centrifuge stator platform. The rings are wired individually to a series of four (4) electrical connectors that interface the customer's Centrifuge Stator.

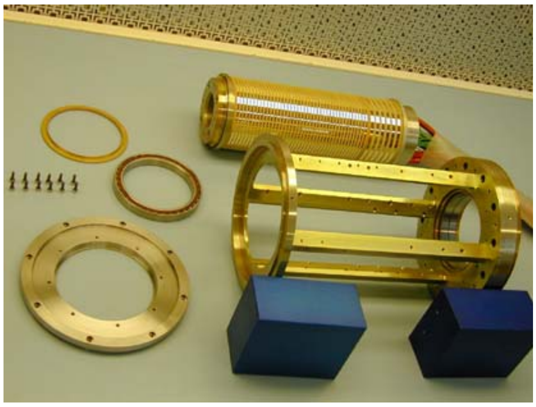

Figure 2 Rotor and stator assemblies

The rotor carries the sintered carbon-silver brushes that are redundant (80 total) for the signals circuits and dual-redundant (24 total) for the power and safety ground circuits. All brushes are mounted on conductive, cantilever leaf springs that provide the means to adjust the contact force at the brush/ring interface and provide an electrical path for the power and signals. The form factors of the brushes are distinct for power and signal use. The brush pairs/quads are wired individually to a series of four (4) electrical connectors that interface the customer's Centrifuge Rotor. The SRA rotor is attached to the Centrifuge Rotor using four (4) captive fasteners provided on the mounting flange of the SRA.

One double bearing with stiff preload at one end and a single bearing supported by a flexible membrane at the other end provides the structural rotational interface between the SRA stator and rotor.

The program philosophy included the development and production of one (1) Engineering Model (EM), one (1) Qualification Model (QM) and three (3) Flight Models (FMs).

The EM was used to verify by development tests the analytically predicted performance of the initial SRA design and to permit optimization of design parameters according to the development test results. The development test campaign on the EM included an accelerated life test.

The design revisions based on the development tests performed on the EM were implemented in the QM. Most notable were the changes in contact ring design from gold plated brass rings to solid gold rings, and the optimizations of the contact geometry and contact blade profile.

The QM was used to qualify the final design for use in the ISS. An accelerated life test was also performed on the QM.

2. FLIGHT CONSTRAINTS

The SRA is required to operate for up to 120 million revolutions at up to 65 RPM and a nominal speed of 45 RPM within the habitable area of the International Space Station (ISS).

Since the SRA is to be installed in the habitable area of the ISS, serious consideration was given to both gaseous contamination from material offgassing and particulate contamination from wear debris. The latter consideration was particularly scrutinized by the customer due to the use of the carbon-silver brushes and the fact that the SRA could not be sealed to provide 100% containment of brush wear dust: measurement of the debris that escaped the SRA during life testing was a verification requirement.

Consideration of astronaut physical safety was provided by the specification of minimum radii on all edges to which they may be exposed during normal operation and during maintenance operations. Implementation of this requirement was provided during the design phase by assuring that the proper edge radii were defined on all detail and final assembly engineering drawings.

3. DEVELOPMENT TESTING

The initial SRA design, in the form of the EM, started with the conception based on experience of existing non-space designs with similar functional requirements, backed up by sub-model breadboard model testing.

Early in the design cycle, the life design goal for the SRA of 120 million revolutions in combination with the power transmission requirements and the environment of the Centrifuge Rotor was known to stretch the capabilities of existing successful designs and applications.

To assess the adequacy of the proposed design and to reduce any potential risk, a development test program was initiated in March 2001. The test article, the EM, consisted of a full-size SRA of 46 rings (6 power rings with dual-redundant brushes and 40 signal rings with redundant brushes) and was operated with rated currents. Each ring consisted of a brass base material with gold over nickel plating. All brushes were sintered carbon-silver soldered to a conductive, cantilever leaf spring.

The EM life test was operated at an accelerated speed of 225 RPM (5 times nominal operating speed). The goal was to achieve 120 million revolutions without failure. There are effects of the high rotational speed of the SRA – especially since the contact brushes are in the rotating part of the SRA – that were analyzed, notably the increased heating due to the contact friction and the increased electrical dynamic resistance due to the higher sliding speed. The higher dynamic resistance can also lead to a more rapid degradation of the contact interface. Another factor affected by the higher rotational speed of an SRA where the contacts are mounted in the rotating part is that some of the contact force is lost due to the centrifugal force from the rotation. All these parameters were taken into account when choosing the rotational speed of the accelerated life test.

Approximately 50 million revolutions into the test the resistance noise (variation) of one of the power rings was observed to exceed the requirement of 3 mOhm RMS. The test was stopped and a failure investigation was initiated in cooperation with the customer.

Upon disassembly of the unit, one of the power rings (#4) was noted to be discolored relative to other rings.

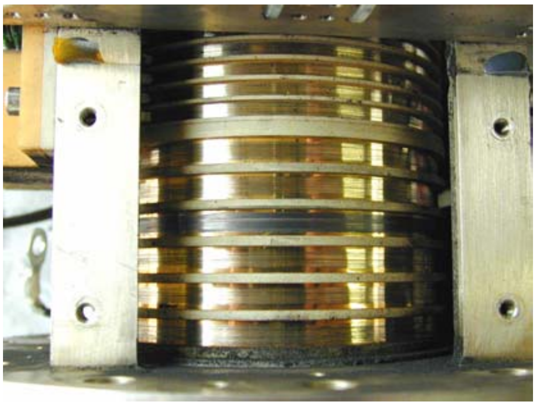

Figure 3 EM power ring #4

Further, one of the dual-redundant brushes on that ring showed high wear compared to other power brushes.

And, one of the dual-redundant brushes for ring #4 had experienced heat sufficient to melt the attachment solder which allowed it to be displaced from its normal position during rotation of the unit.

Complete disassembly proceeded to allow detailed measurements of the wear and contact force on all brushes. Except for the one brush described above, all measurements were within normal, expected boundaries.

Examination of the plated rings under chemical and Scanning Electron Microscope analyses revealed that the gold plating was wearing at a rate that could not sustain life of the rings through 120 million revolutions.

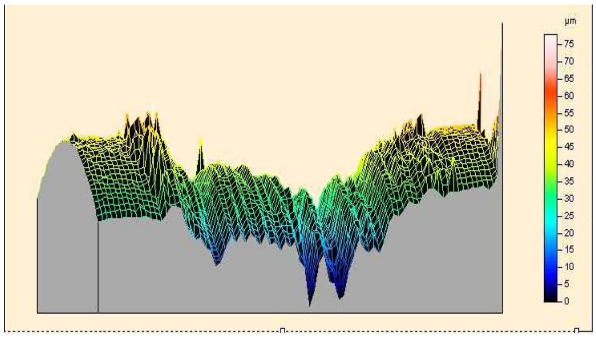

Figure 4 EM ring #4 gold plating profile

The failure analysis determined that an acceptable performance was maintained as long as the gold plating remained intact. Once holes in the gold plating began to appear (from excessive gold wear), momentary resistance fluctuations occurred when the underlying nickel made contact with the brush. This condition got progressively worse as the gold continued to wear which resulted in an increase in brush temperature as the resistance fluctuations persisted. Resistance fluctuations, increased temperature, and degraded brush/ring surface profiles unfavorably combined to create extreme brush/ring wear condition. The resistance fluctuations continued to worsen as the brush/ring surface profiles continue to degrade. Eventually, brush temperatures increased to a point sufficient to melt the solder that attached the brush to the conductive, cantilever leaf spring.

Based on the results of an additional smaller test unit, it was determined that a sufficient thickness of gold that would guarantee successful operation to the design goal of 120 million revolutions could not be applied by plating.

The SRA design was therefore revised to use solid gold rings to eliminate plating wear-through and the profile of the cantilever blade springs for the contact brushes as well as the contact brush geometry was altered to provide a more robust design that maintain a low current density at the brush/ring interface over the life of the contact.

4. QUALIFICATION TESTING

Mecanex performed a complete qualification program for the SRA, including:

- Static and dynamic resistance measurements
- Rotational torque measurements
- Insulation resistance
- Dielectric strength
- VSWR measurements

- Cross-talk measurements
- Electrical bonding measurements
- Current capacity test
- Over-speed test
- Vibration test (verified by full functional test)
- Thermal cycling test (10 days continuous monitoring of electrical continuity and periodical functional tests at high and low temperatures)

Due to the large size and mass of the SRA, the vibration testing was particularly difficult. The initial vibration support fixture had to be modified in order to support the high mechanical load, which could only be delivered by the vibration bench in the vertical direction. Due to the cable configuration of the SRA, the vibration fixture became complex, as shown in Figure 5.

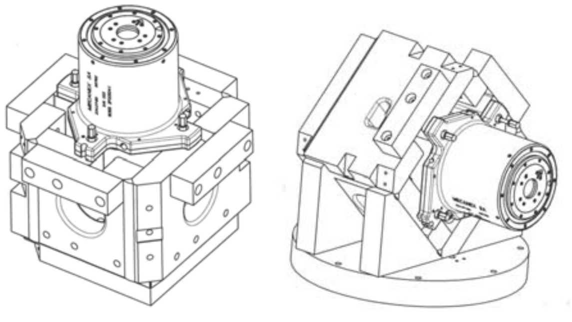

Figure 5 Vibration test fixture

During the qualification level vibration in the SRA axial direction, the fixation bolts between the SRA outer casing and the inner housing broke off. The failure analysis showed that the main cause of the failure was the bolts losing axial preload, thereby being subject to an unforeseen load case. The corrective action was to:

- Replace the fixations with larger diameter bolts, in order to be able to increase the axial preload.
- Applying a compressive force to the bolt joint by an external tool before applying prescribed torque to the bolts.
- Applying glue to the bolt thread (was previously only applied on the bolt head).

After the implementation of the corrective actions, the acceptance and qualification level vibration tests were successfully completed.

All other tests were performed with results well within the specified values, leading to a successful qualification of the SRA.

5. LIFE TESTING

Subsequent to the successful completion of the formal qualification test, the qualification unit was subjected to a life test.

The design goal for life was 120 million revolutions. Since the nominal rotation speed is 45 RPM, performance at nominal speed would take just over five (5) years to complete based on operating 24 hours per day and 7 days per week.

To allow completion in a reasonable time period and thus reduce costs, testing at an accelerated speed for fewer than the required number of revolutions was considered with the customer. An agreement was reached that the number of revolutions could be reduced dependent on the measurements of limited functional parameters continuously at an accelerated speed throughout the life test coupled with additional complete testing at the nominal rotation speed on a periodic basis. These measurements were to be used to analytically predict the end of life values on the key parameters.

It was known from the results of the development testing that operation at accelerated speeds would cause an increase in temperature at the brush/ring interface with an attendant artificial increase in brush wear. Since the brushes are contained on the rotating portion of the SRA, any acceleration in speed would also lessen the brush/ring contact force due to centrifugal forces. This can to some extent mitigate the increase in temperature from frictional force but would also affect the dynamic resistance of each brush/ring interface thereby increasing the dissipated heat from the electrical current.

Thus, a trade-off between the rotational speed (time of performance) vs. affects on realistic prediction of the life test results was required.

A rotation speed of 225 RPM, five (5) times the nominal operating speed, and a total life test of 60 million revolutions was agreed with the customer. Key parameters were measured continuously at the accelerated speed. At each 5 million revolutions the SRA was brought to nominal speed and complete test measurements were recorded for a total of 13 functional tests. The resulting measurements were analyzed to predict performance at the 120 million revolutions end of life and 240 million revolutions double life.

Measurements taken at accelerated speed consisted of verification of injected current, continuity of each circuit type, temperature of the rotor, stator and environment, and running torque.

Measurements taken at nominal speed for prediction purposes consisted of dynamic resistance, starting torque, and running torque. Circuit-to-circuit insulation resistance was also measured but was exempted from predictive analysis due to unknown dispersion of brush wear dust in earth gravity. Examination of the peak-to-peak running torque over a 15 second span allowed determination of the torque fluctuation (also known as torque noise).

Subsequent to the life test, the SRA was disassembled to assess contact wear for predictive analysis and to observe internal aspects.

The confidence gained in the SRA design based on the development testing results and the successful qualification program provided high expectations that the life testing would be completed without failure.

The only uncertainty was the effect that brush wear dust would have on the insulation resistance testing that was required at each 5 million revolutions. It has always been known and accepted by Mecanex and the customer that the micro-gravity conditions under which the SRA will operate on orbit could not be duplicated in either the qualification program or the life testing. The concern during the long duration life test was that adverse concentration of brush wear dust could cause a reduction in the insulation resistance between any circuits and produce an apparent failure. Under microgravity, it is expected that since the brushes are spinning the most likely dispersion of brush wear dust will be to the outer wall of the rotor away from the brush terminations and rings. This dispersion should not present an insulation resistance problem. During life testing under earth gravity, any spin orientation (vertical or horizontal) was going to produce brush wear dust dispersion that most likely would be on the rings which could disrupt the ring-to-ring insulation resistance. Because the testing in earth gravity was not representative of on-orbit operation and because the dispersion of brush wear dust could not be predicted, the insulation resistance was exempted from the predictive analysis. All other periodic functional parameters that are sensitive to wear were put through the predictive analysis.

5.1 225 RPM Continuous Test Results

A requirement of the SRA is that there be no micro-interruptions on any ring during rotation. This was verified by applying a 25 ADC current through all power rings connected in series and 1 ADC current through all signal rings connected in series. Both currents were continuously monitored during rotation at 225 RPM. Due to the close tolerance finish machining of the rings and the use of dual-redundant and redundant brush configurations, there were no micro-interruptions observed at any time. It was noted at approximately the half-way point of the life test that the monitored circuit continuity became less noisy in response to the brushes conforming better to the rings due to brush wear-in.

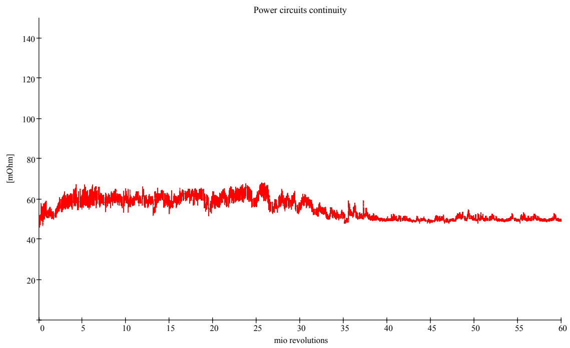

Figure 6 Life test resistance of all power circuits in series (25 ADC, 225 RPM)

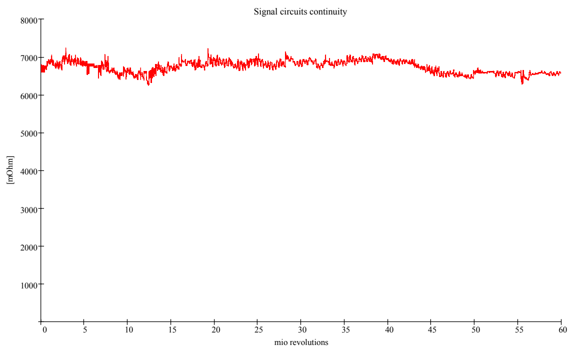

Figure 7 Life test resistance of all signal circuits in series (1 ADC, 225 RPM)

The positive effect of brush wear-in was also observed in a reduction of the resistance noise on the individual rings, as is expected given the reduction in circuit continuity noise.

A video demonstration was performed before and after the life test, in order to qualitatively show that there is no visible degradation to the signal transfer over the analogue EIA-170 NTSC video signal lines. A camera broadcast a signal that was captured by a video recorder. The signal was passed (1) directly from the camera to the recorder via a cable and (2) from the camera to the recorder with the signal passing twice through the SRA (stator to rotor and rotor to stator). There was no visible degradation in image quality neither before nor after the life test.

As was learned from the development testing, an increase in resistance variation will raise the temperature of the system. Conversely, a reduction in resistance variation should result in a reduction of system heating. This was borne out by the monitoring of the stator, brush block and ambient temperatures throughout the testing. When the internal temperatures were adjusted for variations in ambient temperature, the internal self-heating trended down.

As seen in Figure 8 the temperature difference falls down to zero at each point where the functional tests were performed, because the nominal current through the SRA is removed when performing the tests.

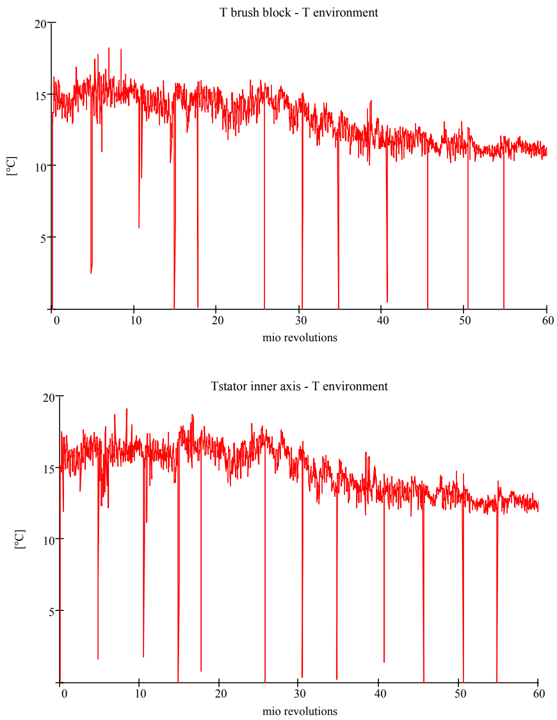

Figure 8 Life test internal temperature measured on brush block (top) and inner axis (bottom)

The positive effect of the total wear-in of the SRA (brushes, rings, and bearings) was also observed in the running torque that was monitored continuously at the 225 RPM test speed.

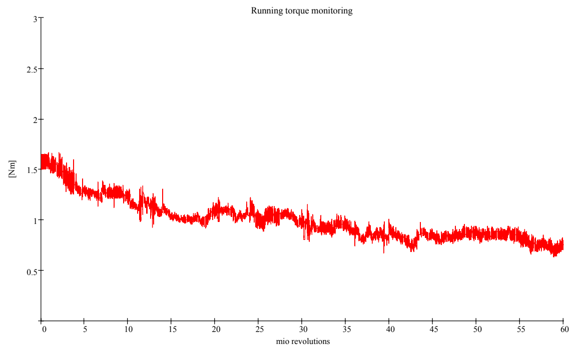

Figure 9 Life test running torque (225 RPM)

A lesson learned is that in the design phase a trade study should be made of the cost of forming the brushes to the contour of the rings in production versus the cost benefits of expected reduction in torque, faster brush/ring wear-in, and concurrent reduction in system self-heating.

5.2 45 RPM Periodic Test Predictions

Prediction of values at the end of 120 million and 240 million revolutions were made using a linear predictive approach for the wear-sensitive measurements made during the 13 periodic tests at the nominal operating speed of 45 RPM. Other curve fitting techniques were tried but did not yield sensible results.

As illustrated on Figure 10, Figure 11, Figure 12 and Figure 13, dynamic resistance, and starting/running torque are predicted to remain within the required values through the 240 million revolution double-life point.

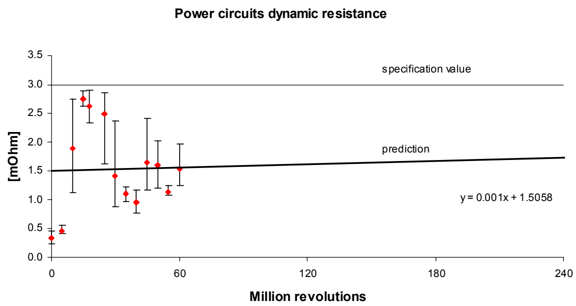

Figure 10 Life test power circuits dynamic resistance prediction

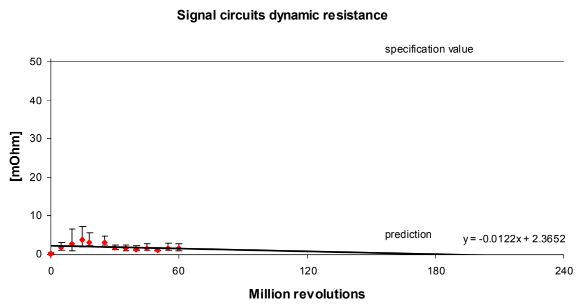

Figure 11 Life test signal circuits dynamic resistance prediction

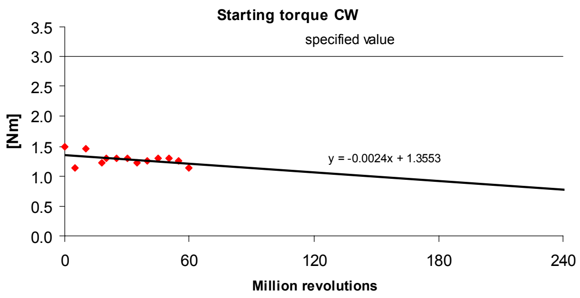

Figure 12 Life test starting torque prediction (CW shown, CCW is similar)

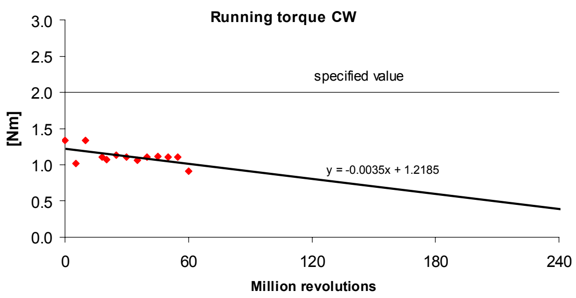

Figure 13 Life test running torque prediction (CW shown, CCW is similar)

Each of the redundant and dual-redundant brushes was measured for wear. The prediction of brush wear to be within that required for proper operation at 120 million and 240 million revolutions was based on an empirical equation based on the experience from many SRAs of similar design. The predicted contact height at 120 million and 240 million revolutions is shown in Table 1.

Table 1. Life test electrical contact wear prediction

	Power	Signal
0 rev. (initial)	0 %	0 %
$60 \cdot 10^6$ rev. (measured)	17.6 %	24.2 %
$120 \cdot 10^6$ rev (predicted).	33.6 %	45.1 %
$240 \cdot 10^6$ rev. (predicted)	44.5 %	75.8 %

The only parameter predicted to be within requirement at 120 million revolutions but beyond requirement at 240 million revolutions was the torque variation or torque noise.

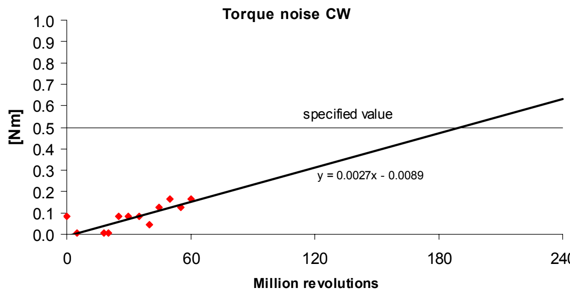

Figure 14 Life test torque variation prediction (CW shown, CCW is similar)

The torque variation requirement of less than or equal to 0.5 Nm to be measured as a peak-to-peak value assumed that the torque variation would be periodic in nature, related to the rotational speed of the SRA. A lesson learned is that this is not necessarily the case and that the larger excursions of instantaneous torque may be sporadic as opposed to periodic in nature. The system in which the SRA will be used is considerably less sensitive to variations in torque that are short in time than periodic variations related to the SRA rotational speed.

It was found after the completion of the life testing that a part of the measured torque noise is due to the wear of the torque noise measuring tooling. Unfortunately the evolution of torque noise in the tooling is not known, as it was not known at the beginning of the life test. This could indicate that the torque noise increase from the SRA is smaller than indicated in the above results. A better statement of measurement technique should be considered for future projects taking this effect into consideration.

6. CONCLUSION

The SRA for the ISS Centrifuge Rotor has been successfully qualified, and has been subject to a 60 million revolutions life test during six (6) months of continuous operation at rated currents without violating any specification requirement.

Based on the life test, forward extrapolation has been used to predict the performance parameters to 120 million revolutions. All performance parameters are predicted to remain within the requirement specification.

The SRA developed and qualified under this program is different in many ways from typical space SRAs. Some specific features are

- the particular configuration with the contact brushes in the rotating part of the SRA;
- the large size, due to the high number of complex circuits requiring special cabling with shielding terminations inside the unit;
- the high rotational speed and
- the very long running life.

The use of the SRA in a manned space environment expands further the requirements on the unit, adding for example requirements on environment contamination and astronaut safety. These requirements have permitted Mecanex to gain considerable experience in working with NASA specifications such as SSP, SSQ and NHB documents.

The successful program has shown the importance of allowing for development tests on a dedicated EM in development programs. The use of one or several EMs is a secure approach that leads to a better end product, while often giving cost and planning benefits compared to a program where development issues are detected during qualification testing of the unit. The development tests performed here were essential for the validation of the initial design and lead to improvements and optimizations of the final design that could not have been predicted analytically. The lessons learned from the development testing lead to the achievement of a design that was validated during the qualification test campaign, with tight control of both delay and cost.