1 ABSTRACT

The increasing complexity and sensitivity of rotational on board equipment (such as antennas, pointing mechanisms and oscillating actuators) requires a miniaturized electrical signal and power transfer mechanism showing not only very low electrical noise and resistance but often also constant torque over the whole rotation.

A Slip Ring Assembly (SRA) is the most suitable system for applications with such demands. The large potential to optimize the ratio of size to electrical power in a SRA is a considerable advantage compared to a traditional limited angle flexible cable connection devices like a cable wrap, even in limited angle oscillating systems.

A series of miniaturized SRA’s have been developed in order to comply with the new technical requirements of such applications. Verification and optimization of the important tribological system providing the sliding electrical contact has been performed in order to guarantee good electrical and mechanical performance over a spinning and/or oscillating life time. Studies and tests have been performed to assure conformance to high level vibration and shock requirements while minimizing the SRA size and mass.

A preliminary life test has been performed on a breadboard SRA by Centre National d’Etudes Spatiales (CNES), demonstrating the suitability of the chosen technologies in the miniaturized SRA [1]. The latest evolution of the design has recently been extensively tested to confirm its aptness to the foreseen technical requirements for a miniaturized SRA.

2 INTRODUCTION

Miniaturized SRA’s used in rotational equipment often have to withstand a large number (several millions) of rotational cycles. These cycles can be continuous rotation cycles or cycles of alternate rotation direction with well defined or quasi random angular amplitude.

The principal advantage of using SRA’s in oscillating on board equipment is the size reduction compared to a limited angle rotary joint. SRA’s can be produced in smaller sizes than the cable wrap mechanisms generally used for limited angle applications. Moreover, SRA’s offer a torque of only very limited variation over the whole angular movement, properties difficult to reach with most cable wrap mechanisms.

Previous studies performed on space application SRA’s were almost exclusively dedicated to applications with nearly unidirectional rotational movement, generally with very low rotational rates such as in SRA’s for Solar Array Drive Mechanisms (SADM).

Based on Mecanex’ long experience in SADM SRA’s [2], a new generation of SRA’s dedicated to the integration in rotative on board equipment for power and signal transfer purposes has been developed. The angular speed of these oscillating SRA’s has been estimated to be typically up to 30 rpm with a required life time of up to several million revolutions.

The development described in this paper takes into account the wide range of working temperatures and constraining mechanical environment during the launch and in orbit phases. The aim of the developed products is to be compatible with diverse on board equipment such as antennas, pointing mechanisms and oscillating actuators.

Careful component selection and optimization of the design for manufacturing and assembly of the final product has been included in the later stages of the
development. This has allowed for a cost and time efficient design that also minimizes the production risk.

3 DEVELOPMENT STRATEGY

The development of this new mechanism is based on the SCARAB SRA technology which is both extensively tested [3] and has flight heritage. This technology has shown good behavior during long life and has been an excellent basis for further development.

The design optimizations performed on the SCARAB SRA [3] were taken into account on the new product. The heritage of the SCARAB contact sizing and the increased height of insulating barriers were retained on this product.

The knowledge acquired on the SCARAB technology is however not sufficient to guarantee the conformity of the technology with respect to the new requirements involved by the SRA implementation in oscillating on board equipment. Two design elements requiring optimization or verification have been determined:

- The miniaturized bearing configuration required optimization to sustain more severe mechanical environments at launch.
- Electrical contacts behavior under oscillations instead of continuous rotation had to be tested in order to verify its compliance with long life time requirement.

The optimization and verification performed on the bearing configuration and on the electrical contact system made in the frame of this study are presented below.

4 BEARING CONFIGURATION

Different bearing configurations have been studied in order to have a product that can be adapted to various levels of environmental requirements, and depending on the functional requirement of the on board equipment.

The aim of this part of the study is to design a bearing configuration that while keeping the small size of the SRA can withstand use over a wide temperature range and is able to withstand the severe mechanical environment at launch without failure. Moreover, the bearing configuration shall guarantee that the relative movements between stator and rotor parts remain within tolerable limits so that a good electrical contact can be assured.

4.1 BEARING CONFIGURATION TRADE OFF

4.1.1 Two single ball bearings preloaded by elastic washers

![Figure 1: Two single ball bearings preloaded by elastic washers.](image)

The ball bearings configuration shown on Figure 1 consists of two identical ball bearings located at the shaft extremities. This configuration is identical to the configuration of the SCARAB SRA [3]. The bearing preload is given by elastic washers and it can be easily adapted to the rotor mass to withstand the mechanical environment.

The elastic preload of the configuration allows it to work well over a wide range of temperatures without creating too high stresses in the rotor and stator structures. One of the main advantages of this configuration is however its small size, a SRA with this bearing configuration is very competitive with respect to power to volume ratio.

This bearing configuration is a good solution for most on board equipment, but its behavior under very high level mechanical environment can be limiting.

4.1.2 One double ball bearing with stiff preload and cantilever axis

![Figure 2: One double ball bearing with stiff preload and cantilever axis.](image)
The ball bearings configuration shown on the Figure 2 consists of a rigidly preloaded ball bearings pair, mounted at one extremity of the rotor. The rotor works then as a cantilever. A displacement limitation ring is mounted at the other rotor extremity. This ring is normally not in contact with the rotor, it only serves as a security device to prevent the rotor to deflect so far under mechanical load as to risk that it fails in bending.

This bearing configuration is extensively used in big sized SRA for space application but there is little experience on this scale of mechanisms.

For this configuration, the rotor diameter has to be increased in order to provide more structural strength to withstand the bending moments in the rotor under mechanical load. SRA's with this bearing configuration therefore tends to be slightly larger than the configuration presented in 4.1.1.

However this configuration shows very good behaviour over a wide temperature range and good performance under mechanical environment, depending on the dimensioning of the rotor.

4.1.3 Two single bearings preloaded by a membrane

The common analytical solutions presented in [4] are therefore not applicable, more advanced analytical methods or empirical methods are needed to determine the membrane characteristics. The membrane behavior is also affected by the thermal dilatation of the membrane itself as well as the axial and radial differential thermal expansion of the surrounding structure. The effect is a behavior that is difficult to predict analytically.

The use of a miniature membrane requires extensive testing in order to evaluate the membrane behavior in the mechanism, including mechanical and thermal environments. The description and the results of the performed tests are presented in 4.2.

This ball bearing configuration has the advantage of not being dependent on a sliding interface for its preload function; it therefore does not have any risk of jamming under thermal or mechanical load. When properly dimensioned, it shows very good performance under both thermal and mechanical loads, although there is a risk of damaging the membrane or losing some of the preload if the loads are high.

4.1.4 One double ball bearing with stiff preload and one single ball bearing preloaded by a membrane

The configuration shown in Figure 4 is inspired by the configuration shown in Figure 3, they are very similar. A double ball bearing is used at the opposite side of the membrane, in order to provide a secure anchoring. The single ball bearing of the membrane limits the bending moment on the rotor and the membrane allows for differential thermal dilatation. The stress in the membrane is much lower than for the configuration presented in 4.1.3, as the axial mechanical load is taken by the double bearing with stiff preload. This configuration is therefore able to withstand considerably higher levels of vibrations and shocks without any risk of loss of bearing preload.

R = d/e = 0.76 > 0.5
due to membrane deformation. It does however imply a slightly longer SRA.

The design of the membrane is similar to the one described in the previous configuration and its behavior under thermal load has to be tested. The tests and their results are presented in 4.2.

This configuration is extensively used on big size SRA’s for SADM application. This configuration is a good solution for high mechanical loads and it minimizes the risks involved with a mechanically loaded membrane, but has the disadvantage of a larger size and of a rotational torque that is slightly higher than the configurations with only two bearings.

4.2 TEST ON THE MEMBRANE

The difficulty in analytically characterizing the membrane implemented in the SRA has called for a test campaign in order to determine the membrane behavior under thermal and mechanical environment.

4.2.1 Initial characterization

The membrane behavior has been established by measuring the axial displacement under an axial load, this gives a stiffness curve, see Figure 5. This permits to find the initial working point for the bearing preload that is sufficiently high to guarantee that there is never a loss of preload and not so high as to risk that the membrane is plastically deformed.

4.2.2 Thermal characterization

These tests are performed to check that the membrane is not overstressed under thermal load. If there is a thermal overstress the membrane will have lost some or its entire preload after the thermal cycle. The results of these tests are independent of the bearing configuration at the opposite of the membrane.

4.2.2.1 Test set-up

The membrane has been mounted in the SRA structure with the nominal preload determined from analysis of the results in the initial characterization of the membrane in 4.2.1.

![Figure 5: Initial characterization of the membrane.](image)

![Figure 6: Membrane mounted in the SRA structure.](image)

The test was performed in a thermal chamber using the worst case temperatures defined for the SRA. The SRA is mounted in a test jig allowing continuous monitoring of the SRA rotational torque. The rotational torque is related to the bearing preload but the torque measurement was made for information and was not used as a criterion to evaluate the membrane performance. The thermal cycles performed are shown in Figure 7.

![Figure 7: Thermal cycles.](image)

4.2.2.2 Test Results

At the end of the thermal cycling, the SRA was dismounted from the jig, and the preload was measured.
No loss of preload was observed. Thus the thermal stresses did not induce permanent deformation in the membrane.

A second test was performed with an initial preload 25% higher than nominal in order to show margin to the plastic deformation of the membrane. The results were identical, no preload was lost.

The torque during the thermal cycling was constant during the whole test.

4.2.3 Characterization under mechanical load

Complete vibration and shock tests were used to verify the membrane performance under mechanical load. The tested SRA was of the configuration presented in 4.1.3.

In this configuration, the membrane takes a very large part of the axial mechanical load. Based on preliminary tests and analysis, shock loads have been determined to be more severe than vibration loads.

4.2.3.1 Test Set up

Before the test, the membrane was instrumented by means of strain gages on the membrane (see Figure 8).

Strain gages were located as near as possible to the external diameter of the active part. Two full bridge gages systems were implemented at 90°.

![Figure 8: Strain gage integration on the membrane.](image)

Shock tests at different level have been performed.

4.2.3.2 Test Results

The records of the deformation indicated by the gages show that the membrane plastification threshold has been reached. The preload measurement performed after this shock test confirms the observation that the membrane had been subject to plastic deformation, as some of the initial preload of the bearing system had been lost.

It is thus shown that the membrane is more sensitive to shock loading than foreseen. Permanent deformation of the membrane leading to a loss of preload can occur at limited shocks levels.

4.2.4 Membrane characterization conclusion

The characterization of the membrane under thermal load shows a good behavior over the tested temperature range. The stresses induced in the membrane by the thermal load did not produce any degradation. The sizing of the membrane is thus adequate, with respect to the thermal load.

The shock test performed on the instrumented membrane shows that the stresses induced in the membrane under shock loads are difficult to estimate by analysis, the sensitivity of the membrane to shock loads in the axial direction is high and permanent degradation can be observed even with relatively low shock levels. In systems with high mechanical load it is recommended to implement another system to take the axial loads induced under shock loading.

In order to provide a more robust design for high shock loads, a double ball bearing with stiff preload has been introduced. The design shown in Figure 4; removes the mechanical loads from the membrane while maintaining the excellent performance of the membrane under thermal load.

The implementation of a ball bearing with stiff preload is recommended for models subject to high mechanical loads.

5 CONTACT SYSTEM PERFORMANCES

The contact system performance for a continuous rotation system has already been proven by the tests on the SCARAB SRA [3]. Additionally, different tests have been performed to characterize the contact system performances under oscillating conditions and under different environmental conditions. Two different tests have been carried out in parallel:

- Thermal cycling test performed on a breadboard SRA by Mecanex SA, under dry nitrogen.
- Tests performed on a breadboard SRA by CNES under vacuum at ambient temperature.
5.1 THERMAL CYCLING TESTS

5.1.1 Tests Set-Up Description

A dedicated SRA rotor breadboard was manufactured and assembled in a test housing in order to verify the behavior of the track - brush system submitted to oscillations and thermal cycling. The lines of the test breadboard were connected in series and the voltage drop was recorded during the full test. A current of 0.1 A was supplied to the test breadboard. The maximum rotation rate achieved during the oscillations was 60 rpm.

The test was performed in a thermal chamber, in a dry nitrogen atmosphere, as shown in Figure 9 and Figure 10.

![Figure 9: Thermal test chamber with measuring set-up.](image)

![Figure 10: Dry nitrogen environment in the test chamber.](image)

The performed thermal cycle is presented in Figure 11.

![Figure 11: Temperature variation of one thermal cycle.](image)

A test bench was manufactured in order to provide the oscillatory rotation of the breadboard rotor. A view of the test bench is presented on Figure 12. The motor is controlled through temporized relays in order to provide an oscillatory rotation. The oscillatory rotation is of about 240°. The angular reference is however rotating randomly because of the uncertainty on the relay switching delay. Thus brushes slid on the whole circumference of the tracks during the life test.

![Figure 12: Mecanex thermal test equipment.](image)

Various parameters of the test breadboard were recorded during the full testing or at periodic intervals, like voltage drop, insulation resistance and drag torque.

The recorded voltage drop, normalized with respect to the highest value, is shown on Figure 13 for the first 120 hours. The variation of the voltage drop with respect to the temperature can clearly be seen on the graph. The periodic variations of the voltage drop are indeed correlated to the thermal cycles. The peaks and other local variations of the voltage drop are related to the thermal regulation of the test chamber (temperature over shots) and to other tests performed on the breadboard during the thermal cycling. The voltage drop remains very stable during the full life test, except the variation due to the temperature. There is no noticeable increase or decrease of the voltage
drop, at a given temperature, between Beginning Of Life (BOL) and End Of Life (EOL), after 500 hours oscillatory rotations, approx. 2 million cycles.

![Figure 13: Normalised voltage drop on multiple tracks measured during the thermal cycling test.](image)

The other parameters of the test breadboard (like insulation, drag torque) remain always in the specified range.

5.1.2 Tests conclusion

The measurements of electrical performances performed during the thermal cycling test have shown the relevance of the selected brush - track system for the use in an oscillatory rotation SRA. The relevance of this choice under vacuum conditions has also been demonstrated by the test described in paragraph 5.2.

5.2 BREADBOARD SRA VACUUM TEST

5.2.1 Test Set-Up description

The test has been performed by CNES on a SRA breadboard model including 27 tracks (8 power tracks, 18 signal tracks and 1 ground). This breadboard model was an early version of the SCARAB SRA, adapted to vacuum use by the use of compatible ball bearings.

The test was performed in a vacuum chamber at 10^-7 Torr at ambient temperature.

The SRA shaft was fixed to a stationary torque sensor and the SRA part holding the contact brushes was driven by a stepper motor as shown in Figure 14.

![Figure 14: Test mounting configuration](image)

The SRA was driven with oscillations in both directions with random amplitudes between -200° and 200°. One cycle represents a movement 0° to +α° to –α° to 0°, with α being a random angle up to 200°.

The SRA performed more than 2.7 million cycles.

A data acquisition system was used to automatically record SRA torque and electrical parameters (insulation resistance and series line resistance).

The insulation resistance was measured between adjacent circuits. A voltage difference of 100V was applied between the adjacent circuits as shown in Figure 15. The leakage current was continuously recorded during the lifetime testing.

![Figure 15: Insulation Resistance Evolution control](image)

The series line resistance was recorded using groups of SRA lines (8 lines) connected in series with a resistance. The circuit is powered by a voltage source of 2 V. The current running through the circuit was approx. 400mA. The total circuit resistance was calculated from the voltage drop over the resistance.
5.2.2 Tests Results

5.2.2.1 Driving Torque Evolution

The driving torque was recorded at an interval of 20 cycles. At the beginning of the test, an increase of the driving torque was observed (run-in effect), as shown in Figure 17. After this initial run-in, the recorded torque decreased slightly and remained stable during the entire test duration.

5.2.2.2 Insulation Resistance

The measurements of the insulation resistance were made with the electrical connection shown in Figure 15. The insulation resistance remained high and stable during the whole test.

5.2.2.3 Series Line Resistance

The measurements of the series line resistance were made with the electrical connection shown in Figure 16. The evolution of the series line resistance was inferior to 2% during the whole test.

5.2.3 Test conclusion

The measured torque and electrical parameters show very good and stable results over the entire test duration of more than 2.7 million oscillating cycles.

6 CONCLUSION

The new generation of miniaturized SRA developed by Mecanex SA has shown its suitability for the use in high speed, oscillating long life space equipment. The optimization of the configuration and material permits to achieve high quality electrical transfer during a very long life time, on a miniaturized unit able to withstand very high external load levels during launch phase.

A representative breadboard model was successfully tested under vacuum with alternative random oscillations of the rotor, showing a very good behavior during the whole life time testing. 2.7 millions random oscillations were performed during the life test under vacuum. Alternative oscillations were also applied on a breadboard model in a thermal environment, to verify that no contact degradation could occur related to temperature variations.

Different mechanical configurations were investigated with the aim to comply with high external mechanical load levels. A trade off of these different configurations was performed in order to optimize the size with respect to the mechanical load environment. The SRA’s developed by Mecanex SA in the frame of the present study are good candidates to replace cable wrap system in oscillating mechanisms. The main advantages of the SRA are compared to cable wraps are their very small size, a constant torque on the whole circumference and no angular limitation.

The designs presented in the present paper can easily be adapted to customer requirements, with respect to the size, the lines number and the mechanical environment.

7 REFERENCES