RISK MITIGATION TESTING
WITH THE BEPI COLOMBO MPO SADA

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ABSTRACT

A Solar Array (SA) Drive Assembly (SADA) for the BepiColombo mission is being developed and qualified at RUAG Space Zürich (RSSZ). The system is consisting of the Solar Array Drive Mechanism (SADM) and the Solar Array Drive Electronics (SADE) which is subcontracted to RUAG Space Austria (RSA).
This paper deals with the risk mitigation activities and the lesson learnt from this development. In specific following topics substantiated by bread board (BB) test results will be addressed in detail:
Slipring Bread Board Test: Verification of lifetime and electrical performance of carbon brush technology
Potentiometer BB Tests: Focus on lifetime verification (> 650000 revolution) and accuracy requirement
SADM EM BB Test: Subcomponent (front-bearing and gearbox) characterization; complete test campaign equivalent to QM test.
EM SADM/ SADE Combined Test: Verification of combined performance (accuracy, torque margin) and micro-vibration testing of SADA system
SADE Bread Board Test: Parameter optimization; Test campaign equivalent to QM test

The main improvements identified in frame of BB testing and already implemented in the SADM EM/QM and SADE EQM are:

- Improved preload device for gearbox
- Improved motor ball-bearing assembly
- Position sensor improvements
- Calibration process for potentiometer
- SADE motor controller optimization to achieve required running smoothness
- Overall improvement of test equipment

1. INTRODUCTION

1.1. Mission Description

The BepiColombo mission is an interdisciplinary mission to Mercury in collaboration between ESA and ISAS (Institute of Space and Astronautical Science)/JAXA (Japan Space Exploration Agency) under overall responsibility of ESA. The BepiColombo mission consists of two scientific orbiters, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO) which are dedicated to the study of the planet of Mercury and of its magnetosphere. The Mercury Transfer Module (MTM) is used to carry the two orbiters to Mercury.
To generate the required electrical power for the BepiColombo MPO module it is equipped with a single wing solar array (SA).
The wing orientation is achieved through a Solar Array Driving Assembly (SADA) composed of the Solar Array Driving Mechanism (SADM), its driving electronic (SADE) and the interconnecting harness.
Mission parameters / deviations from standard (e.g. Geostationary) boundary conditions are:

- 6 years interplanetary journey, (MPO SA already deployed)
- MTM/MPO separation close to Mercury (shock with operating, deployed SA)
- 1 year nominal and 1 year extended orbiting mercury for scientific data acquisition; solar radiation 10 times higher than close to earth; typical orbital period 2.3h.
- High position accuracy for SA already directly after power on. (0.2°)
- Fast mode (6°/s) to rotate SA away from thermal critical orientation

1.2. Design Drivers

In the following the requirements where the MPO SADA deviates considerably from a “standard” (typically geostationary) applications are identified.
Thermal Environment: The vicinity to the sun and additional high surface temperature of the Mercury cause SA I/F temperatures up to 170°C (initial design target 210°C) and S/C I/F temperatures up to 85°C. At long interplanetary journey nevertheless the temperatures can be quite low (SA I/F -80°C). Due to the seen high risk, acceptance and qualification margins are extended for the mechanisms to $\Delta T = \pm 10°C$ instead of usual $\Delta T = \pm 5°C$.

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SA / Sun inclination accuracy: In typical application it is tried to hold the SA normal to solar direction to maximize the gained energy. For BepiColombo the SA is inclined in a flat angle to the sun to have a comparable large backside area radiating to deep space and so contributing to cooling the SA. As consequence a small inclination variation has a dramatic impact on the SA temperature. Thus the SA position has to be known at any time (also immediately after powering) very accurately → position accuracy 0.2°.

SA overheat protection: In the so called Fast Mode the SA can be rotated with a speed of 6°/s (roughly 100 times faster than a typical operational speed of a SA) out of an orientation harmful to the SA. This speed is reached within 0.5s which causes remarkable resistive inertial torques coming from accelerating the SA superposed by dynamic effects from overall SA flexibility.

Microvibration/Disturbance Torques: The MPO carries sensitive instruments that should not be disturbed by vibrational loads emitted from the SADM. These needs are reflected on one hand by a given disturbance torque spectrum limiting the emitted torque as a function of frequency and on the other hand a running smoothness requirement defining a maximum allowed deviation from a given commanded profile (deviation < 5arcsec within 0.5sec).

1.3. SADA Design Description

The SADA consists of the Solar Array drive mechanism to orient the SA wing and to provide power and signal transfer to the spacecraft. Separated from the mechanism, the Solar Array Drive Electronics is required to command and control the mechanism and the interfaces to Power and Data handling subsystems.

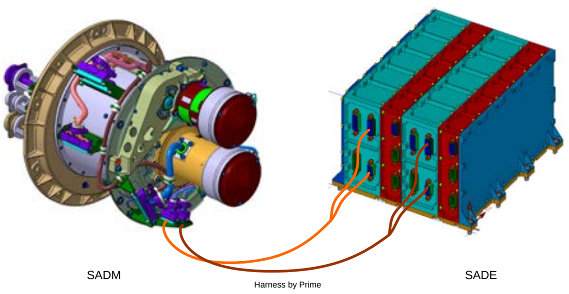

Figure 1. SADA Design Overview.

1.4. Overall SADM Design Features

The overall SADM design, as shown on the figure below, compromises the following main components:

- Slip Ring Assembly (SRA), composed of a power and signal slip ring
- Front Bearing Assembly (FBA)
- Position Sensors (coarse and fine potentiometer)
- Gear Assembly using spur gears
- Customized Hybrid Stepper Motor

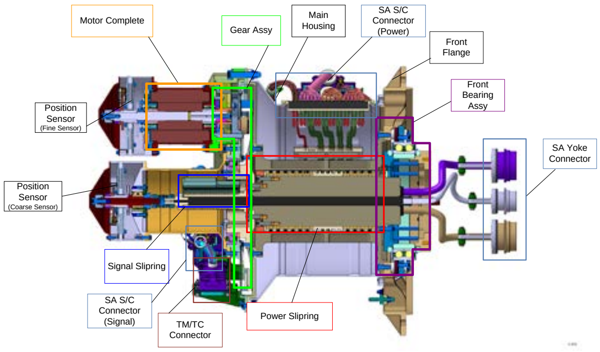

Figure 2. SADA Design Overview.

A detailed description of the SADM design can be found in [1].

2. Risk Mitigation Testing Approach

2.1. SADM

Slipring Bread Board Test: Relatively unique for the European Space Industry, carbon brush technology was selected for the power slipring over wire brushes due to its better suitability to high temperatures. As the signal slipring is located in a significantly colder section of the mechanism, wire brush technology could be kept for the signal transfer. The performance of carbon and wirebrush technology was mechanically, electrically and life tested at breadboard level. It was demonstrated that the assembly is compliant to the BepiColombo needs.

Potentiometer Tests Bread Board: As specific mission requirement (SA overheat protection), the MPO SADM has to provide the SA position with a high accuracy of 0.2 degrees at any time. For the SADM , a fine /coarse potentiometer solution was selected due to the very demanding thermal and radiation environment close to Mercury. The solution was iteratively improved by 3 dedicated potentiometer breadboard tests and on the SADM EM. Fine tuning was needed to achieve the required number of revolutions.

SADM EM: By building up subassembly by subassembly a SADM EM identical to the QM/FM (with the exception of the slipring), it was possible to identify design and manufacturing weaknesses before QM/FM testing. All loading (static and vibration) and thermal tests foreseen for QM testing were done with this EM. A full life test was performed with the EM as well.

The main steps for the subassembly characterization and testing at qualification level were:

a.) The Front bearing assembly was TV tested to determine the resistive torques under various thermal conditions.

b.) Main Housing; slip-ring dummy and gear assembly was assembled together and first, by a blocked motor shaft, the stiffness of the gearbox was characterized and then, by an auxiliary actuator with torque sensors between actuator and gearbox, the gearbox is characterized at various torques and various TV conditions

c.) The SADM EM was finally assembled and a complete QM test campaign (with exception of the slipring related electrical tests) was done.

d.) The SADM EM was in addition used for combined SADM/SADE BB tests (function and microvibration).

e.) SADM EM was used in frame of the EMC qualification of the SADE.

In the following the EM tests starting from the complete assembled EM are presented below in more detail. Due to encountered non-conformances, the flow evolved during test campaign and got with the time much more complex.

2.2. SADE

The SADE BB is identical to the EQM/PFM SADE models with the following exceptions:

- not redundant
- no special radiative surface treatment applied (no thermal tests were performed)
- commercial and MIL-grade parts instead of space-qualified components

The SADE BB test focus lies on the verification of the electrical function and performance under ambient conditions and the support of the combined SADM / SADE BB testing.

Figure 3. SADE-BB S/N01

3. SLIPRING BB TEST/ FINDINGS

The slipring BB3 test confirmed the expected behaviour as reported in [1].

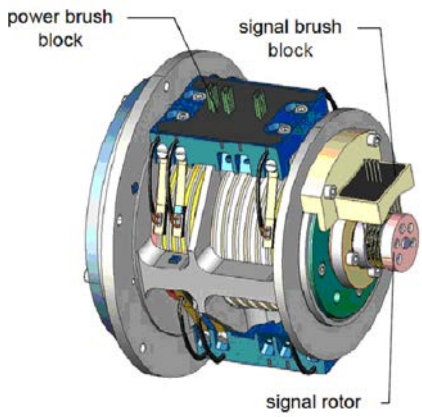

Figure 4. Slip Ring Breadboard.

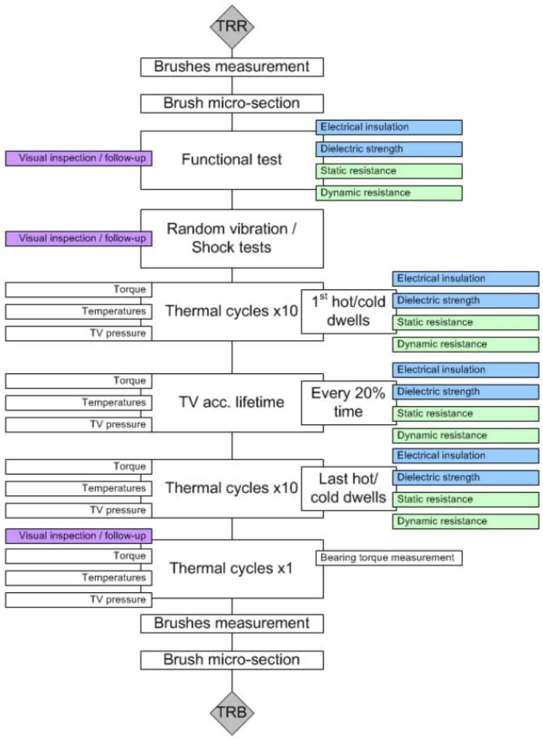

Figure 5. Slipring BB Test Sequence .

Although the slipring BB tests were successful some minor improvements resulted for QM and FM manufacturing and testing for example a run-in sequence will be included for the QM and FM. The QM and FM sliprings have been successfully manufactured and tested on component level and delivered for integration in the QM/FM SADM.

4. POSITION SENSOR (BB4) TEST / FINDINGS

In order to mitigate the risk of a lifetime failure at a very early phase of the project, the potentiometer has been breadboard tested. The component has been subjected to the following tests:

- Potentiometer characterization, including accuracy/linearity measurement under different environments and speeds

- TV-Cycling
- Lifetest under hot and cold condition in vacuum representative to the BepiColombo sequence (more than 650000 rev)

The test was performed on the test rig shown on the figure below.

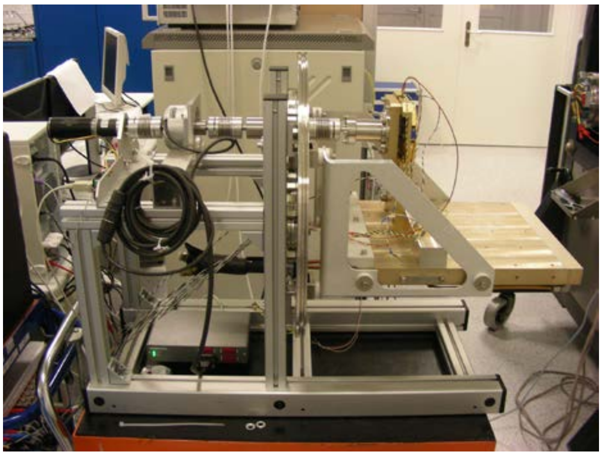

Figure 6. Potentiometer Test Set-up.

The potentiometer discs are mounted on a hot/cold plate. The potentiometer disc is stationary and the crabber assembly rotates. Additional heaters are attached to hot/cold plate to achieve the relatively high temperatures required for BepiColombo.
The crabber assembly is mounted on the driving shaft and was driven by a standard brushless DC-motor. As the motor operated outside, the necessary transmission between the crabber assembly and the motor was done via a feed-through in the vacuum chamber. A 28 bit optical encoder was fitted between the motor and the crabber assembly to compare the potentiometer output signals against the actual position.

The breadboard tests were performed under TV conditions with the main focus to achieve the lifetime requirement of the fine position sensor. The majority of the life test was carried out at a temperature of +108°C. The tests were run under the maximum possible speed of the mechanism (6°/s on the SA shaft which is equivalent to 0.8 rpm at motor level). The motor reversed direction every 50000 revolutions When changing the direction, characterization tests with slower speed and higher acquisition rate were performed. In total, ~650000 revolution were performed at hot whereas about 200’000 revs were performed under cold condition.
After having completed about 200’000 revolutions, noise appeared on the hemispheric track. In the subsequent characterization test with the initial setup at slow speed, the noise disappeared. However, it built up again within the first 10000 revolutions (at fast speed) of the 50000 revolution test sequence and remained than stable.
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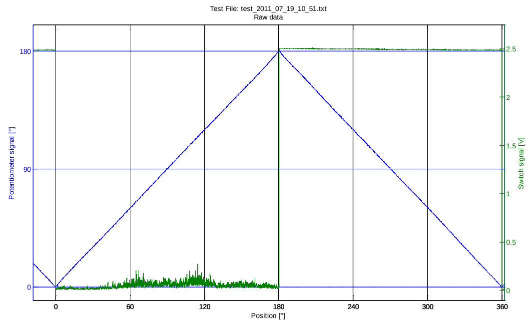

Figure 7. Position sensor Signal after 160000rev

As the speed was reduced again for the next characterization test (after another 50’000 revs), the noise vanished rapidly. The hypothesis that debris were accumulated and removed by reversing direction could not be verified. This behavior repeated throughout the entire lifetest. After completion of about 650’000 revolutions, when temperature was set to cold condition, the noise vanished as well. Thermal deformation analysis of the setup however gave no indication for relevant thermal deformations causing slider load variations and thus a change of the noise level.
Finding: after 870000 revolution, the potentiometer track worked for the complete lifetime in slow mode (normal operation) fine; the hemispheric track showed in hot and longer unidirectional operation, a build-up of noise that rapidly vanishes if speed was switched to slow mode.

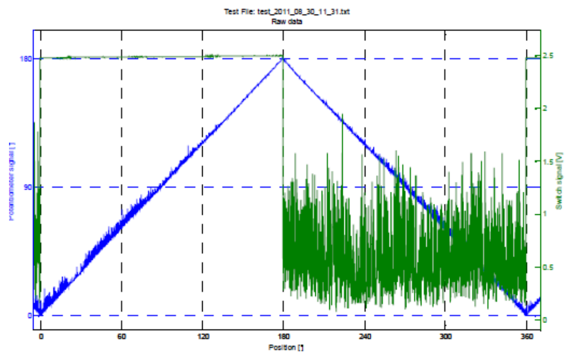

Figure 8. Position sensor Signal after 866715

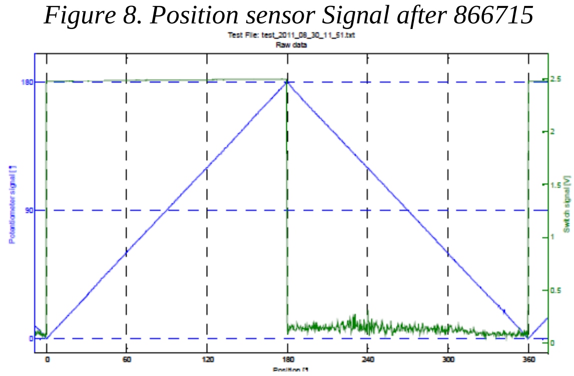

Figure 9. Position sensor Signal after 866745

From the first breadboard test, it was found that the position sensor needs to be improved but is close to fulfill its operational needs.

The test was then repeated with an improved position sensor (wet lubrication was added). It completed the required 800000 revolutions without problems.
The deviation of the potentiometer begin of life (BOL) to end of life (EOL) is < 1° which will give in the application with coarse /fine potentiometer an overall error contribution of 0.02°. Note, the deviation from the linearity itself is compensated by a lookup table in the SADE.

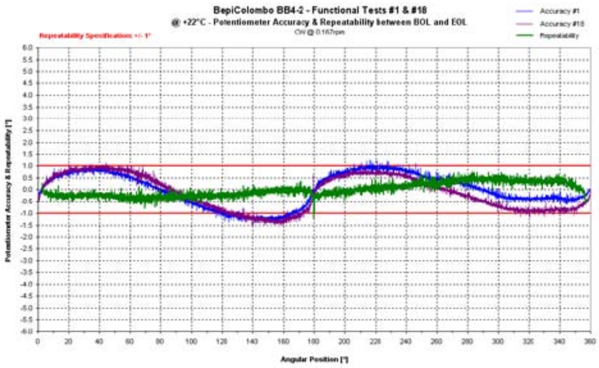

Figure 10. Deviation from Linearity BOL/EOL

Based on the positive results, the last test was declared successful and the position sensor ready to be implemented into SADM EM (and QM/FM).

5. SADM EM TEST / FINDINGS

5.1. BB Test activities with SADE EM

The following section gives a detailed overview of the test activities performed on the SADE EM including the delta tests after design improvements as a result of the encountered non-conformances. Note that in the figure below only the main blocks are presented. In addition to the test shown after each main block, functional verification test were done including continuity and isolation test; motor margin verification and concentricity and coning angle tests.

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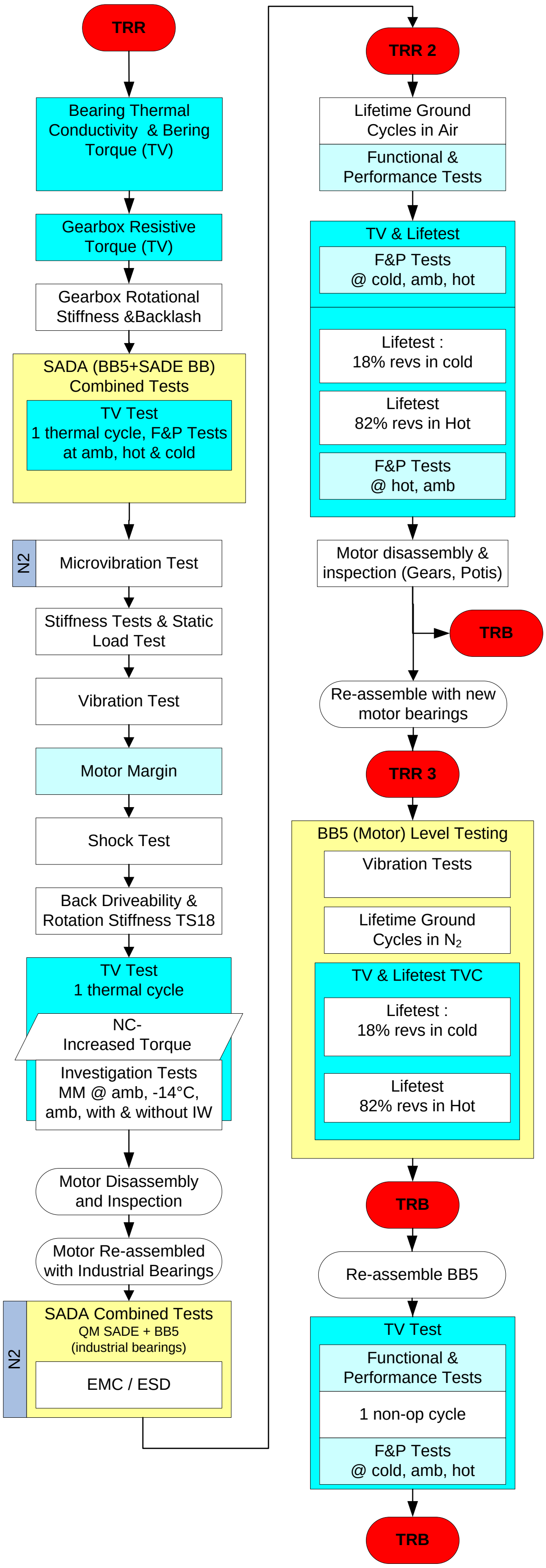

Figure 11. SADM EM BB Test Flow

5.2. Front-bearing and Gearbox Test

The test was carried out to determine the efficiency and resistive torque of the gearbox and the front bearing under various loads. The test confirmed the analysis assumptions.

5.3. SADM BB5 / SADE Combined Testing

TV/Functional Testing

After final assembly of SADM EM a combined test of SADM BB (in TV chamber) and SADE BB was done.

Test Setup:

Figure 13. SADM TV/Life Test Setup

The SADM was placed into a dedicated TV chamber; with a mechanical feed-through connecting an external encoder as well as an SA inertia simulator. The SA simulator is representative to the SA with respect to the inertia and the first eigenfrequency. The SA I/F is equipped with dedicated heaters to simulate the high temperatures of the SA.

The test showed that the interaction SADM/SADE works fine in regular operation mode. The SADE commands and processes data in the expected way.

A minor finding was that running the test with a look-up table in the SADE using non calibrated data for the potentiometers, turned out, for some fast mode runs, to be inadequate for the SADE processing (superposition coarse fine potentiometer).

The running smoothness test (ability to follow a given profile) confirmed the predicted expectations.

5.4. Microvibration Testing

The disturbance torque test was performed on the micro-vibration test facility at Astrium Friedrichs-hafen. Due to geometrical limitations, a much smaller inertia mass compared to the original solar array was used. The test results were used to confirm/calibrate the mathematical model of the prime. The dominating contributor to the micro-vibration was found to come from micro-stepping.

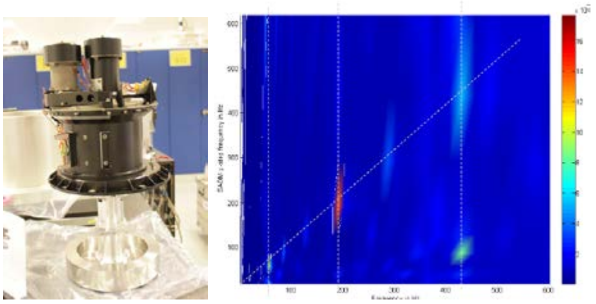

Figure 14. Microvibration

In the figure above the BB5 with the Microvibration dummy and a waterfallplot μ-Step frequency/vs. measured frequency is shown.

5.5. Mechanical Testing

The mechanical tests (static load test, sine, random and shock tests) were performed without problems. However, some notching was required to protect the motor ball bearings from onset of gapping.

5.6. TV and Life Testing

After the mechanical tests, the TV test campaign was started. Unfortunately, at the end of TV testing a significant internal torque increase was observed that was localized on the motor bearings. In order not to compromise the schedule, it was decided at this time to continue the tests with industrial motor bearings. A drawback of this decision was that the verification of the motor had to be carried out separately after completion of the SADM EM level tests. The test was concluded successfully with respect to the mechanical parts (main bearings, gears) but unfortunately a certain position sensor noise exceeding threshold was observed at the very end of the test.

5.7. Motor Lifetest

As the remaining part of SADM was meanwhile life tested with industrial motor bearings, it was necessary to perform a lifetest at motor level. In order to provide reliable lifetest results, the motor assembly was preconditioned by a vibration test. Subsequently, the motor was integrated on the SADM EM to make a TV test for final performance verification. This verification was performed without torque margin problems; the positive torque budget was demonstrated in the final configuration for begin of life (BOL) to end of life (EOL).

6. SADE BB/SN 01 TEST / FINDINGS

SADE testing was carried out using a dedicated EGSE with a MIL-1553 interface card to command the unit and read back telemetry data. A customized test adapter provided access to all interfaces and served as a SADM simulator during unit level tests.

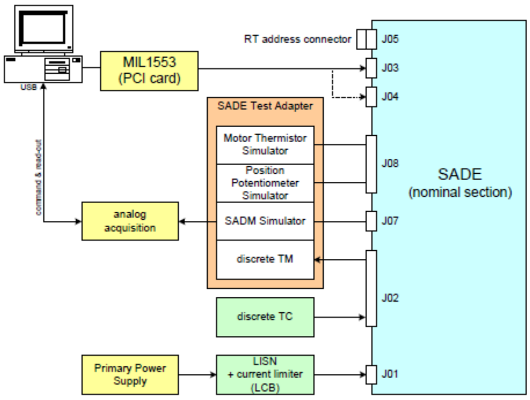

Figure 16. SADE-BB Test Setup

The SADE BB testing concentrated on an initial verification of the functionality and performance of the design under ambient conditions. Thermal/vacuum and mechanical environmental testing, full EMC testing and formal MIL1553 verification was not done before the EQM unit

Test	Objective
Initial Switch-On	Initial powering of the SADE BB unit
SADE Power-Up Test (TE-SADE-FT01)	Verify power-up timing
Discrete TC/TM Test (TE-SADE-FT02)	Verify discrete TC and TM interfaces
MIL1553 TC/TM Test (TE-SADE-FT03)	Verify MIL1553 TCs and TMs
Mode Change Test (TE-SADE-FT04)	Verify SADE mode changes
Torque Test (TE-SADE-FT05)	Verify torque commanding
EEPROM Programming Test (TE-SADE-FT06)	Verify EEPROM commanding and inhibit functionality
Static Accuracy Measurements (TE-SADE-PT01)	Verify SADE pointing accuracy based on static phase current measurements
Dynamic Accuracy Measurement	Verify SADE pointing accuracy based on dynamic phase current measurements
Motor Thermistor Test (TE-SADE-PT03)	Verify the motor thermistor interface accuracy
Position Potentiometer Test (TE-SADE-PT04)	Verify the potentiometer acquisition interface accuracy
External Interface Protection Test (TE-SADE-PT-05)	Verify all external interface protections
Power Consumption Test (TE-SADE-PT06)	Measure the SADE power consumption
Power Up Timing (Autonomous Start-Up)	Check of autonomous start-up timing
Impedance and Protection Diodes Measurement (TE-SADE-PT07)	Measure DC impedance of all external interfaces
Inrush Current Measurement	Measure SADE inrush current

Figure 17. SADE-BB Tests

All tests on SADE level were successfully completed with all results within the expected limits. The measured parameters were used to verify the predicted performance (reduction of uncertainty) and the lessons learned were used to refine test procedures for the EQM/PFM units.

During combined testing the internal interfaces between SADM and SADE were verified and the functionality and performance of the complete SADA system was tested. As planned from the beginning, the SADE motor driver parameters were tuned to the actual SADM motor to optimize the performance.

7. LESSONS LEARNED

7.1. Motor Ball Bearings

The selected Ball bearing design was MoS_2 sputtered steel rings with Si_3N_4 balls. This design was selected to minimize the risk of cold welding. The design was also baselined as it was assumed that ceramic bearings provide in a failure case (complete breakdown of the lubrication layer) still reasonable performance when compared with full steel bearings.

The bearings were optimized to show low torque in the hot case which is the condition when the mechanism is close to mercury and mostly operated. The drawback was a relatively high torque in cold and the risk of onset of ball gapping under hot worst case qualification thermal boundary conditions. In the frame of the root-cause analysis of the increased torque non-conformance, detailed investigations revealed that there was also a mismatch between the calculated preload and the actually adjusted preload in the built in state. (the deviation was masked by an inappropriate preload measurement). By this finding, it became clear that the main root-cause for the torque problems observed was too high preload in the motor ball-bearing assembly enforced by CTE effects in cold case. To minimize thermal effects, the bearing design was completely updated by use of 440C balls. In addition to that and to further mitigate the risk of a lifetime failure, both balls and races were MoS2 coated [2] and heaters were installed on the motor.

In order to further increase the margin with respect to the lifetime, N2 purging for ground testing was included in the motor design.

Prior integration on the SADM EM, the updated bearing design itself was successfully life tested at component level under dry N2.

7.2. Position Sensor

Although the positions sensor tests at component level provided good results, the position sensors showed throughout the SADM EM test campaign still some temporary noise, mainly on the hemispherical track. Detailed investigations and development tests helped to stabilize the performance.

Following findings in frame of inspection and improvement processes can be reported:

Potentiometers without and with lubrications were tested. Lubricated potentiometers showed in general significant lower set-up of noise; but the crabber wear was higher. This was interpreted that under wet condition abrasive products are clustered and work as an abrasive paste. Unlubricated potentiometers on the other hand, showed less crabber wear but continuous increasing of electrical track resistance and associated noise over the life. This finding was substantiated by EOL track resistance measurements comparing values of the contact zone of the crabber fingers (traces) with (virgin) values obtained between the traces. For wet potentiometers the track resistance stays low with a low scattering, in general independent of used or unused track. For dry potentiometers, the opposite picture is seen: On the traces itself a relatively high resistance is seen having a high. The increased resistance in those areas is assumed to be a result of a “tribolayer” built-up leading to a lower conductance in the contact zone. As a consequence, if all fingers of the crabber run on a heavily used track, very high resistance and noise results which in the worst case may lead to a complete loss of electrical contact.

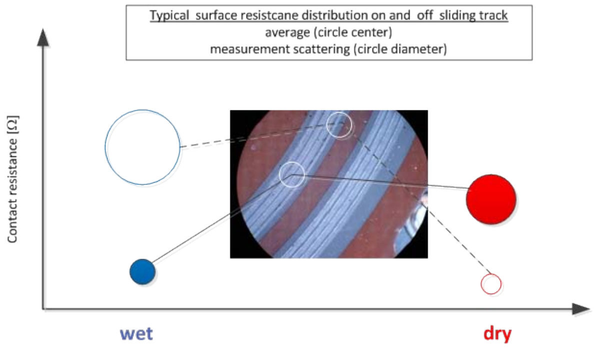

Figure 16. Multi Point Position Sensor Surface Resistance Test Result Dry and Lubricated Sensors blue: wet, red: dry; full on track empty off track

The aim of these development tests was to optimize the lubrication process in order to minimize the wear whilst having still good conductive properties throughout the entire lifetime. In order to achieve this, the lubrication film was optimized.

8. CONCLUSION

The risk mitigation activities in frame of an extensive breadboad test campaign confirmed the analysis assumptions. They helped to identify some weaknesses in the design and production process which were continuously improved. Based on the findings of the BB test campaign, the test equipment could also be improved. The achievement of the required performance of the MPO SADE was verified as well.

9. Acknowledgement

RSSZ wants to thank the BepiColombo industrial team (TAS-I Turin, ASD Friedrichshafen and our suppliers) as well as ESA for supporting the development activities.

10. References

1. Heinrich, B., Zemann, J. & Rottmeier, F. (2011). Development of the BepiColombo MPO Solar Array Drive Assembly (SADA). *ESMATS 2011*

2. Kreuser J. et al. (2013). Development of Motor Bearings for a new SADA (BepiColombo). *ESMATS 2013*