LESSONS LEARNT FROM THE ROOT CAUSE INVESTIGATION ON THE SAD-LP SOLAR ARRAY DRIVE MECHANISM

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ABSTRACT

Over the last few years, Oerlikon Space AG has been developing a low power Solar Array Drive mechanism (SAD-LP) that is used as the basis of the Galileo IOV SADM.
As part of the qualification testing, the mechanism was subjected to a life test under temperature cycling conditions for some 22,000 oscillation cycles between ±8° and ±95°, and some 2,000 full rotation cycles.
Although the performance margins were maintained during the test, occasional anomalies were witnessed that were partly attributed to the performance of the electronics driver (which actually exhibited a failure), and to a gradual degradation of performance of the SADM.
Subsequent to the completion of the life test, the SADM was completely disassembled and the slip ring and actuator examined to identify the cause of the witnessed anomalies.
During disassembly it was discovered that the motor rotor and stator had made contact and that there was significant debris within the actuator mechanism.
In the course of the Root Cause Analysis that was performed to identify the cause of the problem and the origin of the debris, comprehensive analysis was performed which included the effects of vibration and thermal dilatation on the mechanism. This analysis was backed up by material investigations and breadboard tests to check the hypotheses.

This paper will describe the observations made and the extensive investigations that were undertaken to identify the cause of the problem and the origin of the debris. It will show that it is important not to underestimate stiffness issues relating to mechanisms and also test equipment, to understand the test loading conditions and also to ensure that the effects of materials with each other are understood.

1. INTRODUCTION

In preparation for the Galileo IOV programme, Oerlikon Space (OSZ) undertook a development of a Solar Array Drive Mechanism (SADM) which was to meet the preliminary requirements of the Galileo Mission.
This development was reported in [1] and was intended to provide a qualification for the mechanism.

Unfortunately the qualification had to be repeated due to a failure of the potentiometer which was reported in [2]. This meant that during the qualification had to be repeated with the consequence that the SADM mechanism was subjected to following tests:

- 2 Vibration Test Campaigns
- 1 Shock test Campaign
- 2 Thermal Vacuum test Campaigns
- 1 Life Test Campaign

During the life test an anomaly was noted which was due to damage of the FPGA in the electronics controller. This was repaired so that the test could be continued but afterwards, it was noted that the performance of the mechanism gradually degraded, although at the end, the mechanism still provided sufficient torque to meet the ECSS margins.

2. DISASSEMBLY OF THE SADM

After the life test where the mechanism had survived some 22,000 oscillation cycles between ±8° and ±95°, and some 2,000 full rotation cycles under temperature cycling conditions, the mechanism was disassembled to evaluate the condition of the bearings and the gears.

During the disassembly the following issues were discovered which are summarised on figures 1 and 2.

- There had been contact between the motor rotor and stator.
- There were extensive deposits of dry black particles on the motor.
- Wet particles were distributed throughout the actuator which could be attracted by a magnet.
- The bearing nearest to the motor (MoB) was highly contaminated with black particles & was dry. The bearing ring was highly

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contaminated with dry black particles which were ‘fused’ together.

- The next bearing in the chain was dry on the motor side and far less contaminated on the other side.
- Lubricant on the other bearings and the gears was in good condition as was the creep barrier.

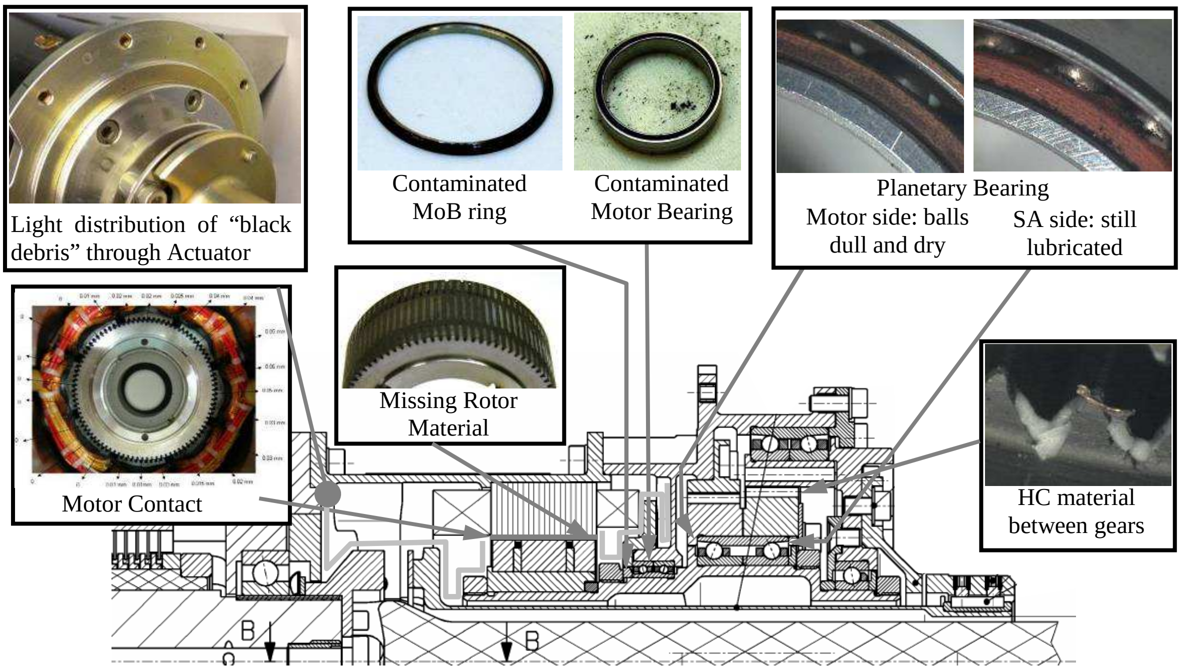


Figure 1: Pictures of Disassembled SAD-LP components and Key Findings.

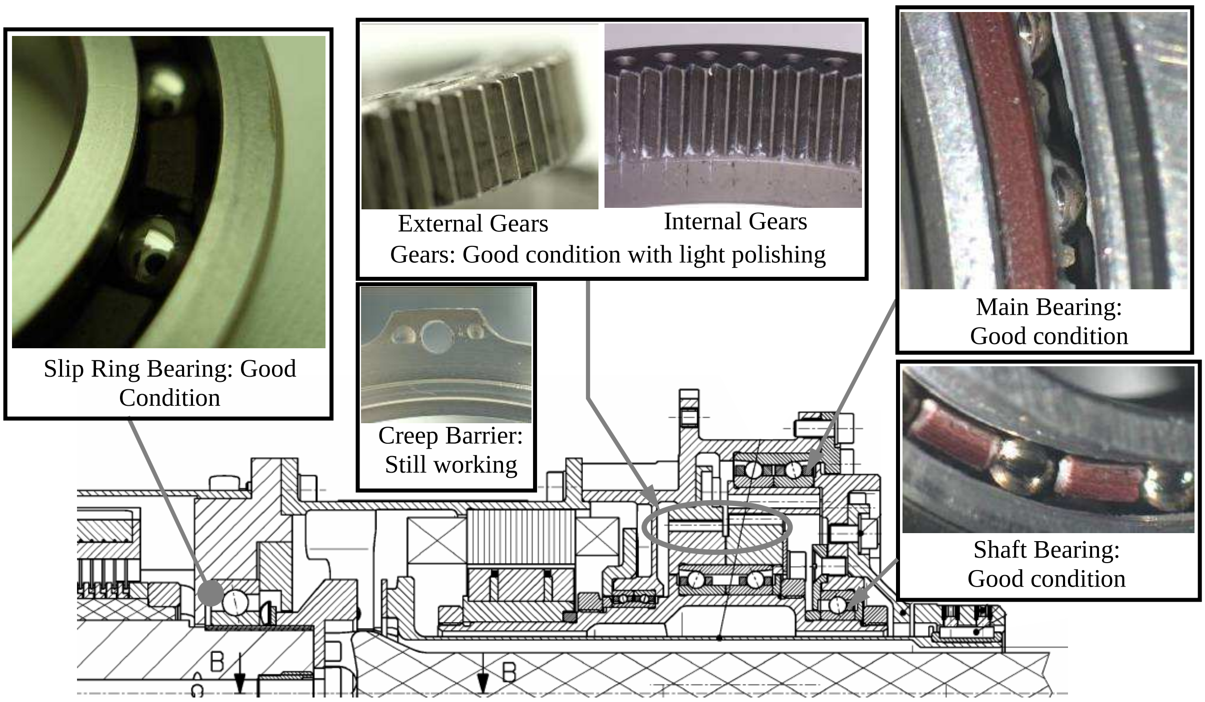


Figure 2: Pictures of Disassembled Gears and Bearings.

From the results obtained from the inspection, it was not clear whether the initial failure had occurred in the bearing or by contact between the stator and rotor.
The purpose of the evaluation was to establish what actually happened within the mechanism so that it could be corrected in the further development of the mechanism.

3. EVALUATION OF BEARING

As part of the investigation, the bearings were inspected more closely to examine the surfaces for damage and wear that may have caused misalignment of the bearing which could lead to contact between the motor rotor and stator.
These investigations are shown on the following figures:

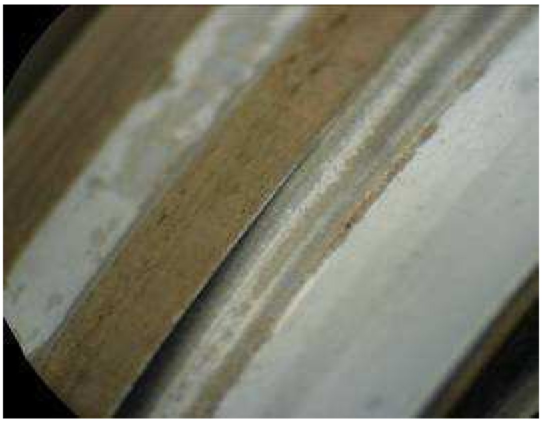


Figure 3: Inner Raceways

The inner raceways were dull, ‘pitted’ and this extended to the dams. Contact marks from cage riding were seen on the land. One raceway track was uneven due to axial loading.

Figure 4: Outer Raceways

There was also some noticeable ‘damage’ in the form of contact marks from cage on the land.
There was a change in the circularity of the bearing of about 8µm which was due to the applied loads.

The cage was dry, i.e. no lubrication was present. There were marks on ball pockets and rubbing marks on ID & OD.

Figure 5: Phenolic Cages

The main issue arising from these findings was the contamination and the lack of grease present in the bearing. An SEM and EDX analysis was made on both the cage and the ring of the bearing to determine the chemical breakdown of the materials present on the bearing.
The results from these analyses are shown on the following.

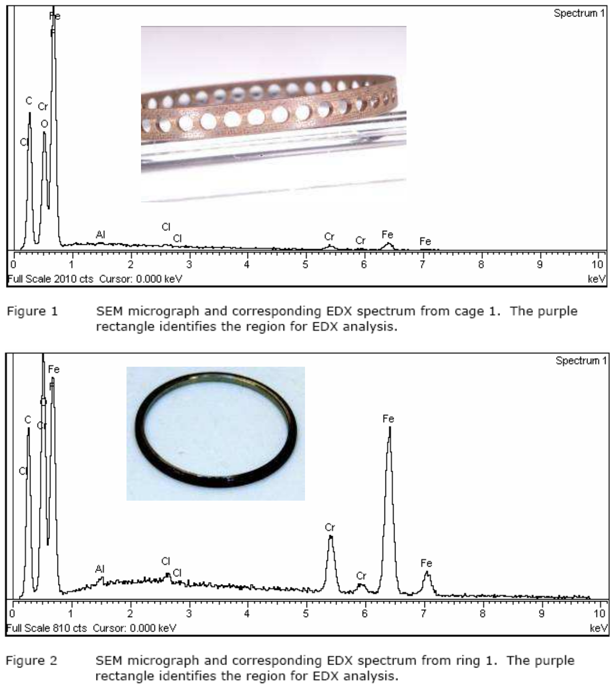


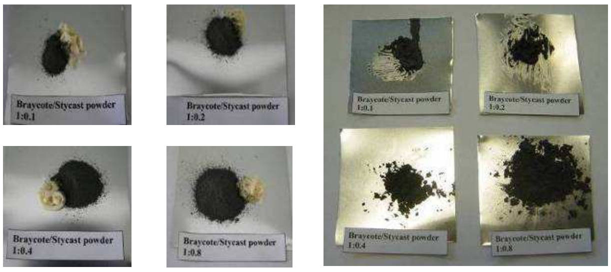
Figure 6: Results from SEM Micrograph and EDX analysis.

An FTIR analysis was also performed on the deposits on the cage and ring materials, on samples of Stycast contained within the rotor, and on Braycote to provide a control signature to allow for comparison.

The results showed no evidence of Soft Iron from the motor (Vacoflux: Fe, Co, V, Ni) at the motor stator interface but there was evidence of the rotor potting material (Stycast epoxy: C, H) within the bearing contamination material and also evidence of the Braycote 601EF grease (C, F, H & PTFE).

In the initial investigations, a black cake crumb substance was found within the bearing. Since both Braycote and Stycast were identified in the residue material, an additional investigation was undertaken to establish whether there was a reaction between the Braycote and Stycast.

Powdered Stycast and Braycote were mixed together in various quantities to determine if the Stycast (by the increase in surface area and/or mild chemical reaction) would react with the lubricant. These mixtures were then subjected to a vacuum under 80 mbar at 80°C for about 2 months to see what the effects of evaporation were on the mixture.



Samples before mixing Samples after mixing

Figure 7: Stycast / Braycote Absorption Test

It was possible to reproduce the initial reaction between the two materials where they form a cake substance (or 'crumbs') but they did not form an emulsion and there was no further reaction between the materials.

Apart from the moisture loss on the bearing, there was no measurable weight loss of the braycote. The braycote was however fully absorbed by the staycast which leads to a loss in the effectiveness of the braycote which may lead to the bearings will tend to wear quicker. It is apparent that a small quantity of stycast can cause increased wear in the bearing when mixed with the braycote.

Based on the chemical analysis, the appearance of the debris, and the mixture/absorption tests, it can be concluded that the debris originated from the motor potting exclusively. Some of the crumbs observed seemed to contain traces of a mildly magnetisable material which is consistent with the mild wear observed on the bearing ring but does not originate from the motor.

4. CAUSE OF FAILURE

After reviewing the design, which incorporates a small air gap of 60µm between the rotor and stator of the motor, it was established that the origin of the anomaly was at the bearing nearest to the motor.

Although the bearing had been sized according to the predicted loads, the appearance of the bearing was such that it had clearly been subjected to significant loads.
This led to the following conclusions regarding the mode of failure in the bearing. The possible causes of failure are:

- Environmental Loading
- Internal Loading
- Contamination

A decision tree was established to help decide whether the motor contact occurred first (causing particles to enter the bearing increasing the wear dramatically), or whether the bearing failed first (causing a misalignment of the bearing and hence causing contact in the motor).

5. SUMMARY OF THE INVESTIGATIONS

Various analyses and investigations were undertaken to establish the cause of the failure. These are summarised in the following.

5.1. Overload of Bearing due to Static Loading

This investigation concentrated on the performance of the bearing under the loads induced by the vibration test which could cause either temporary or permanent overloading of the bearing which leads to excessive deflection within the bearing.
From a careful examination of the bearing configuration, it was established that the preloading of the shaft bearing acts as an external load on the motor bearing and affects the applied preload within the bearing. The effect of this is shown on figure 8.
This effect leads to a change in stiffness of the MoB which means that the bearing off loads earlier than anticipated during the vibration testing.
During the vibration test, this change in stiffness and off loading leads to a significant displacement at the bearing which eats into the available margin on the motor air gap.
The displacement on the bearing due to the stiffness variations is shown on figure 9.
Here it can be seen that as the stiffness decreases, the displacement increases significantly.

<u>Lesson Learnt 1</u>*: It may seem obvious but check for internal design effects that for example may cause a redistribution of the preload in bearings which could in turn lead to a change in bearing stiffness.*

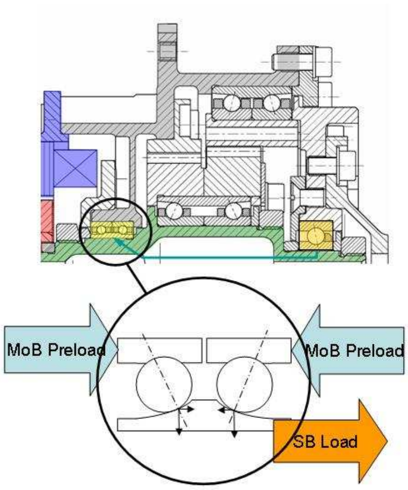


Figure 8: Eccentric Preload on Bearings

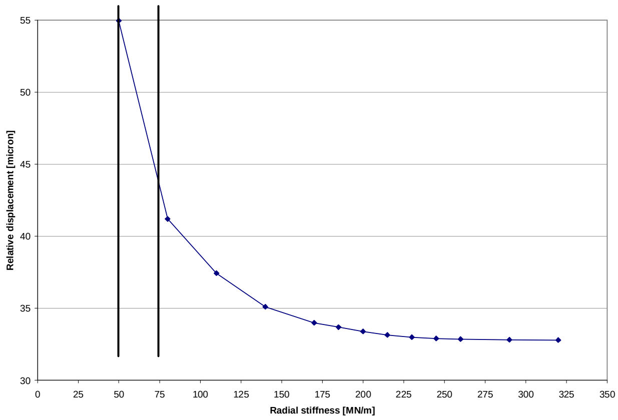


Figure 9: Displacement Increase as Result of Stiffness Variation on Motor Bearing

5.2. Motor contact during Vibration

As discussed previously, the motor bearing is affected by the preload in the shaft bearing which has the effect of altering the stiffness of the bearing.
During vibration this will lead to an off loading of the bearing and as a consequence, the radial deflection induced could cause the motor to contact.

In the analysis that was performed during the design phase, this effect was overlooked and only the nominal stiffness of the bearing used to predict deflections.
When the actual stiffness is taken into account in the analysis, it showed that there contact in the motor was possible depending on the assumptions made.
Since this was only a prediction, it was necessary to prove this by test to demonstrate that the motor made contact during the vibration test.

To do this the mechanism was rebuilt with new bearings and with mass dummies to represent the slip ring and the position sensor.

As it is extremely difficult to see whether there has been contact within the motor, it was decided to bond gold leaf to the rotor to be used as a witness specimen to show any marking that may occur during the vibration.
Gold leaf is a good material as it is quite thin (4 µm) and is also soft enough to provide a record of any contact in the motor.
The loads on the bearing shaft were measured with the aid of an accelerometer located within the hollow shaft.

It was intended to subject the assembly to the same level of vibration loading that was used during the qualification test with a duration that covered all the previous tests, however, significant cross talk from the test setup was witnessed which meant that test reached levels 20% less than those previously tested.
From an analysis of the results, the loads and amplitudes were assessed to be within 10% of those experienced on the previous tests.

After the test, the mechanism was disassembled to determine whether or not there had been contact between the rotor and stator. Despite the lower vibration levels, marks were seen on the gold coated motor which indicates that the rotor and stator have made contact with each other.

These marks, seen on figure 10, can be differentiated from those that occur during disassembly because these would show as scratches while the contact marks in question are clearly ‘imprinted’ in the soft layer.
The undisturbed surface with the rotor structure shining through can also still be seen.

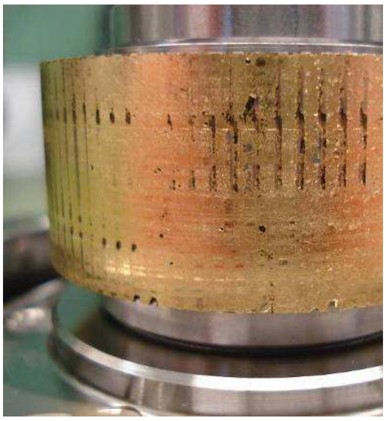


Figure 10: Gold Coated Rotor showing contact marking

The results from the test verified the assumptions that the bearing stiffness changed during the test causing displacement at the bearing causing the motor to contact.

<u>Lesson Learn 2</u>: *Account for the variable bearing stiffness when loaded externally (i.e. Vibration) to*

account for bearing deflection and loads. This effect can be significant.

5.3. Overload of Bearing due to Thermal effects

The loads in the bearing can also be affected by the steady state thermal dilatation in the mechanism during the Thermal Vacuum Test and the Life Test.

The factors need be considered in this analysis include the effect of the temperature variations on the MoB; any thermal distortion due to the differential expansion between parts within the actuator; and loading effects from the GSE supporting the mechanism within the TV chamber.

The analysis showed that under the limits of -64°C and +76°C, the allowable Hertzian stress is exceeded, but not to the maximum value. This means that it is unlikely that the bearing was overloaded during the thermal test.

It was also discovered that there was a mismatch between the GSE used to support the mechanism within the chamber and the mechanism which lead to a bending effect which lead to a high Hertzian stress on the MoB; although this stress was still below the limit stress for the material.

<u>Lesson Learnt 3</u>: *As well as checking the mechanism for differential thermal expansion effects, also check GSE as this can influence the stresses in the mechanism*.

5.4. Reduction in bearing life due to thermal load effects.

The consideration here was to establish whether the bearing problem was caused by fatigue in the bearing due to the thermal and mechanical loads.

The usual equation for calculating bearing life:

$$L_{10} = \left(\frac{C}{P}\right)^3$$

Where L_{10} = Basic Rating Life (x10^6 revs)
- C = Basic Dynamic Load Rating
- P = $XF_R + YF_A$
- F_R = Radial Force
- F_A = Axial Force
- X, Y = Geometric Factors

This is optimistic and should only be used for indicative purposes as the life of a bearing is dependant on the operating speeds and effects of boundary lubrication.

During the TV test, the MoB bearing was subjected to some 250,000 cycles of operation at the steady state cold and hot conditions. Calculation for the lifetime at the steady state operating conditions was performed as shown on table 1.

Especially at the cold operating conditions, it can be seen that a significant proportion of the allowable life has been expended.

Steady Thermal Loads on Motor Bearing					
Load Case	Temperature [℃]		Hertzian Stress [MPa]	Nominal Lifetime [x10^6 Cycles]	Factored Lifetime (SF=1.5) [x10^6 Cycles]
	Housing	Shaft			
Ambient	20	20	1997	510	150
Cold Operating	-56	-56	3446	1.1	0.3
Hot Operating	65	65	2434	2.7	8.1

Table 1: Lifetime on MoB due to Steady State Thermal loads

For the transient conditions, calculations were performed using the TV Test thermal results to calculate the stress in the bearings and hence the expended lifetime. It was discovered that during the cold cycles a significant proportion of the useable life as shown on table 2, was already expended before the life test had started.

Transient Thermal Loads on Motor Bearing					
Load Case	Temperature [℃]		Hertzian Stress [MPa]	Nominal Lifetime [x10^6 Cycles]	Factored Lifetime (SF=1.5) [x10^6 Cycles]
	Housing	Shaft			
Cold Operating (ΔTMoB=2.5℃)	-15	-8.5	2880	5.1	1.5
Cold Operating (ΔTMoB=5.8℃)	-15	-5.5	2953	4.0	1.2
Hot Operating	58	60	2610	12	3.3

Table 2: Loads and Lifetime on the Motor Bearing

In addition to the number of test cycles during the TV test, the MoB was subjected to 4.4x10^6 cycles up to the point when the first anomaly was discovered during the test.

Since the mechanism is subjected to very slow thermal cycling, it was considered that 50% of the total revolutions were applied at more or less steady state hot and cold operating conditions which is more critical in terms of life.

After the anomaly, a further 3.3x10^6 cycles were performed on the MoB leading to 7.7x10^6 cycles in total.

In summary, the effect of the steady state thermal loading is more critical than the transient thermal loads. It is certain that the lifetime of the bearing has been compromised under cold conditions and this will have certainly contributed to the anomaly witnessed, but did was not the sole cause of the problem.

The evolution of the number of life time cycles used up during the test programme is shown on table 3.

Event	Stress regime	# cycles	life used
Vibration test	3500…3700 MPa	100 k (<1 k high level)	5% (estim.)
TV test, cold	3446 MPa	250 k	23%
TV test, hot	2434 MPa	250 k	9%
Life test, cold	~3000 MPa	~1900 k	~30%
Life test, heat-up	~2900 MPa	~1900 k	~25%
Life test, hot	~2600 MPa	~1900 k	~15%
Life test, cool-d	~2900 MPa	~1900 k	~25%
Total			**~130%**

Table 3: Summary of Bearing Life during Testing

Lesson Learnt 4: *It is important to breakdown the lifetime of a bearing to consider the various temperature/load test phases to ensure that the life is not exceeded in one particular phase.*

5.5. Reduction in bearing life due to mechanical load effects.

When a load is applied at the output flange of the SAD-LP, this translates into a radial force on the motor bearing due to the gears as shown below:

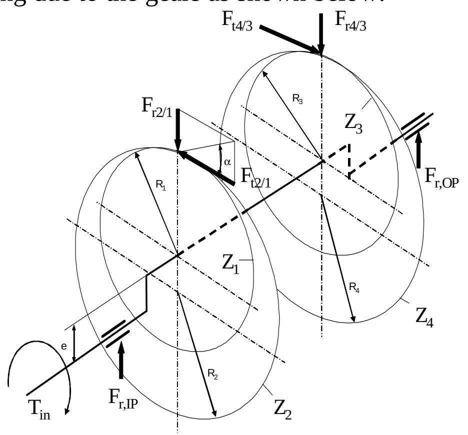


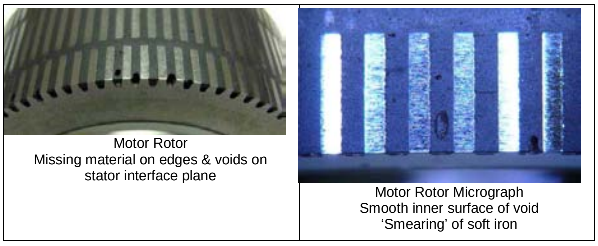
Figure 11: Bearing Forces due to Gear eccentricity

If a load of 20Nm is applied to the output flange of the mechanism, the result is a radial load of 425N acting at the Motor Bearing. During the life test, there was a long phase where the mechanism was driven at 0.5°/s with a large inertia attached to the output flange.
This led to a higher than normal load at the output flange but this still only corresponded to a moment at the output shaft of only 1Nm. This results in a load at the motor bearing of only 22.6N which is considered insignificant and therefore has no significant impact on the bearing allowable life.
The load issue on the gears is reinforced by the inspection where it was seen that there was no noticeable wear.

Lesson Learnt 5: *When using a fixed output inertia to simulate external loads, the speed of operation of the mechanism should be considered as higher speeds to accelerate testing may lead to higher than expected loads on the mechanism.*

5.6. Reduction in bearing life due to contamination

As pointed out earlier in this paper, a significant quantity of Stycast migrated into the MoB and reacted with the Braycote to form cake like crumbs.
From an examination of the rotor surface, it was seen that there were a number of voids in the Stycast. After discussing this issue with the supplier, ETEL SA, it was clear that the voids occurred because the resin was not degassed during preparation. Without degassing of the resin, the machining operation can leave very thin areas over the voids which when placed in vacuum could break off and migrate towards the bearing and then break up into a powder form and react with the Braycote.
These voids are shown on figure 12.



Motor Rotor
Missing material on edges & voids on stator interface plane

Motor Rotor Micrograph
Smooth inner surface of void
'Smearing' of soft iron

Figure12: Voids on Motor

Based on the experience of working with Stycast available within OSZ, it is unlikely that the contamination originated in this manner.

Lesson Learn 6: *When using resin materials, always ensure that the mixture is degassed before use to remove air bubbles.*

5.7. Contact between the rotor and stator due to insufficient clearance during vibration and thermal testing.

If the rotor contacts the stator during the vibration and thermal tests, particles will be generated.
Under the vibration test, the contact can happen when the bearing is overloaded or the stiffness is reduced such that significant displacement occurs.
When analysing the motor clearance, the following factors have to be considered:

- Concentricity Errors – axis misalignment
- Dimensional Errors – deviation from nominal gap
- Play in mounting – possible eccentricity mounting

The results from the calculation on the remaining gap are shown on table 4.

Motor Gap Analysis		
	Arithmetic [µm]	RSS [µm]
Nominal Gap	**61**	**61**
Assy, Play & Concentricity Errors	**35**	**18**
Remaining Gap	26	43

Table 4: Gap Analysis on Motor

These results show that there should be at least a gap in the range of 30 to 40 µm when all tolerances are taken into account.
Prior to the retest on the mechanism to demonstrate that contact occurred at the motor, the gap was measured between 54 µm and 58 µm which indicates a good build standard for the unit.
This gap is shown on figure 13.

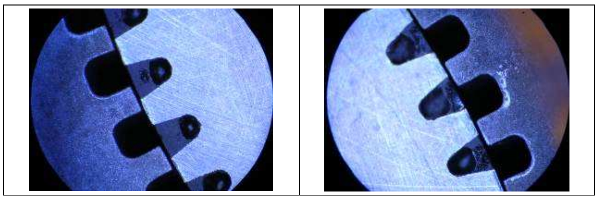


Figure 13: Gap between Rotor (lighter colour) and Stator of SAD-LP Rebuild

Having established the baseline condition for the air gap in the motor it was necessary to establish how this air gap changes under the thermal loading. The effects were calculated for both the steady state and transient conditions and are shown on tables 5 and 6.

Steady State Thermal Displacements			
Load Case	Temperature [℃]		Relative Displacement Rotor / Stator [mm]
	Housing	Shaft	
Ambient	20	20	0
Cold Operating	-56	-56	+0.0110
Cold Non-Operating	-64	-64	-0.0028
Hot Operating	65	65	+0.0020
Hot Non-Operating	76	76	+0.0008

Table 5: Displacements between Rotor and Stator under Steady State Thermal Conditions

Transient Thermal Displacements			
Load Case	Temperature [℃]		Relative Displacement Rotor / Stator [mm]
	Housing	Shaft	
Cold Operating (ΔTMoB=2.5℃)	-15	-8.5	+0.0035
Cold Operating (ΔTMoB=5.8℃)	-15	-5.5	+0.0036
Hot Operating	58	60	+0.0044

Table 6: Displacements between Rotor and Stator under Transient Thermal Conditions

With the exception of the cold steady state condition where the gap decreases, under all other conditions, the motor gap increases which means that this effect could not have caused the anomaly.

The next effect to investigate is that contact occurred during the vibration testing.
It was only possible for analysis to be performed here even though the retest had shown that contact did occur. The purpose of the analysis was to show the degree of displacement that could occur at this location.
This analysis showed the following:

Vibration Test displacements calculated from measured PSD based on scaled prediction		
Excitation	Axial Displacement [mm]	Relative Radial Displacement between Rotor and Stator [mm]
X-axis	Not relevant	0.032 (using comparison to FEM figures by above K factors) 0.017 (using test data converted to displacement and 3σ) 0.026 (using test data converted to displacement and 4.5σ)
Y-axis	Not relevant	**0.074 by comparison to FEM figures and above K factors**
Z-axis	-	-

Table 7: Axial and Radial Displacement of Motor Bearing during vibration

The results show that contact should occur within the motor during vibration as the analysis shows a calculated displacement of 74 µm. When the motor contacts, it is probable that debris will be released although during the retest, very few particles were seen. This is probably due to the gold layer on the surface which will retain any particles.

To reduce this displacement it is necessary to increase the capacity of the MoB bearing. This will increase the stiffness and the eigen-frequency of the mechanism and will the effect of decreasing the bearing loads and also the displacement

<u>Lessons Learnt 7</u>: Ensure that there is sufficient clearance between the rotor and stator to account for the displacements under vibration and thermal load.

6. DISCUSSION

The investigations of the anomaly witnessed during the SAD-LP life test have been discussed and various possible sources of the problem identified.
The main cause that was identified was that the deflections in the MoB allowed large displacements of the rotor shaft with respect to the stator under the vibration environment.
It has been established that the initial problem occurred during vibration where contact occurred between the rotor and stator and lead to the development of debris which migrated to the bearing and reacted with the Braycote.
The main contributors that lead to this problem are:

- The under sizing of the motor bearing which allowed gapping in the bearing during the random vibration test, with the result of a loss of stiffness leading to excessive movement on the rotor.

- The bearing was loaded close to its stress limit through the test programme which reduces the life expectancy of the bearing.
- The absorption of the lubricant by the Stycast and the presence of particles then during operation generated the wear observed on the bearing and hence a higher resistance torque in the bearing.

The obvious corrective action to these problems was to increase the capacity of the Motor Bearing to avoid the unloading effects, stiffness loss, and excessive displacement, and also to remove lifetime issues for the other test phases.
This should be accompanied by improvements in the GSE to avoid induced loading caused by thermal gradients on the mechanism.

The question whether a lifetime failure would have occurred had no particles been generated cannot be conclusively answered but is not relevant as the critical element, namely gapping of the bearing, has been clearly identified as the cause of the problem.

7. CONCLUSION

In the process of this investigation, seven issues have been raised that need to be addressed during mechanism design and analysis activities.
Some of these issues are obvious but sometimes get forgotten as was the case with this development.
These issues, which are listed again here, have to be considered when designing mechanisms otherwise unforeseen problems may occur which lead to additional development costs.

- *Check for internal design effects that may cause a redistribution of the preload within the mechanism and may affect the stiffness path.*
- *Account for the changing bearing stiffness when loaded externally to account for bearing deflection and loads. The effect can be significant.*
- *Check GSE for thermal and mechanical influences as this can influence the stresses in the mechanism.*
- *Consider external loads during accelerated life testing.*
- *Breakdown the lifetime of a bearing to consider the various temperature/load test phases to ensure that the life is not exceeded in one particular phase.*
- *When using resin materials, always ensure that the mixture is degassed before use to remove air bubbles.*
- *Ensure that there is sufficient play between the rotor and stator to ensure account for the displacements under vibration and thermal load.*

8. REFERENCES

[1] Wood, B., Sutter, G. Mrs. N. Hamze, *The Development of a Low Power Solar Array Drive Mechanism*, 10th European Space Mechanisms and Tribology Symposium 2003 – ESA SP524

[2] Wood, B., Mussett, D., Cattaldo, O. and Rohr, T. ,*SADM Performance and Anomaly Investigation*, 11th European Space Mechanisms and Tribology Symposium 2005 – ESA SP591