TESTING OF ADVANCED GENERIC SCAN MECHANISMS (AGSM)

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ABSTRACT

AGSM was envisaged as a generic scan drive mechanism for large across track scanners (e.g. EGPM mission). The two Breadboard Models (BBM's) tested in this programme were foreseen as technology demonstrators and incorporated some novel features, i.e:

- Electrical power transfer through the ball bearings
- Lead-lubricated bearings with lightweight, ball riding cages for long lifetime (120 million revs) with lead-bronze inserts to replenish lubricant.
- A small (< 1 microlitre) drop of Z25 oil added to one bearing to help reduce wear of the lead lubricant film during ground operation.

This paper details the results and findings from testing BBM2 and compares them to those from testing carried out on a previous BBM (BBM1) [1].

1. BACKGROUND

ESTEC supported development of the AGSM by funding the design, building and testing of the BBM's. ESTL supported the development of the AGSM by procuring bearings, designing and manufacturing cages and by, lubricating the ball bearings. BBM2 began its life and thermal vacuum test at RUAG, Switzerland. It it is illustrated in the Fig.1 and the following features are evident.

- The support bearings were SEA95 ball bearings manufactured by SKF and they were mounted back-to-back as illustrated. A spacer (red) was used to set the hard preload and it was installed between the inner rings.
- Zirconia inserts (green) were used to electrically isolate the ball bearings from the Ti-alloy housings and shafts and also from each other.
- Electrical contact to the inner and outer rings was made through sprung contacts as shown in Fig 1.

There were some differences between BBM1 and 2, i.e. BBM1 was compliantly preloaded, BBM2 was hard preloaded, the BBM1 bearings were electrically insulated with an SiO_2 coating and the BBM2 bearings were insulated with bulk zirconia as the SiO_2 coating proved unsuccessful in isolating the bearings electrically in BBM1 testing [1]. BBM1 also incorporated a smart slip ring unit which allowed offloading of brushes when power or signals not required so that their lifetimes could be extended [1].

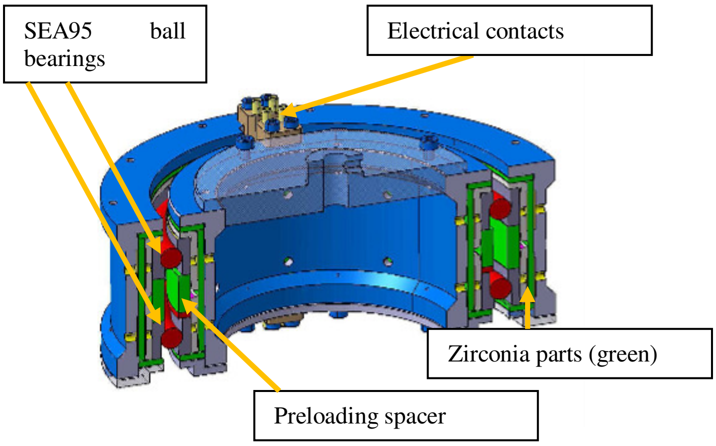


Figure 1: AGSM BBM2 – 3-D cross-section

2. SCOPE AND OBJECTIVES

ESTL performed a test programme on BBM2. The main objectives of this test campaign were:

- To demonstrate the power transfer efficiency through the ball bearings
- To establish baseline data with respect to torque and electrical behavior.
- To demonstrate the suitability of the bearing insulation.
- To demonstrate that the mechanism functionality was capable of withstanding vacuum without degradation.
- To prove that the function of the mechanism did not degrade beyond the required acceptance criteria (less than a 30% difference from initial torque and resistance values at the end of the test) after life testing in vacuum (mechanism running 120 million revolutions at a nominal accelerated rotation rate of 300rpm). This objective was modified due to anomalously high torques during testing which required additional investigation.

3. TEST PROGRAMME

3.1 Previous History

During thermal vacuum testing of BBM2 at RUAG, the torque of BBM2 increased rapidly with rising temperatures above 50 deg C (Fig.2).

As the main function under testing (i.e. the current flow through the bearing) was not compromised by this behaviour at nominal temperature, it was proposed to carry out the accelerated life-test at ambient temperature at ESTL and then complete the work by carrying out a thermal investigation of the torque behaviour.

Figure 2: Torque increase above 50 deg C during testing at RUAG

3.2 Bearings, Lubrication and Cage Design

The test bearings were manufactured by SKF (formerly SNFA) and designated SEA95CE1. Further details are provided in Table 1. These bearings were lead-lubricated at ESTL and one drop (1 mg) of Fomblin Z25 was applied by RUAG to the lower bearing only with a view to reducing wear during running-in. RUAG also applied creep barriers to prevent migration of oil to the surrounding areas.

Table 1: Bearing Details

Parameter	Details
Ring and ball material	AISI 52100 steel
Outer ring diameter (mm)	120
Inner ring bore (mm)	95
Width (mm)	13
Ball complement	24 (8 balls removed from original complement of 32 to accommodate lightweight cage)
Ball diameter (mm)	7.14
Inner and outer ring conformities	1.04
Free contact angle (degrees)	15
Initial preload (N)	160 +/- 10 (set by RUAG)
Peak Hertzian Stress (MPa)	670 at 160N preload

Table 1 (contd): Bearing Details

Parameter	Details
Lubrication	0.5 micron thick film of lead applied to raceways. Lead bronze inserts fitted to cage to replenish lubricant on raceways. One drop of Fomblin Z25 applied to lower bearing only

Ball riding cages were designed by ESTL and manufactured from carbon fibre with self-lubricating lead-bronze inserts. The insert design was such that the cage was restrained from contacting either land during normal operation, as shown in the right-hand ball pocket in the schematic diagram (Fig 3). The nibs, or restraints, were designed such that lateral motion of the cage is limited. Alternate pockets are not restrained (left hand insert in the following Figure) to allow some movement of the cage to prevent cage hang-up from occurring. Should excessive wear occur at the restraints, the cage then becomes inner race riding.

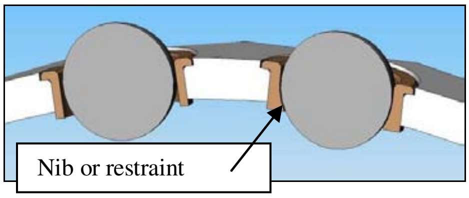


Figure 3: Schematic diagram showing design of cage inserts

Following assembly, the bearings were inspected to ensure that the cages were ball riding. The gap between the inner ring land and the inserts was inspected using a low-power microscope while the bearings were rotated slowly by hand to enable the cages to be observed. It was visually confirmed that the cages did not contact the inner ring land during rotation.

3.3 Life Test Details

ESTL carried out a life test in vacuum followed by a thermal vacuum investigation. The test activities were as follows:

Life testing comprised the following activities:

- Receipt inspection of the AGSM BBM2
- Design and manufacture test fixtures, shaft and heat exchanger
- Setting up the test facility. Tasks comprised mounting BBM2 on Kistler table and connecting temperature sensors and the torque cable.
- Installation of BBM2 and connection of electrical harnesses. A current of 5A was passed through the outer ring of Bearing 1 which was electrically

linked to the inner ring. The inner rings of both bearings were electrically connected within the vacuum chamber. The current exited the vacuum chamber via the outer ring of bearing 2.
- Monitoring the supply current and voltage drop in the measurement circuit – no slip ring units were included in this test set-up. The remaining measurements comprised ball bearing torque and test temperatures.
- It was originally intended to carry out an accelerated life test of 120 million revs at 300rpm. However, following the occurrence of high torques early in the test programme, the life test was aborted and a thermal investigation carried out.

3.4 Thermal Investigation

A thermal investigation was carried out in vacuum following the premature ending of life testing. This test was performed at temperatures between -30 and +70 deg C in an attempt to reproduce anomalies previously observed in testing conducted by RUAG, Switzerland.

3.5 Strip Examination and Test completion

Following testing, BBM2 was removed from the test chamber and carried a strip examination carried out.

3.6 Mechanical Test Set-up and Description

The AGSM BBM2 was installed in a vacuum chamber and mounted upon a Kistler piezoelectric torque transducer, whose output is converted to a voltage proportional to torque by a charge amplifier. These instruments have a tendency towards signal drift with time and it was therefore necessary to reverse the rotation direction of the AGSM at regular intervals to determine the torque zero position when taking a slow-speed torque measurement at 30rpm. Signal drift over the measurement period (5 to 10 minutes) is normally negligible.

Once the zero was determined from the mid-point between the clockwise and anticlockwise measurements, the mean and peak torques were determined.

Rotation of the central shaft was accomplished by a drive motor located externally to the vacuum chamber and at a rotation rate of 30 to 300 rpm. The test set-up is illustrated in the following Figure.

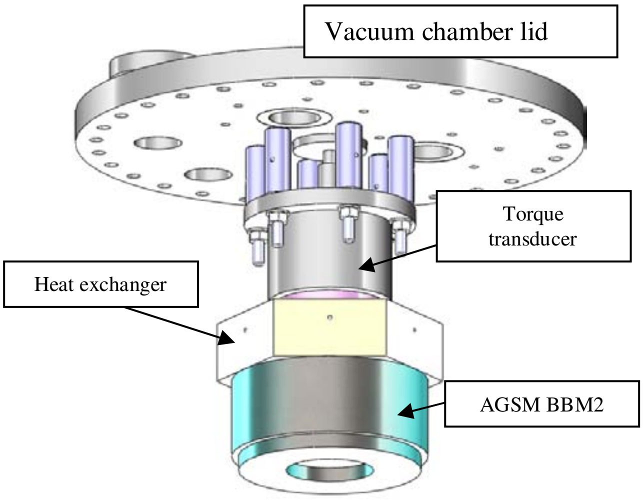


Figure 4: Test set-up

3.7 Electrical Set-up and Layout

A current of 5A was passed through the outer ring of the upper bearing and the bearing inner rings were connected within the vacuum chamber as illustrated in Fig 5. The current exited the vacuum chamber via the outer ring of lower bearing.

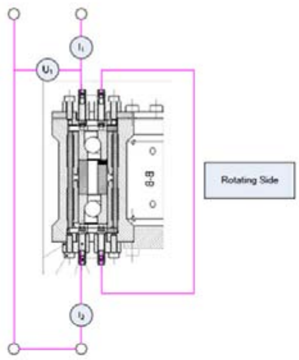


Figure 5: Electrical connections to ball bearing.

4. TEST RESULTS

4.1 Electrical measurements

The current and voltage drop as indicated in Fig 5 were measured throughout the test and the results are summarised in Fig.6.

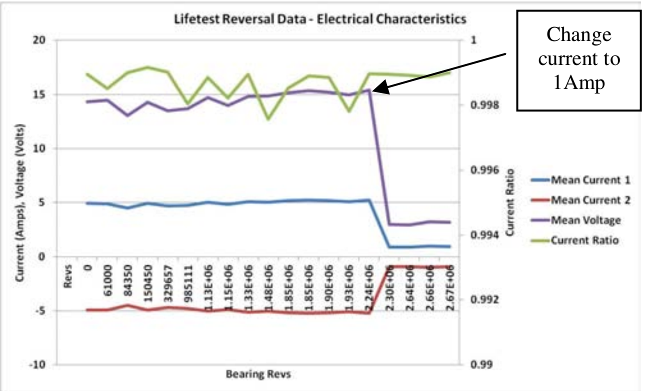


Figure 6: Summary of electrical data from torque reversals

4.2 Torque measurements

The ball bearing torque was measured at intervals during testing and the results are provided in the Fig 7. Note that the torque progressively increased when 5A was passed through the bearings and the power was stopped at 1.5 million revs. The torque then decreased and subsequent testing with and without current indicated that there was a correlation between passing current and torque increases.

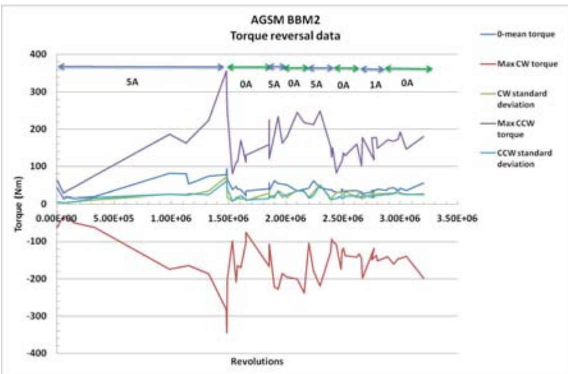


Figure 7: Summary of torques measured during reversals

At approximately 3.2 million revs, anomalously high torques suddenly occurred in vacuum at room temperature as illustrated in the following Figure.

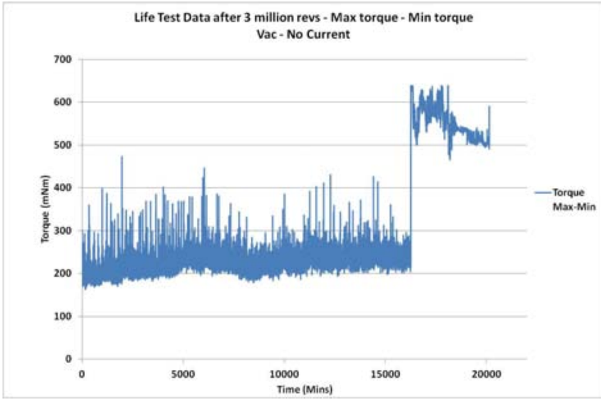


Figure 8: Torque increase at 3.2 million revs

The test was suspended and BBM2 removed from the vacuum chamber for further investigations. A number of observations were apparent:

- The bearings could not be rotated by applying a torque to the drive shaft by hand
- Flakes of lead-bronze were present at the bottom of the vacuum chamber
- Heavy lead bronze transfer to balls had occurred
- “Burrs” or flakes of lead bronze were present at the edges of lead-bronze inserts
- A solvent rinse of the bearings was carried out and the bearings could then be rotated
- It was agreed with ESTEC to abort the life test and proceed with torque vs temperature measurements (thermal testing) to prevent any further degradation of the bearings.

4.3 Thermal Testing

The thermal test comprised heating and cooling the bearings and measuring the torque at stable temperatures. The results are provided in Fig 9.

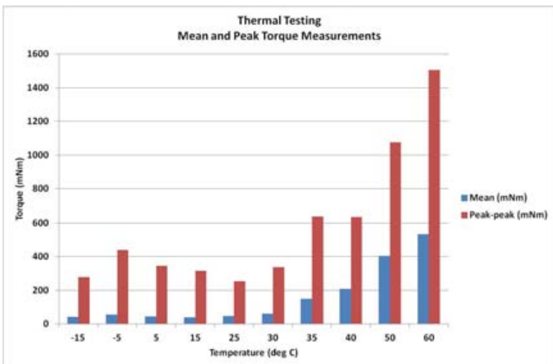


Figure 9: Results from thermal testing

From the thermal tests, it was apparent that the torque increased as temperature increased. Upon completion of thermal testing, the bearings were removed from the vacuum chamber for a post-test examination.

5. POST-TEST EXAMINATION

The bearings were disassembled and the raceways, balls and cages examined using a low-power optical microscope. The findings are illustrated in Fig 10.

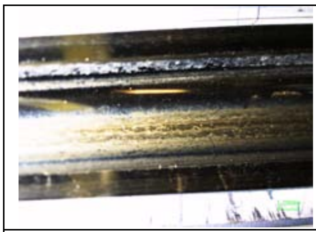
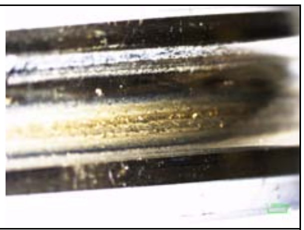
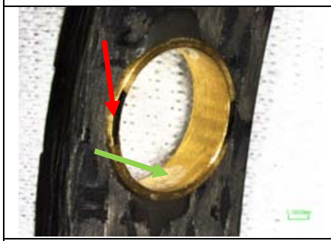
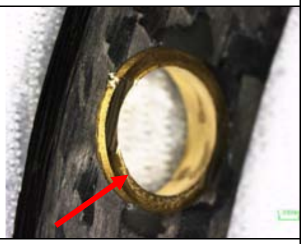
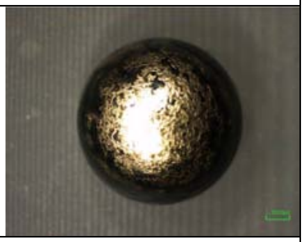
	
Inner Race	Inner Race
	
Cage Insert. Green arrow denotes internal mark and red arrow where pocket has contacted inner ring land	Cage Insert. Arrow denotes burr
	
Upper Bearing Ball	Upper Bearing Ball

Figure 10: Upper Bearing Inspection

From the visual examination, a number of observations were apparent:

1. Lead-Bronze Debris: Loose debris flakes were observed during disassembly of bearings. Debris was also compressed onto the inner and outer raceways.
2. Cage Condition: inserts displayed evidence of wear due to contact with the inner ring land – the cage was no longer ball riding. (it was designed to be inner race riding if the nibbed restraints wore out). All inserts displayed evidence of wear to the pockets, nibs and I.D. The nibbed inserts exhibited evidence of wear and "burrs" have formed on their internal diameters.
3. Ball Condition: Large, irregular patches of lead bronze material were compressed onto 12 of the 24 balls in upper bearing. These balls exhibited a clearly defined track where the ball had been in contact with the inner and outer race.

Dimensional checks of the cages using a co-ordinate measuring machine indicated that no changes in their shape could be identified when compared with the measurements prior to the test.

6. ADDITIONAL THERMAL TESTS

In an additional test, a hot plate was used to warm the bearings to further investigate clearances at the inserts and IR lands at +60 deg C. It was found that the clearance was consistent with the designed clearance of approximately 0.3 mm. It was therefore unlikely that contact between the inserts and inner ring land was the root cause of the high torques. However, it was noted that the upper bearing became stiff and "notchy" when heated to +60 deg C on the hot plate.

In order to demonstrate the influence of lead bronze upon the balls, a further test was carried out in which the balls from the lower bearing, which were in good condition compared with the upper bearing balls, were installed in the upper bearing in place of its own ball set. The hot plate test was then repeated for the upper bearing.

Upon reassembly of the upper bearing, the bearing felt less notchy than it was originally when fitted with its own ball set. During warming the bearing to +60°C the bearing felt easier to rotate in comparison to the first hot plate test undertaken with the upper bearing. During cooling back to room temperature it was possible to manually rotate the bearing at all times throughout the test.

7. DISCUSSION

It was concluded that the high torques measured in these tests was attributable to abnormal quantities of lead-bronze debris compressed onto the balls of the upper bearing. The hot plate tests revealed that the upper bearing was exhibiting high torques at +60 deg C and this behaviour was consistent with the compressed lead-bronze debris present upon the balls resisting rotation of the bearing as the balls move onto a different part of the raceway due to thermally induced dimensional changes in the rings. During continuous operation, lead-bronze debris is normally flattened at the ball to raceway contacts and rougher regions are formed at the edges of the ball tracks as debris is pushed aside. It is therefore proposed that the presence of abnormal quantities of compressed lead-bronze debris upon the balls and at the edges of the raceways contribute to the high torques measured at +60 deg C.

Hard preloaded bearings are less forgiving of debris in bearing than compliant preload. Using a micrometer, it was found that some balls from the upper bearing had diameters 3-6μm greater than the nominal value at accumulations of lead bronze debris. A larger ball diameter produces additional loading, possibly up to 300 to 400N from the bearing's load-deflection characteristics which were investigated using CABARET (in-house bearing analysis software). In addition, the heating effect from current (approx 1 Ohm x $5A^2$ = 25W) may also have impacted local contact stresses and increased the cage wear rate.

The reason for the presence of excessive quantities of lead-bronze is not entirely clear, although the following points were considered.

- In the BBM1 test carried out at ESTL, 100 million revolutions were successfully completed in vacuum, although it should be noted that no current was passed through the bearings in this test. Although some lead-bronze flakes were present in the BBM1 bearings, the balls appeared discoloured and slightly pitted. Large flakes of compressed lead-bronze debris were not present upon the balls [1] and the bearings resembled the lower bearing from BBM2.
- The cage inserts from the BBM1 test also exhibited wear and burrs [1].
- The restraints on the cage inserts exhibited wear which led to the formation of burrs and as they detach from the inserts they create the lead-bronze debris in the bearings.
- There was less wear in the lower bearing to which the drop of Z25 oil had been added before testing at RUAG.
- Wear was observed in the cage ball pockets and this wear in the restraining inserts resulted in the cage being able to contact the inner ring land. It is proposed that for future designs of this cage type that alternate pockets are machined as slots to accommodate more ball movement, thus reducing ball to cage contact and wear (refer to Fig 11 for an example illustrating the concept).

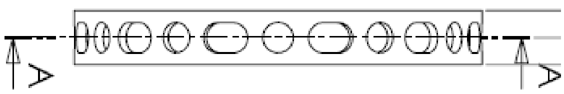


Figure 11: Example of "hole-slot-hole" cage

8. SUMMARY AND CONCLUSIONS

Upon completion of the AGSM BBM2 test and the post-test investigations, the following conclusions can be drawn, taking comparisons with BBM1 into account. Refer to Table 2 for additional details relating to comparisons between the BBM's:

- Comparisons of wear in the cages from BBM1 and BBM2 demonstrate that far more lead bronze debris was generated in the latter test. Note that the cage designs were identical in both BBM's. In the tests, BBM1 completed 100 million revs without failure (no current after 600k revs) and BBM2 only completed 3 million revs (current up to 5A continuously).
- The restraints on the cage inserts exhibited wear which led to the formation of burrs and as they detach from the inserts they create the lead-bronze debris in the bearings. Hard preloads, as was the case in BBM2, are less forgiving of debris than the compliant preload used in BBM1. The diameters of some balls increased by 6 microns due to compressed debris.
- The combination of lead-bronze debris and increased local temperatures led to increased preload and so increased contact stress and wear rate
- The lower bearing, in which the drop of Z25 oil was added, exhibited less wear. However, it is not feasible to draw a definitive conclusion from this single result, but the potential effects of an oil drop should be investigated in the future.

Table 2: Comparison of examinations of BBM1 and BBM2 ball bearings

Component		BBM1	BBM2
Bearing pair	Duty	100 million revs	2 million revs
Upper Bearing	Raceways	Frosted appearance with relatively light lead bronze transfer	Heavy lead-bronze transfer
	Balls	The balls appeared bronze coloured and looked dull and slightly pitted at X10 magnification	Heavy lead-bronze transfer resulted in formation of an uneven layer on surfaces of balls
	Cage	Inserts displayed wear marks of varying degrees. Some pockets lightly polished and others showed slight elongation at their trailing edges. Roughened, raised edges were also present on the cage inserts	Similar to BBM1, but wear heavier and flakes present on nibbed inserts
Lower Bearing	Raceways	Marginally better condition than upper bearing	Better condition than upper, but transfer of lead bronze heavier than on BBM1 bearings
	Balls	As Upper Bearing	Better condition than the upper bearing. Less debris present compared with Upper
	Cage	As Upper Bearing, but wear and the associated features were less pronounced	Similar to Upper Bearing cage

9. REFERENCES

1. Heinrich B, Anderson M.J., Humphries M.E., Spycher P and Watters R.B. (2007). Study, design and component testing of an advanced scan mechanism including power and data transmission for a microwave radiometer, Proc. '12th Euro. Space Mechanisms & Tribology Symp. (ESMATS)', Liverpool, UK, 19–21 September 2007 (ESA SP-653, August 2007)