THE USE OF DRY LUBRICATED BEARINGS IN REACTION WHEELS

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ABSTRACT

Over the last 11 years SSTL has successfully been flying reaction wheels with self-lubricating (i.e. dry) bearings on all of its missions and has supplied wheels to other space programmes world wide, totalling over 100 wheels in orbit or awaiting launch. During that time the typical mission life has extended from 3 to 7.5 years, increasing the demand on the self-lubricating bearings which dependent upon transfer of a PTFE, chopped glass-fibre/MoS2 cage material (PGM-HT) from balls to raceways, a process ultimately limited by wear-out of the cage.

The increased life requirements are not without their challenges for this type of lubricant and coupled with often very short concept-to-flight development and delivery schedules of typically less than 18 months there is the need to be able to qualify wheels quickly. This paper discusses the successful development and life testing of the SSTL 200SP wheel which is an evolution of the SSTL microsat wheel and highlights some of the challenges, important considerations and lessons learned from the development and accelerated test campaigns.

1. GENERAL SPECIFICATIONS

In 2004 SSTL with support form ESTL (European Space Tribology Laboratory) embarked on the development of the 200SP Smallsat wheel the first unit of which was intended to fly only 15 months later in late 2005. Given the need for a highly compressed development and Qualification cycle, the starting point for the development was to build on SSTL's successful history with the microwheel family [1] which utilise self-lubricating bearings and scale the design to a larger wheel. Basic specifications from each wheel are:

Micro wheel - 10mNm / 0.4Nms / 1Kg
Mid wheel - 120mNm / 1.5Nms / 2.3Kg
SmallSat wheel - 200mNm / 12Nms / 5.2Kg

In some respects this was an unusual lubricant selection. Whilst use of solid lubricants in long-life scan mechanisms is relatively common, their use in reaction wheels at that time was practically unknown, potentially due to their perceived short lifetime (compared to the requirements for typical high speed-biased wheels) and relatively high torque noise for a given preload by comparison with liquid lubricated wheels.

Whilst oil lubrication combined with active re-lubrication offered potential for lifetimes well beyond the target duration, for the 200SP wheel, liquid lubrication could not be considered because the short development time necessitated a highly accelerated test method. No tribologically valid accelerated test methodology exists for liquid lubricated bearing systems which guarantees a fully representative result [2] and hence the need to opt for some form of dry solid- or self-lubrication.

Given this need a system level decision was made to optimise the AOCS system to enable the wheels to run with relatively low speed bias. This optimised methodology permits SSTL to typically run wheels on most of its spacecraft <500Kg at ~ 300rpm. Even for larger spacecraft in the 500 to 3000Kg class speeds can be managed <1000rpm with full spacecraft control.

At the time of the lubricant selection SSTL had already noted some considerable success with small wheels using self-lubricating SR4 size bearings. One such application in orbit ultimately completed >7 years operation at a speed bias >1000rpm (>3.7×10^9 revolutions).

For such self-lubricating bearings, there was a substantial pre-existing and growing body of both test and dedicated lifetest data [3,4,5] which showed there to be a quite strong correlation between bearing lifetime and peak Hertzian ball raceway contact stress. In the early days much of this data [3] was generated by the UK NCT (National Centre of Tribology) examining the performance of the Duroid 5813 material for industrial bearings. However since ESTL was tasked under ESA funding with identifying and qualifying the closest available substitute for Duroid 5813 for space applications (at the time its production ceased) recent work has focused on the well-known PGM-HT material [4,5,6,7,8].

Taken as a whole, this data includes both in-vacuum long lifetime application data with both PGM-HT and Duroid 5813 materials and an in-air test campaign of approximately 3000 bearings aimed at generating design guidelines for industrial applications using this class of self-lubricating bearing .

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The graph presented in Fig 1 shows the relationship between preload and life which comes from experimental data from tests and predictions from design analysis.

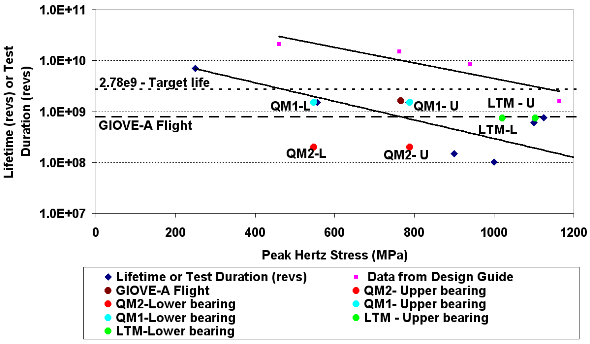


Figure 1. Lifetime V's Hertzian stress for PGM-HT / Duroid also showing 200SP wheel test durations

For solid lubricated bearings it is usually accepted that acceleration of the test by increasing speed can be justified without significant impact on the overall wear behaviour. However given the above relationship an accelerated test methodology was defined which accelerated test by a combination of both speed and increased preload [7]. This methodology was adopted for test with wear some care needs to be taken in the treatment of constant speed operation and period of acceleration/deceleration.

The original 200SP required life target was $2.78x10^9$ revolutions (including ECSS margins), which based on the experimental data shown in Fig 1 seemed achievable with self lubrication bearings being between the two trend lines from the industrial design guide and actual test data in a space-related applications (note some of these tests were suspended early due to fulfilment of the test requirement and were not at end-of-life). Shortly after starting the wheel development ESA contracted SSTL to build the Giove-A spacecraft on which the 200SP wheels would be baselined. The target life remained since the wheel is a generic product but reflecting the achievable revolutions from the life tests which did not achieve this target, the GIOVE-A wheel speeds were reduced early in the mission from a nominal 1875rpm to ~500rpm equivalent to a total mission requirement of $<800x10^8$ revolutions, which was intended to cover all foreseen life operations for the 27 month mission, with the applicable ECSS safety factors.

2. DEVELOPMENT BACKGROUND

During the main 15 month development 2 life test wheels were run. The first known as the Life Test Model (LTM) Fig 2, which consisted of a flight bearing assembly with elevated bearing preload and inertia which was run at 5 times nominal flight speed to gain confidence in the bearing design quickly while the electronics and wheel architecture matured.

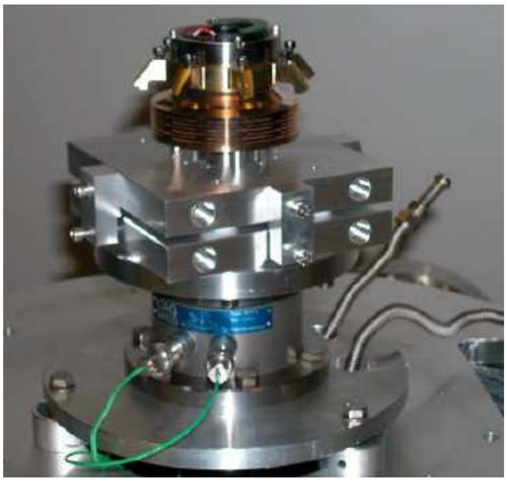


Figure 2. LTM in thermal vacuum chamber, (inertia disc removed)

The second was a full flight standard wheel known as QM1 and shown in Fig 3, which was preloaded to correct flight values and was just run at increased speed to qualify the wheel.

Figure 3. QM1 in thermal vacuum chamber

Both LTM and QM1 wheels reached end-of-life, the onset of which was caused by excessive cage wear in one of the bearings before completion of the generic target revolution durations. However both wheels achieved the minimum required number of revolutions for the Giove-A mission as shown in Fig 1 and on the strength of which the flight on Giove-A was agreed.

It was concluded that improvements to the cage design to increase the lifetime were feasible. Ball-to-cage and cage-to-land contact results in wear which limits the life of the cage. If the contacting forces and frequency of contact could be reduced by optimising the design of the self-lubricating cage, then longer lifetimes could be achievable. Given the goal of a longer Qualified life, 3 years after the successful launch and operation of the wheels in orbit on Giove-A a 3rd wheel (QM2) was developed and tested.

The purpose of QM2 was to permit implementation of lessons learned during the previous development in order to attempt to increase the qualified life beyond that which could be demonstrated within the original development timescale. QM2 featured a further optimized bearing cage design and the test method was modified to be more representative of the typical orbital use of the wheel, albeit with a slightly increased speed and periodicity.

3. WHEEL DESIGN

3.1. Overview

Fig 4 shows a section view of the 200SP smallsat wheel. The wheel consists of 4 main parts, motor (outer rotor design housed above the main bearings), bearing assembly (integral structural preload system with inner rotating bearing design), drive electronics (imbedded within the wheel for compact design and radiation shielding) and structure.

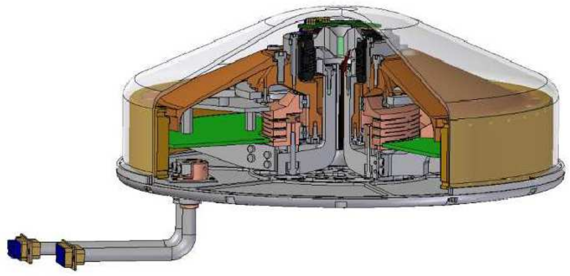


Figure 4. 200SP Smallsat wheel section view

The 200SP is based upon a compliantly preloaded pair of relatively thin-section SEA40 bearings fitted with PGM-HT self-lubricating cages. The bearing system is supplied, assembled, and pre-characterised by ESTL as a deliverable bearing cartridge sub-assembly.

The total rotor mass supported by the bearings (including all rotating elements, shaft, inertia disc, bearing inner rings etc) is ~2.665kg and the total moment of inertia of this rotating mass about its rotational axis is ~0.0229kgm^2. Due to this mass, the upper bearing of the wheel assembly is subjected (in 1g) to an elevated bearing load (combination of preload plus part of 1g shaft weight), whereas the load on the lower bearing is reduced below the nominal preload.

3.2. Bearing preload

In order to keep the bearing torque losses low over the range of operational temperature, the preload of the bearings in the bearing cartridge is set relatively low and a thermally active semi-rigid housing is used which provides compliant preload without sliding of bearing rings and tends to minimise this preload under the nominal thermal conditions. The semi-rigid housing is a novel concept manufactured from one piece of material with a matrix of angular slots configured to provide an effective preload spring stiffness of ~5N/micron.

The bearings in the cartridge assembly are spaced apart in a back to back configuration which due to their size provide a good stability of the wheel keeping the first frequency >200Hz. The nominal flight preloaded is ~35N which equates to peak Hertzian contact stress ~750MPa. Due to what could be conceived as a low preload (for this mass of wheel) required to maintain the life capability Fig 1, shaft deflection under vibration needs to be managed and the design utilises 3 Vespel snubbers to limit shaft travel under launch vibration. The snubber function can be clearly seen during vibration testing where the onset of snubber contact severely attenuates the responses at the first resonant mode.

The preload for the LTM was increased to ~82.5N to allow quicker qualification due to the correlation of the PGM-HT material contact stress and life, Fig 1. This higher preload combined with the 1g axial load means an on-ground peak Hertzian contact stress in the upper bearing of ~1104MPa. The preload could not be increased much beyond this level because at stresses around 1200MPa or more PGM-HT becomes ineffective as a lubricant..

3.3. Bearing cage selection

The design of a cage is a partly intuitive and experimental process in which analysis and established design rules must be supported by a suitably representative test programme. In standard configuration the SEA40 bearing has 29 balls, and the initial design of PGM-HT cage used an Inner Race Riding (IRR) cage with conventional cylindrical ball pockets (a so-called hole-hole-hole (HHH) cage). However an initial set of off-line high-speed screening tests in both horizontal and vertical axis operation showed this initial cage became unstable and generated large torque noise at high speed >4000rpm.

The bearing cage was re-designed using CABARET (ESTL bearing analysis code) and experience from other solid-lubricated systems where introduction of alternate slightly elongated ball pockets has been shown to improve stability by allowing more 'free' movement of the some balls. A 24 ball outer race riding (ORR) hole-slot-hole (HSH) cage design was generated and this was shown in test to produce lower torque noise. This design was then carried forward to the LTM and QM1.

During the QM2 development 4 more cage designs were developed and subjected to screening tests. It was decided to keep the ball complement fixed at 24 so as not to effect the vibration qualification/load capacity of the wheel. Initial lessons learned from the testing of LTM and QM1 were fed into the design and selection process and a number of parameters were explored experimentally:

- Form of the cage – roundness
- Thermal treatment of the cage
- Land to cage clearances

- Hole size / pocket spacing
- Riding position stability over life

The following cages ORR-HSH, ORR-HHH, IRR-HSH, and IRR-HHH were selected for screening test to see if small changes improved the design.

Note that at this time the recent findings concerning PGM-HT material shrinkage and thermal strain behaviour were unknown and in common with all cages at the time no thermal pre-conditioning was initially proposed for the cages and initial cage designs were in danger of providing insufficient clearance to accommodate the variability of CTE ultimately discovered [9,10,11].

However there were some preliminary indications of material stability issues for cages of this relatively large size and thin section and therefore a 24hr heat treatment at 140°C was introduced during cage manufacture. A greater cage/land clearance allowance was also permitted to accommodate thermal strains and the manufacturing process was modified to accommodate expected anisotropy of the PGM-HT with respect to CTE.

3.4. Bearing cage screening tests

Fig 5 summarises the mean torque evolutions for the relatively short duration screening tests together with from earlier (2004) screening tests and testing of an additional QM1 cage design which included heat treatment. As can be seen, most cages were similar in terms of torque behaviour versus test duration (no. of revs). Pre-and post-test cage mass measurements also showed minimal wear. The specific mass loss per bearing rev or each cage type showed in order of least mass loss ORR-HSH>IRR-HHH>ORR-HHH>IRR-HSH.

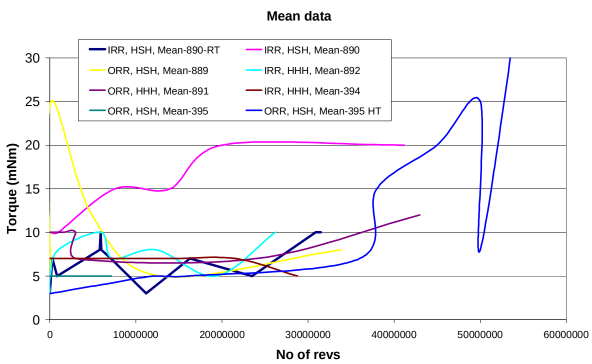
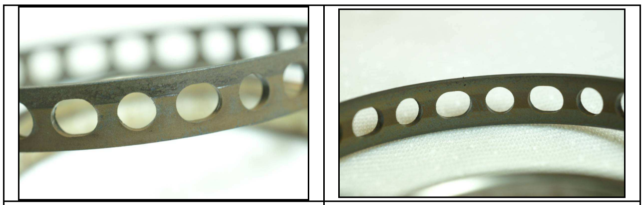


Figure 5. Bearing cage screening test mean torque

During dis-assembly of these test bearings, evidence of contact on both riding AND non-riding cage surfaces was discovered. The pattern of light polishing shown in Fig 6 should not be possible for the nominal geometry assuming the cage remains rigid and round (note in the bearing the outer race is relieved).



Outer race of cage	Inner race of cage

Figure 6. IRR-HSH Post test cage photos

As a general design goal, the drag forces between cage and bearing lands needs to be minimised so as to minimise the ball/cage interaction forces and frequency of collision so reducing cage wear. Despite this it is also clear that some ball/cage interaction must occur to permit transfer from cage via balls to raceways, although the high forces and wear rates resulting from cage instability should be avoided. It was hoped that during screening tests a clearly more optimal design might be identified which would be baselined for QM2.

However this was not the case; there were neither outstandingly good nor bad cage behaviours were experienced and so selection was extremely difficult. Furthermore the elevated typical operational temperature and CTE of the cage material also seems to promote higher friction and thus wear due to potential contact. Given the relatively in-conclusive cage performance data a trade-off was conducted considering the following key criteria,

- Mean torque
- Peak torque noise
- Pocket divider width
- Post test dimensional changes
- Post test mass loss
- Heritage data
- Thermal expansion

On the basis of this trade-off, the IRR-HHH-24 ball cage design with increased land clearances was selected for QM2. The main advantages seen for this design are that there is a large amount of material between pockets and the tolerance to an increase in temperature should be higher than for a corresponding ORR design as the onset of cage/land contact purely due to thermal strains and the prospect of thermal run-away or other cage misbehaviour should be much reduced.

As in the screening tests the cage material would also be thermally preconditioned at 140°C for 24 hours in vacuum prior to final machining.

4. WHEEL-LEVEL TESTING

4.1. Overview

Each test wheel followed a similar test campaign. Characterisation at bearing cartridge level measuring the mean low speed torque performance which was typically ~12gcm mean, ~20gcm zero-peak (without magnetic detent) was followed by functional performance testing as part of the complete wheel system.

As part of the bearing pre-conditioning, all of the wheels successfully completed a vibration test campaign, with random vibration equivalent to ~ 17g rms (Z-axis) and ~14g rms in X and Y axes for 180 seconds.

The wheels were mounted to a kistler torque transducer throughout the life test and the torque noise constantly monitored. Note that because the entire wheel is mounted on the Kistler table, the torque measured includes the reaction torque from the bearings, magnetic cogging torque from the motor and the inertial component due to acceleration/deceleration of the rotor/inertia disc.

The life test was performed in vacuum at a nominal 20^{o}C. Each unit was also subjected to thermal cycles at the beginning and end of the test to -40 to +60^{o}C non-operational and -30 to +50^{o}C operational temperature extremes.

4.2. LTM

The objective of the test programme was to perform an accelerated life test with acceleration by increased speed and load, ideally at >7000rpm for a minimum duration of 8.73x10^{8} revolutions. In order to verify the torque, the speed was periodically reduced to a lower operational value and a torque reversal (several revs in each direction) performed. Given the correlation between Hertzian contact stress and life shown in Fig 1 this test would be the equivalent of the mission life including margins at nominal preload.

The test ran to 734 million revs without significant incident. There were periodic incidences of increased torque noise, however these are considered quite normal for this lubricant solution, and in all cases near nominal performance followed such excursions. Fig 7 shows the torque noise evolution over the life..

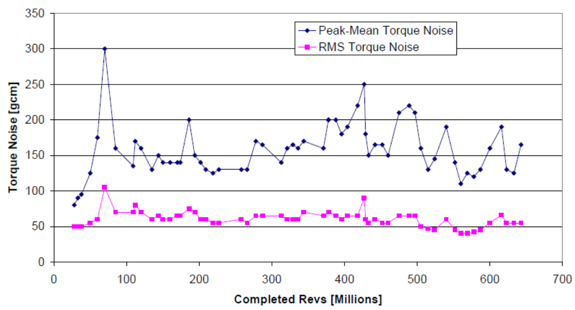


Figure 7. LTM bearing torque evolution over time

The last normal torque reversal carried out at approximately 720 million revolutions showed the reversal torque and torque noise were both typical of previous tests and showed no indication of end of life. At ~731 million revolutions the vacuum test chamber lost vacuum due to a fault and the pressure slowly increased over the following 10-15 hours. During this time there was a significant increase in the torque noise and the performance became erratic which can be clearly seen in the speed profile (the motor was controlled open loop). During this period the wheel conducted ~3x10^{6} revs before a large torque spike was observed which coincided with a rapid deceleration of wheel from 5770rpm to zero rpm in 15 seconds Fig 8.

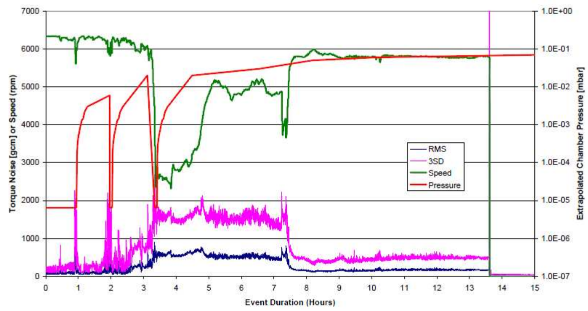


Figure 8. LTM speed, pressure, torque just before the LTM stopped

During the 15 hours some considerable wheel speed and temperature excursions were noted, with temperatures up to 120°C on the bearing cartridge itself (during inspection post test some temperature sensors had become lose so it is possible that temperatures could far exceed 120°C). When considering the ORR cage in this design and the high CTE over about 80°C the cage can theoretically contact the land. Such behaviour is indicative of a so-called "thermal run-away", when some phenomenon creates temperatures which themselves tend to feed-forward into increased temperatures, with ultimate rapid and often catastrophic failure of the bearing system.

The LTM would not re-start after vacuum was restored to the chamber. Upon inspection the LTM inertia disc was found not to rotate, a controlled dis-assembly and inspection was then conducted which found a failure in one of the bearings. The failure had occurred at approximately 94.6% of the minimum test duration.

Though the LTM did not complete its target revolutions and had significant cage wear, from the post-test inspection Fig 9, the condition of the upper bearing (more heavily loaded due to the 1g), which is the main subject of the life-test, was in relatively good condition, but significant wear can be seen from land contact it is not known if this was due to normal wear over life or just during the failure and possibly only due to the increased bearing temperatures.

The failure of the LTM appears to have been initiated at the lower bearing of the pair were the cage pockets had worn through leading to ball crowding and damage which prevented free rotation of the bearing. The lower bearing experiences a lower total load due to 1g and therefore a reduced contact stress so would be expected to last longer than the upper bearing. A number of failure scenarios were considered in order to explain this result, however it seems most likely that the failure of the lower bearing was the result of increased temperatures causing cage-land contact before similar contact occurred at the upper bearing. This contact seems to have lead to a “thermal runaway” at the lower bearing in which higher temperatures generated increased contact forces and dissipations due to cage drag and ultimately such significant wear that premature failure was caused in a very short period of time.

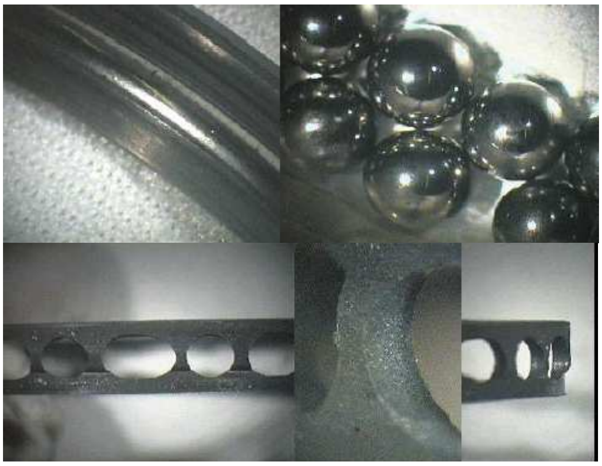


Figure 9. LTM upper bearing race, balls, cage post test

The test suspension also occurred shortly after some disruption to the nominally stable thermal environment. This disruption was instigated by the failure of the laboratory air supply, which lead to the vacuum valve closure. A Delta-Test was repeated on a re-built bearing assembly in an attempt to simulate the even however, perhaps because the Delta-Test bearings were in new condition (i.e. with no cage wear or debris) the failure could not be repeated.

4.3. QM1

When considering the achieved LTM revs with respect to the contact stress the achieved life sits between the 2 trend lines in Fig 1 and so could be considered “in – family”. Given also that the LTM test was suspended prematurely due to a failure which seemed to be initiated by test facility, rather than test-item issue, a decision was made to use the same cage design on the subsequent QM1 unit as for the LTM.

QM1 performed most of it’s testing at constant speeds, from the start a cautious approach was taken due to the LTM failure and the speeds were built up gradually before achieving the target life test speed >5000rpm,

The torque noise performance was relatively stable but slightly noisier bearing performance was noticed approaching 1000 million revolutions Fig11. Due to the proximity of the launch date ~6 months the wheel was tested in a flight representative operational mode cycling around ~1800rpm for the remainder of the test, which, though providing a lower mean operational speed, allowed monitoring of what could be considered normal performance of the wheel with respect to torque, current draw and temperatures

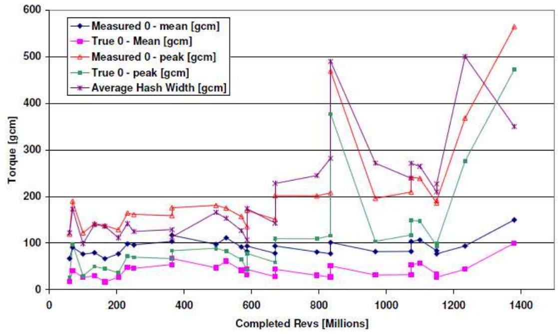


Figure 11. QM1 Torque performance V’s revolutions

At ~$1.5x10^9$ revolutions an increase in temperature tripped one of the temperature sensors which turned the power to the wheel off and allowed the wheel to coast to zero speed in approximately 8 minutes. This “coast-down” time, a very sensitive indicator of bearing performance, was characteristic of normal bearing health. The torque noise and current measurements at this point were also not considered anomalous in any way when compared to recent performance. However the wheel would not restart and upon initial investigation the wheel inertia was found to be misaligned which was later found to be related to ball bearing crowding related to cage pocket wear-through in the upper (higher-loaded) bearing Fig12. This was different to the LTM failure although expected as it is the higher loaded bearing of the pair.

Figure 12. QM1 upper bearing cage post life test

During inspection the bearing cartridge had contained a substantial volume of very fine cage wear debris which had migrated (possibly during chamber venting) within the bearing cartridge and outside into the wheel enclosure (Fig 13).

Once removed the lower bearing (albeit un-preloaded) could be rotated by hand freely without any “higher-torque” position felt. The cage showed some signs of cage pocket wear and elongation, but was generally in relatively good condition Fig 14. There was some evidence of polishing of cage outer surface indicating contact with the outer land in addition to the inner land, most likely caused by the cage running in this configuration for some time, perhaps due to its relatively low rigidity, or due to thermal strains (this cage was not heat treated). The cages were weighed following testing and showed a reduction of 0.17g measured in the lower bearing and 0.55g in the upper bearing.

Figure 13. QM1 debris over wheel electronics

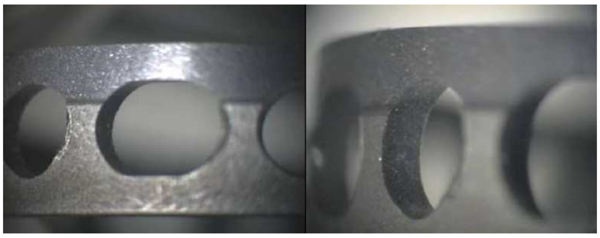


Figure 14. QM1 lower cage post life test

QM1 completed a total of ~1.51×10^9 revolutions and 13680 zero-crossings. Due to the 1g stress distribution, this is equivalent to a lifetime of 1.65×10^9 revs in orbit. When considering the achieved life to Fig 1 the QM1 data points are in line with the lower test trend line and above the minimum required revolutions of the Giove-A life. The lower bearing initial nominal land thickness between each ball slot or hole was measured to be 1.760mm. The thickness of this land post-test was measured and found to be on average 1.264mm, and shows more life remaining in the cage. Furthermore, though this cannot be quantified, it is expected that 1g cage weight and velocity profiles used in a 1g accelerated test also accelerate cage wear beyond that which would be expected in flight and provide for un-symmetric cage wear. This however is an accepted limitation of ground testing.

4.4. QM2

QM2 followed the same test programme as QM1 but at ESA request (this test was funded by ESA as part of the GIOVE-A2 programme) the test was run in a more flight-like profile with only relatively modest test acceleration factor. A +/-1000rpm velocity sine wave was performed with a 6 hour period. This less arduous and accelerated test was agreed due to concerns that previous tests may have been un-representatively harsh and perhaps created un-representative wear caused by fixed high-speed uni-directional motion combined with 1g cage effects leading to premature failure of the bearing cage.

Given also that a further aim of the test was to be able to implement any successful changes into the GIOVE-A2 wheels the build of which was imminent, it was considered essential to make an intermediate inspection in time to change the flight design IF wear was concerning. Therefore an inspection was carried out after about 25% of the planned test duration and this showed nominal cage condition and wear which could be extrapolated to show with good confidence the likely success of the design.

Over the 32-week test a total of 195.8 million revs were completed, which corresponds to 855 cycles and a total of 2,606 zero crossings.

The wheel showed good constant rms torque noise performance at ~20gcm as shown in Fig 16 in which the peak torques correspond to the highest peak measured during the course of each week of testing and were typically recorded as the wheel changed rotation direction and the current data correspond to the largest mean values measured at the maximum wheel speed of 1,000 rpm.

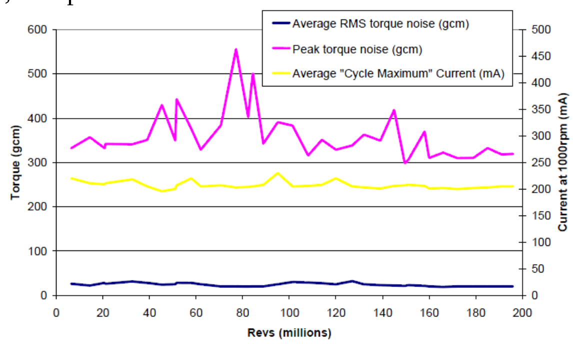


Figure 16. QM2 life test torque, current profile

Upon completion the wheel was stripped down and the bearings / cages inspected. The bearings exhibited features consistent with operation for ~195 million revs, with no excessive quantities of debris or abnormal wear as had been seen in previous tests where the cage land and ball contact had caused significant wear. The appearance of the ball track was consistent with normal operation and transferred lubricant was present on both inner and outer raceways. The balls appeared slightly dulled due to transferred lubricant adhering to the balls, also consistent with normal operation. The cages were in good condition Fig 17, there were witness marks both in the ball pockets and on the ID which are consistent with normal operation and it was predicted on the basis of these observations and cage mass measurements that there was still considerable life left in the cage (assuming that life would ultimately be limited by wear at the ball pockets). There was once again however slight marking on the OD indicating contact with the outer land which should not be possible in normal operation.

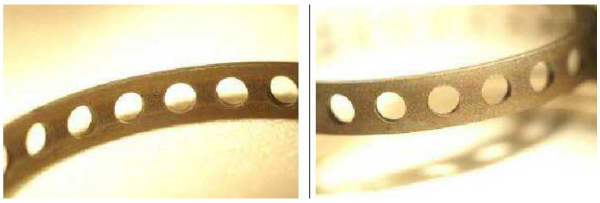


Figure 17. QM2 bearing cage post life test

The cages were weighed and measured following testing and the wear of the cages was minimal, with a reduction of 2mg measured in the lower bearing and 18mg in the upper bearing.

Reductions in both the OD's and ID's of the cages were also measured, although the measurements indicate dimensional changes of less than 0.1%.

5. IN ORBIT PERFORMANCE

In the 66 months since December 2005, 4 wheels have been and continue to be successfully operating on GIOVE-A accumulating ~1.6×10^9 revolutions, so achieving more successful revolutions than any of the previous life tests adding a invaluable point on Fig 1 and so reinforcing the life predictions of the PGM-HT material. The operating mode has changed from the start of the mission to reduce the wheel speeds initially to be certain to achieve the mission life with margin but since to extend the mission life which was originally only 27 months, Fig18. There have been short periods of higher current draw throughout the mission which is quite common for this type of PGM-HT lubrication, and the wheels are currently running in a stable mode with good, constant current draw. As can be seen in Fig19, wheel 1 has a slightly increased current draw compared to the other wheels however this wheel has had slightly higher current throughout the mission.

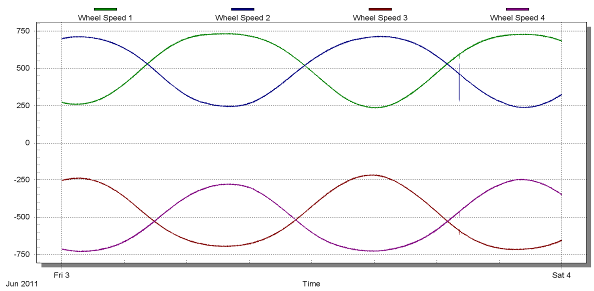


Figure 18. GIOVE-A In orbit wheel data - Speed

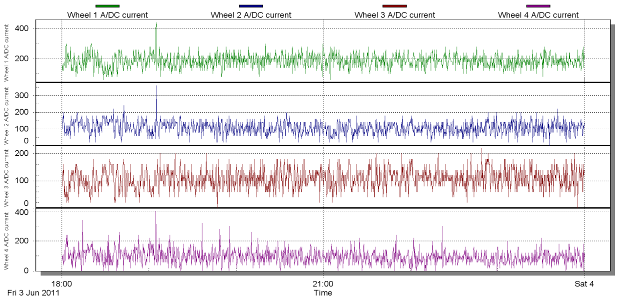


Figure 19. GIOVE-A In orbit wheel data – current

6. DISCUSSION

There are careful considerations to be made when designing and testing self-lubricating wheel systems. As they are sacrificial in nature and rely on cage material transfer to balls and ultimately to the raceway, the speed of the wheels must be managed to be as low as possible in order to maximise life. However it is also clear that, as shown by in-orbit data from SSTL, self-lubricated wheels with PGM-HT have a place in the market.

Moving from use of small bearings with relatively thick-section and therefore rigid snap-over cages to larger thin section bearings and hence more flexible thin-section cages manufactured in PGM-HT was not straightforward. When compared to its predecessor Duroid, or the cotton phenolic material typically used in cages for liquid lubricated bearings, PGM-HT has a inherently much lower stiffness and clearances need to be carefully considered at the design stage.

In thin section bearings it is also clear that the shrinkage and high CTE of the PGM-HT material which was unexpected and not considered during the initial design is also an important consideration. The successful outcome of QM2 life test wheel has shown that if suitably designed and pre-conditioned by heat treatment this self-lubricating cage material can be suitable for larger bearings and systems required to performing billions of revolutions such as wheels or potentially long-life scan mechanisms/radiometers.

There was a very significant difference in the specific mass loss per cage revolution between QM1 and QM2. Even though the cages and test velocity profiles were different in some ways it may also be that this difference reflects the findings presented recently [3] regarding the difference in wear characteristics of un-treated and heat-treated PGM-HT. This effect might be further investigated.

The finally selected cage design of QM2 has clearly been shown to be sufficiently stable to provide good wear properties.

One conclusion from the test campaigns presented here might be that it is essential to vary the test velocity profile in a flight-representative manner even in a highly accelerated test and particularly for thin-section cages to take care to avoid un-representative cage forces due to too frequent or too sharp accelerations/decelerations when compared to the intended flight use.

Previous life tests conducted by ESTL for SSTL on SR6 bearings lubricated with PGM-HT snap-over (cronwed) cages have shown very good performance and little wear after significant running for hundreds of millions of revolutions even with Hertzian contact stresses up to ~1000MPa.

Careful consideration must be given to all contacting or potentially contacting surfaces with in the cage. Given the relatively compliant nature of PGM-HT it is likely not only the ball-cage interaction which could be considered to cause the larger forces and thus most wear. Significant wear can also be found on the cage bore (and even OD) suggesting either that contact forces here could be relatively large or contact more frequent perhaps due to a more "dynamic" stability than for other cages.

7. CONCLUSIONS

The use of self-lubricating bearings with PGM-HT cages in reaction wheels has been successfully proved by SSTL over the last 11 years. The 200SP development programme and successful operation for over 5 ½ years (more than double the mission life) of the GIOVE-A spacecraft has added to this heritage of PGM-HT lubrication in orbit.

Prior to this testing, thin section bearings with this lubricant solution had not been operated for extended periods at high speed in vacuum, either on the ground or in orbit. The operational duration of all the life test wheels fits well within the existing data set for this lubricant collected by ESTL..

8. REFERENCES

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