SOME RECENT EXPERIENCES OF MECHANISM PERFORMANCE AND COMPONENT ASSESSMENT IN THERMAL VACUUM TESTS AT ESTL

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ABSTRACT

The spacecraft mechanism test facilities at ESTL are described. Test results are reviewed on three mechanisms where, in a variety of thermal conditions, the measurement of the reaction torque which would be experienced by the spacecraft was important.
Valuable performance data has been obtained when it has been possible to dismantle mechanisms and examine the condition of all components after the tests. This was particularly important for two ESA mechanisms which had been subjected to 7-year real life tests, one having lead-lubricated bearings and the other oil-lubricated bearings.
A detailed survey is presented of ESTL experience in component examination and failure analysis, with advice on how to improve mechanism reliability.
Keywords: thermal vacuum tests, failure analysis, component examination, reliability.

1. INTRODUCTION

One of the main functions of the European Space Tribology Laboratory (ESTL), operated by the National Centre of Tribology on behalf of ESA, is to do thermal vacuum testing, on behalf of ESA and other European organisations, of mechanisms ranging from small latching devices to large complex solar array and despin mechanisms.

It is not always possible, even with elaborate spacecraft thermal control systems, for an individual mechanism to operate in a predictable isothermal environment. Despite comprehensive thermal analysis it is difficult to obtain accurate predictions, in vacuum, of thermal distribution within complex mechanisms. Also, when several components are operating to different control sequences, resulting in variable power dissipation from motors, slip-rings, cables, etc., thermal gradients can occur over small areas of mechanisms.

Although the performance of individual components may have proved to be satisfactory prior to assembly into a complex mechanism, it is nevertheless true that unpredictable behaviour, and possibly failure, can occur in systems of such components when subject to thermal gradients. Complete confidence in a particular design is only achieved when every possible failure mode has been identified and then either designed out of the system or accepted with adequate demonstration of reliability.

Thus ESA place great emphasis (Ref.1) on performing rigorous thermal vacuum testing on all critical mechanisms. Frequently it is necessary to define two boundary control temperatures, one at the interface between the mechanism housing and the satellite structure, the other at the interface between the rotating shaft and the load which it supports. There are various categories of tests (development, qualification, acceptance, accelerated life) depending on the individual requirements of each project and the level of formality and control which are applied.

When it has been possible to dismantle a mechanism after a test and examine it in detail, very valuable data has been obtained on the performance of all components. The amount of wear, distribution of wear particles, effectiveness of lubrication systems, and the long-term stability of materials have been assessed. If the performance of a mechanism has been outside its specification, the reasons for this have been identified and corrective action advised. This has enabled the ultimate operational life-time of components to be analysed in a way which would otherwise have been impossible. Of great importance is that incipient failure modes have been identified which had not been detected during the operational and measurement sequences in the thermal tests.

2. ESTL FACILITIES

Several types of ultra-high-vacuum test chambers are used for mechanism testing. Certified clean room conditions have proved to be essential in the success of thermal vacuum testing, particularly with regard to the handling and inspection of mechanisms. Part of ESTL is shown in Figure 1.

Thermal shrouds are placed around the item to be tested in the vacuum chamber and, by controlling the temperature of these, various thermal gradient environments can be imposed on the mechanism. Turbo-molecular, sputter-ion and cryogenic pumps are the only types of pumps used, so as to ensure a clean environment.

Figure 1. Part of the ESTL test facilities.

Each system is fully instrumented with mass-spectrometry facilities for residual gas analysis. It is usually considered that a valid tribological test can only be done at pressures below about 10^{-7} mbar, based on considerations of the relative amounts of residual H_2O, O_2, CO, etc. Of course if the only consideration is that of adequately simulating the thermal transfer parameters in vacuum, then a pressure as high as about $5x10^{-4}$ mbar may be satisfactory.

All the facilities are fully instrumented with several different types of data logging, alarm and safety devices as there must be no possibility of the test facility itself introducing possible failure modes.

Further details of these ESA test facilities are available in Reference 2.

3. TESTS INVOLVING INTERACTIVE TORQUE MEASUREMENTS

Over recent years one essential parameter which has been studied during thermal vacuum testing is the reaction, or interactive, torque experienced by the housing of a mechanism when the shaft is rotated. With the increasing use of stepper motors in preference to brushed or 2-phase motors, analysis of this parameter is of great importance because stepper motors often provide greater torque impulses than the other types. Where it has been possible to load the mechanism shaft with an inertial mass which approximates that experienced in flight, realistic assessments have been possible of the behaviour of the mechanism in a variety of thermal environments.

For these tests, the complete test facility structure comprising the mechanism, thermal control radiators and inertial mass, is supported on a sensitive torque transducer. The type used by ESTL is a piezo-electric crystal transducer which has a very high stiffness, high natural resonant frequency, and low variation of charge sensitivity with temperature. It must be emphasised that the measurement system is only suitable for dynamic measurements as a truly constant charge state does not exist. The time constant of the charge measurement system depends on the selected sensitivity range and for many applications it must be remembered that the lower cut-off frequency may be of the order of 0.5 Hz. The recommended precautions for installation and operation must be obeyed as misleading results can otherwise be obtained.

3.1 Advanced solar array drive (L-Sat/Olympus ASADM)

This mechanism (Ref 3) was subjected to a qualification and accelerated life test at various thermal conditions in the range -50°C to +90°C. In addition to evaluating the reaction torque, much valuable data was obtained on the performance of the stepper motors, the redundant motor selector, and the power, signal and pyrotechnic slip-ring assemblies. The measurement of the variations in thermal distribution in the mechanism were very important due to the large power dissipation in the concentric power slip-rings (8 Amps in 50 rings on two discs of different specification).

Figure 2 shows a typical recording of the reaction torque when the shaft, supporting an inertia of 1.5 kg.m^2, was rotating at one revolution per day.

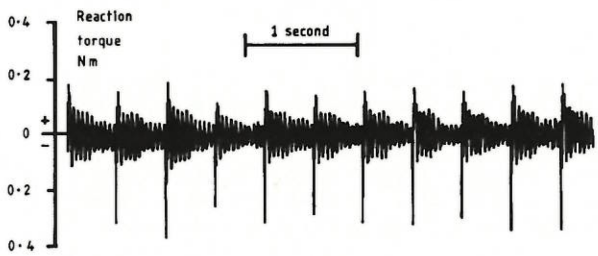

Figure 2. Reaction torque from ASADM at 1 rev/day.

The torque pulse caused by each motor step impulse is clearly evident and the inertial oscillation which follows almost reduces to zero before the occurrence of the next motor step. In the qualification test the average torque pulse was about 0.35 Nm, the highest observed value being 0.66 Nm. As the accelerated life test proceeded, the reaction torque showed a small increase, to give at the end of the test an average value of 0.39 Nm and an overall maximum of 0.72 Nm.

Figure 3 shows a typical torque recording at a speed of 1.33 revs/hour. At this acquisition speed the torque zero reference line is not now evident and at this speed it would usually be necessary to judge the mechanism performance in terms of a peak-to-peak reaction torque specification. In this case typical values of the order of 1.15 Nm pk-pk were found.

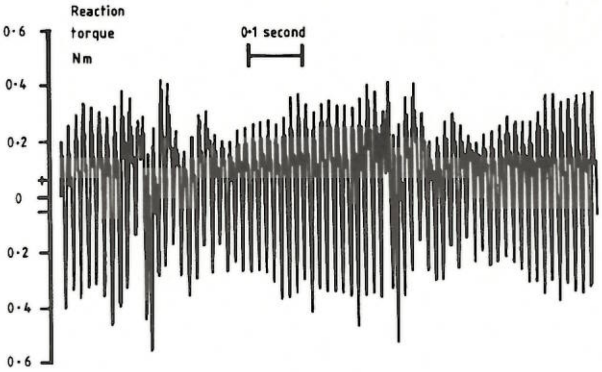

Figure 3. Reaction torque from ASADM at 1.33 revs/hour.

The mechanism performance was satisfactory at all stages of the test. It was interesting to note that the mean slip-ring/brush contact resistance in each power circuit slowly reduced during the test (of about 4000 revolutions) by about 15%. Considerable variation in slip-ring noise occurred from time to time but most rings showed only a modest overall increase. One slip ring module consistently gave higher noise readings than the other. When examined after the test, the slip-ring discs were quite clean with only small amounts of gold wear particles present. The disc with matt-finished rings appeared to be more susceptible to wear than the disc with polished rings and produced larger wear particles. There were several small cracks in the polymer structure which could have had serious consequences.

At the end of the test the lead-lubrication coating on the races was found to be in good condition and the balls had the characteristic uniform dull grey/blue transfer film of lead. Very small amounts of lead-bronze wear debris from the cage were present. A notable feature of this test was the substantial amount of outgassing over a long period of time from the mechanism surfaces, particularly in the 'hot soak' condition during which typical temperatures were +90°C on shaft, +94°C on power slip ring module, 107°C on power slip ring cable connector, 110°C in drive motor, etc. This outgassing caused the test chamber pressure to rise to 3×10^{-6}mbar whereas in a cold test it was 3×10^{-8}mbar. This amount of outgassing at elevated temperatures frequently occurs from mechanisms and thus it is normally ESTL practice to outgas the item under test prior to commencing the formal thermal vacuum test. After the test the cold head of the cryogenic pump was found to be contaminated with condensed volatile residues of potting compounds, insulation materials, etc.

3.2 Space telescope solar-array drive mechanism

This mechanism (Ref 4) is unique in that it has oil (Fomblin Z25) lubricated bearings and the power transfer is via a flexible wire harness (FWH) located within the shaft. In the ESTL test an inertia of 1.5 kg.m^2 was employed but of course in flight a much larger inertia is present. The thermal conditions covered a range of −55°C to +80°C with various thermal gradient conditions being imposed. The FWH power dissipation was simulated by passing 1.9 Amps through it. Several models of this mechanism have been tested at ESTL.

The main criterion of performance was the variation of the torque due to the twisting of the FWH with the angle of slew over about ±170°. Although the manufacturer had done a careful design assessment of the FWH, the tests at ESTL provided valuable data on the characteristics of the system. Figure 4 shows a typical recording of the FWH torque (as a function of the demanded motor control voltage).

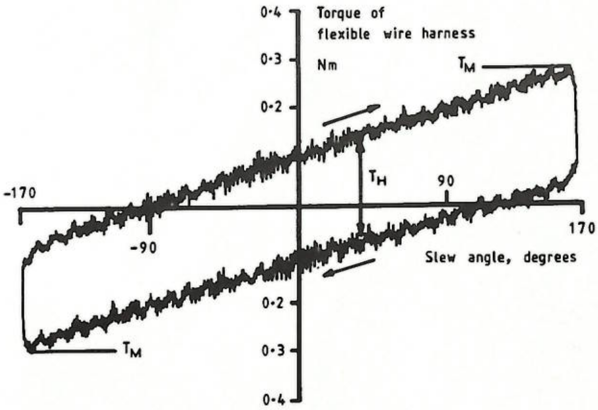

Figure 4. Typical variation of FWH torque with slew angle during thermal vacuum testing.

The torque increases linearly with slew angle. On reversal of motion there is a steep reduction in torque, due to the stored energy in the FWH, before the torque reduces linearly with slew angle. The area enclosed between the wind-up and wind-down curves is a measure of the hysteresis in the FWH. These curves were analysed in terms of the maximum torque, T_M, at the extremities of motion and the hysteresis torque, T_H. These were found to change with temperature and over the range used in the ESTL tests typical values for T_M were from about 0.24 to 0.36 Nm and for T_H from 0.11 to 0.25 Nm.

Using the piezo-electric torque transducer, valuable data was obtained on how these torque fluctuations within the mechanism would be transmitted as interactive torque variations to the spacecraft. The interactive torque was found to be relatively insensitive to the thermal environment, typical values of 0.0085 to 0.0095 Nm peak-to-peak being measured.

3.3 Despin mechanism for ESA Giotto mission

One flight model of this mechanism (Refs 5 and 6) was subjected at ESTL in early 1985 to a thermal vacuum qualification test with an inertial load of 1.85 kg.m^2 applied, this being the true antenna inertia. Information was required on the stability of the speed and pointing accuracy control system in the various thermal conditions anticipated to occur in flight. Measurement of the interactive torque, and its power spectrum, proved to be a critical item in characterising the performance of the system, particularly over the main speed operating range of 14 to 16 rpm.

It was essential to do this in vacuum so as to exclude the effect on the system of the damping factor in air. Figure 5 shows this mechanism in the ESTL test facility.

Figure 5. Giotto despin mechanism being installed in the ESTL 1-metre diameter test facility.

Typical values of the interactive torque were in the range 0.02 to 0.045 Nm peak-to-peak at a speed of 15 rpm. The mean running torque (measured on the reaction torque transducer by observing the step change in dynamic torque at the instant that the motor power was switched off) was of the order of 0.1 Nm. The power spectral density, over the range 0-20 Hz, of the interactive torque was generally of the form shown in Figure 6.

The natural resonance of the system (comprising the motor, inertia and electronic control system) was at or near 1.85 Hz, the position of this resonance peak moving to about 1.75 Hz in a cold test and to near 1.9 Hz in a hot test.

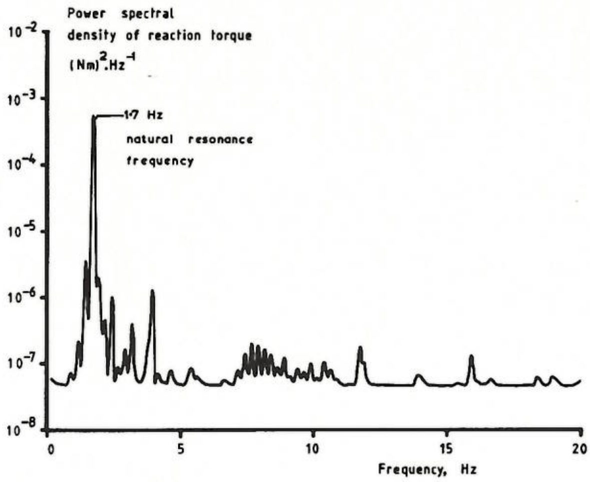

Figure 6. Typical power spectral density (PSD) of interactive torque over the frequency range 0-20 Hz. 15 rpm in cold gradient test.

However, if the resolution of the frequency spectrum was increased by monitoring the PSD over 0-5 Hz it was found, as in Figure 7, that at certain shaft speeds the natural resonance peak was being modified by the presence of a peak associated with the 7th harmonic of the mechanism rotational speed.

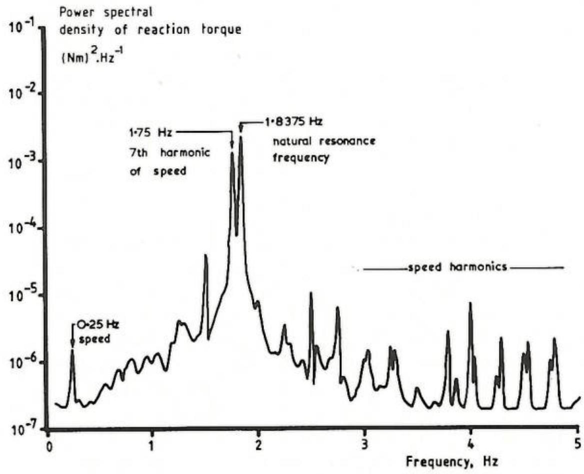

Figure 7. Power spectral density over range 0-5 Hz. 15.0 rpm at ambient temperature.

It was found that the relative position of the 7th speed harmonic and the system natural resonance varied with the mechanism speed and, at ambient temperature, a critical speed of 15.527 rpm was identified at which these coincided to give a very large spectrum peak shown in Figure 8.

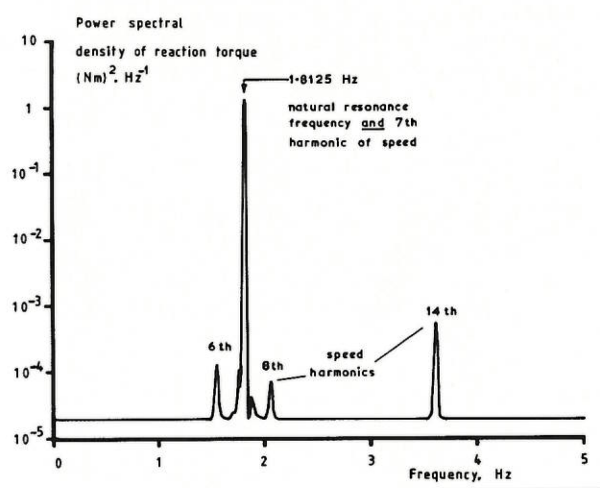

Figure 8. Large spectral peak at critical speed of 15.527 rpm at ambient temperature.

The peak-to-peak interactive torque was thus greater at this speed because of the effect on the system natural response. When the speed was increased above 15.527 rpm, the 7th speed harmonic moved to the right of the system natural resonance and the interactive torque returned to normal levels. From the data obtained in the thermal tests at ESTL it was possible to identify other such critical speeds at which the natural resonance response of the system was modified by the presence of the 6th, 7th and 8th speed harmonics.

Thus this test, involving realistic operating conditions of applied inertia and thermal environment, was essential in characterising the behaviour of the system and generated performance data which was directly applicable to the flight situation.

4. SOME OBSERVATIONS ON LONG-TERM TESTING

Occasionally there are valid reasons for doing long-term tests in order to fully assess the behaviour of a mechanism and its component parts and materials. An important factor to consider because of the very large surface areas of mechanisms is it can take a long time for surface outgassing to reach stable equilibrium. Furthermore, a mechanism may intentionally be partially sealed to protect it from contamination before launch and very long leak-paths may be present in connectors and cable looms. In a short thermal vacuum test, of only a few weeks duration, the vacuum within the mechanism may be at least a decade of pressure higher than outside and this must be borne in mind when assessing the validity of those tests where the behaviour of different materials in contact with each other is being analysed. In order to remove some of these uncertainties, ESTL were contracted by ESA to do a 7-year real life test on two mechanisms, one having lead-lubricated bearings and the other having bearings lubricated by a combination of oil and grease.

4.1 Solar array drive mechanism

Details of this mechanism and the 7-year test results are available in References 1 and 7. The main features of this mechanism are:

Drive	- commutated dc motor
Bearings	- lead-lubricated by evaporation process
Slip-rings	- 5 power rings on shaft
	- 40 concentric signal rings on ceramic discs
	- $Ag/Cu/MoS_2$

One of the main reasons for this test was to establish the validity of accelerated life testing on a lead-lubricated device by comparing the test results with accelerated tests which had been previously done at ESTL on two other identical mechanisms. This validity was indeed proved.

The mechanism behaved in a stable manner, the motor power required to maintain one revolution per day rotation changing by only about 10%. The majority of the slip rings operated satisfactorily. Although considerable variation in contact resistance occurred over short periods of time, it was possible to identify certain trends. The average interface noise had increased during the test by a factor of from 1.5 to 8, most circuits indicating a factor of between 2 and 5. The nominal noise limit per signal slip ring pair of 1mV/A was occasionally exceeded. An unexpected observation was that occasional transients of up to about 2 ohms interface resistance occurred in two of the 500mA signal circuits.

On examination of the mechanism it was found that although the bearings had operated satisfactorily, localised rust patches were observed on the running track of one bearing. These coincided with the ball positions and this suggested that the bearing may have been washed after assembly. If an assembled bearing is solvent cleaned then it is essential to ensure that all residues and contaminants are completely removed. This is not always possible if a complete mechanism is solvent washed.

The slip-rings and brushes were free of wear debris and excess MoS_2 but high contact resistances were sometimes found in all circuits when the mechanism was manually rotated to the positions which coincided with marks on the slip-rings which had been formed during vibration testing. Values up to 24 ohms on the signal rings and 0.7 ohms on the power rings were measured. Radial fractures in the power slip rings were found and although these could lead to failure in some circumstances, they had not grossly affected their performance. No conclusive evidence was available to explain the variable nature of the high resistance transients found in the signal circuits during testing, but the inference is that they were associated with the presence of excess MoS_2 at or near the vibration marks (Ref 8). Similar problems have been previously identified at ESTL as being due to deterioration of the MoS_2 (Ref 9). This deterioration, whether due to excessive operation in normal air or to incorrect storage, is a matter for concern.

4.2 Despin mechanism

Further details are available in References 2 and 10 but the main features are:

Drive	-	2-phase brushless motor
Bearings	-	Grease/oil and reservoir lubrication
Slip-rings	-	5 silver power rings $Ag/Cu/MoS_2$ composite brushes

This was a unique test in that it provided a rare opportunity to assess all aspects of the performance of a liquid-lubricated mechanism rotating at 60 rpm under conditions approaching those of boundary lubrication in the hot part of the test. The bearings were lubricated by a combination of BP110 oil, held in cages and in porous reservoirs, and BP2110 grease. This grease uses an oleophilic lead-graphite thickener which can provide additional boundary lubrication. Shaft seals and anti-creep barriers were used to contain the oil. At ESTL we have made a detailed study of this oil and have found it to be an excellent lubricant, but unfortunately it is no longer available.

The mechanism operated satisfactorily throughout the test which was extended to 8 years, or 2.5×10^8 revolutions. Figure 9 illustrates the fact previously mentioned that the test chamber pressure can take a long time to stabilise, the cyclic variations in pressure reflecting the changes in outgassing due to changes in thermal conditions.

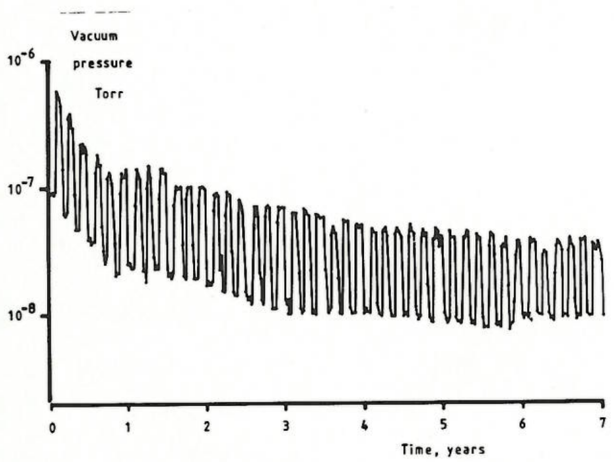

Figure 9. Test chamber pressure during despin mechanism 7-year test.

Although there was no overall change in the slip ring performance, large but temporary increases in noise of up to a factor of 7 were measured immediately after some of the thermal changes. This was probably caused by differential axial expansions in the system resulting in the brushes starting to run in a different track, several days of running-in being necessary before the contact resistance returned to normal. The presence of variable small quantities of oil and wear debris could also contribute to this phenomenon.

A somewhat unusual and at times entertaining feature was a once-per revolution ticking noise which was occasionally quite loud from outside the chamber!

On dismantling, the bearings were found to be extremely clean, the balls and races showing only very slight indications of wear. There was a boundary lubricant film of grease thickener on the running tracks. Excess grease was present on the outer walls of the phenolic cages and there was adequate free oil present in the bearings. The oil reservoirs had apparently released their oil at a satisfactory rate and they still had an adequate reserve of at least one third of the original oil. The labyrinth shaft seals and the anti-creep barriers had been effective in containing the oil but it was evident that additional surfaces adjacent to the bearings should have been treated with the anti-creep barrier.

There was a great deal of wear debris present in the slip-ring compartment but the brushes had only worn by about 10% of their free length. Most of the debris had been spun away from the slip-rings and there was no indication that shorting across rings could ever have been possible. Samples of wear debris were subjected to SIMS (secondary ion mass spectrometry) analysis and it was proved that small amounts of the lower molecular weight fractions of BP110 oil were indeed present. It is important to note, however, that even in the presence of this oil, the slip rings had operated satisfactorily.

The bearing pre-load assembly, a double bellows device was examined. The outer joining ring was found to be loosely crimped onto one of the diaphragm members and when flexed would relax to give the ticking noise noted in the test. This anomaly did not influence the validity of the test.

Thus the design of this mechanism has been successfully established, many of the techniques used being of interest in future designs. The successful operation of the high-precision bearing system was mainly due to the fact that the lubrication system had been correctly designed and had been assembled with careful attention to detail.

5. SOME OBSERVATIONS ON COMPONENT EXAMINATION

5.1 Bearings

The essential requirement for bearings in spacecraft is low mean torque and low torque variation (or "torque noise") over a lifetime often in excess of 10 years. Either dry lubrication or oil lubrication can be used, but for many duties in spacecraft a solid lubricant such as ion-plated lead is satisfactory. It is permissible to solvent wash a solid-lubricated bearing only if all solvent residues are completely removed. It may not be possible to guarantee that this can be achieved if solvent cleaning is done on a partially assembled mechanism. Figure 10 is an example of a lead-lubricated bearing ring where a corrosion spot caused by solvent contamination has formed on the plated surface of the raceway.

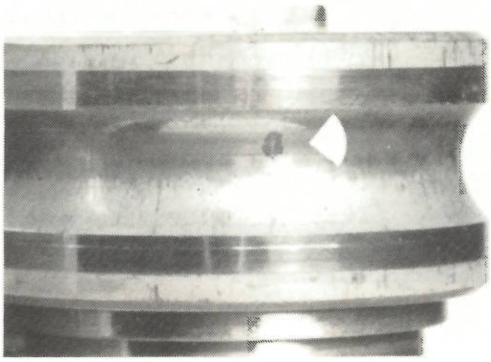

Figure 10. Corrosion marks on bearing

This corrosion is obviously undesirable because not only can rust debris damage the bearing but if it occurs on the abutment faces it can also prevent correct axial movements during thermal cycling.

The practice of etching identification symbols on bearings, as in Figure 11, is undesirable. Several problems have been encountered where this type of engraving has caused misalignment and unacceptable preload variations, particularly in duplex bearings under hard preload.

Figure 11. Engraved symbols on bearing

There has also been evidence that high voltage insulation testing of mechanisms has resulted in pitting damage to balls and races due to pulsed current flow through the bearing.

Figure 12 shows an unusual double wear track resulting from incorrect assembly of a separable lead-lubricated angular contact bearing after validation of the bearing.

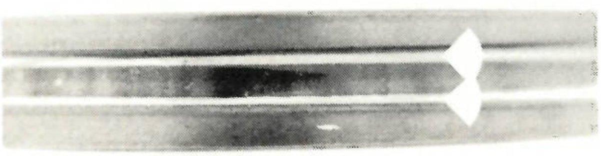

Figure 12. Double wear track on raceway.

It is thus essential that such bearings are asembled to the correct inner/outer race orientation as stated by the manufacturer. Unfortunately, orientation identities differ from one manufacturer to another.

As regards oil-lubricated bearings, those removed from the despin mechanism after its 7-year test (Section 4.2) were in remarkably good condition. Experience with this and other mechanisms has identified some useful practical rules to follow. For example, if it is necessary to use an anti-creep coating, then this must be applied to <u>all</u> adjacent, completely clean, surfaces as well as to holes used for cables, inspection or venting. Anodised surfaces are often porous and must be thoroughly cleaned prior to the application of creep barrier. Oil reservoirs have usually proved to be very effective for long-term operation, but only if the reservoir fabric is in uniform intimate contact with its housing. Some care is needed to achieve this as we have found one example where the reservoir was secured by countersunk screws in such a way that it distorted resulting in insufficient oil flow to the bearing.

5.2 Gears

These are now frequently used in spacecraft mechanisms. The load limitations of plastic gears have inevitably restricted their use to appropriate service conditions and thus satisfactory operation is usually achieved. The problem at the present time is to extend the use of metal gears in high load conditions. The close tolerances required in small gears are not easy to achieve and failures have been reported in small gearboxes employing perfluorinated grease lubrication. There have been many examples of contamination by gear wear debris, and accumulation of such debris in a grease-lubricated gearbox can result in rapid deterioration in performance.

The most serious failures encountered at ESTL were due to incorrect heat treatment and machining techniques. In one instance a gear drive shaft fractured due to fatigue failure where the final machining of the shaft had penetrated the case hardened surface.

On another occasion, several tooth tips of a nitrided gear had fractured and fallen off, as shown in Figure 13.

It was confirmed that this problem was not due to excessive tooth loads or to fatigue but to manufacturing and nitriding factors. In this case it was recommended that the teeth be chamfered, so as to minimise deformation of the tooth tips during hobbing operations, and then stress relieved prior to a more closely controlled plasma nitriding heat treatment. The nitrided depth should be controlled so as to be only slightly greater than the predicted maximum shear stress depth and if possible the side faces of the teeth should be screened by a suitable coating during the nitriding process.

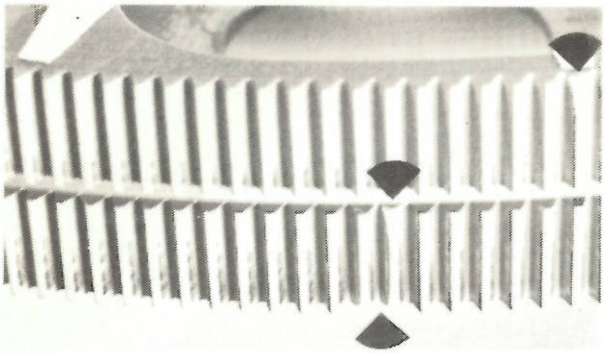

Figure 13. Fracture of gear teeth tips.

A consequence of the failure of some tooth tips was that one or more particles had entered an adjacent bearing. Pitting damage was found on the balls and races and as seen in Figure 14 the shaft had seized within the inner ring.

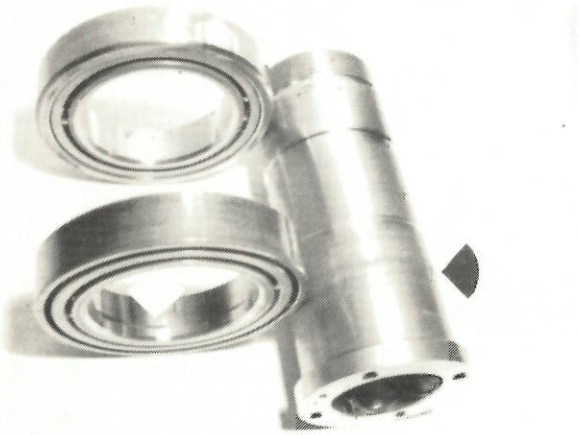

Figure 14. Shaft/inner race seizure.

It was deduced that the high torque generated by the presence of tooth particles had resulted in the shaft rotating within the inner ring until galling seizure had occurred.

5.3 Slip rings, brushes and motors

The most common slip ring assembly examined at ESTL has been a silver ring with silver/copper/ MoS_2 composite brush. Usually the amount of wear debris in a slow speed mechanism, for example a solar array drive, is very small but there have been many examples of deposition of surplus MoS_2 on the rings during vibration testing which can result in large increases in contact resistance. As shown on Figure 15 the width of the vibration mark increases as the distance from the brush block anchorage point increases. The area of the vibration mark will also depend on the degree of conformity between the brush and the ring.

It has been observed that good brush conformity is not always obtained in small brushes held on cantilever springs. This has not, however, resulted in any degradation of performance.

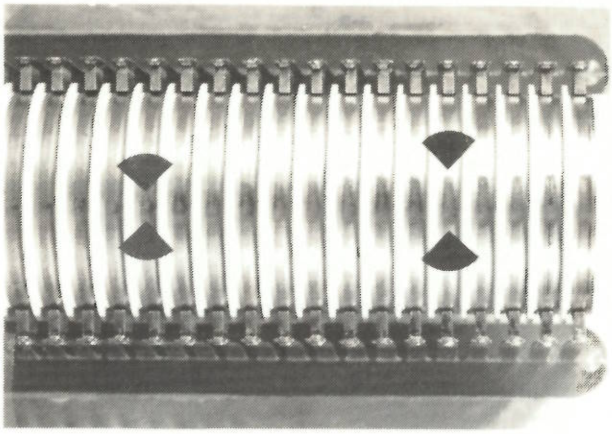

Figure 15. Vibration marks on slip rings.

Because brush wear is almost linear with total sliding distance, the amount of wear debris in a despin mechanism is greater than in a solar array drive mechanism, although the actual wear rate is modest. Typically some 3 cc of loose debris may accumulate, most of it being as very fine dust adhering to the brushes, slip rings and adjacent surfaces. The distribution of wear debris in a spacecraft is difficult to determine from the results of ground testing, but experience at ESTL suggests that it would be beneficial to provide undercut and not flush-mounted insulating bridges between rings. All possible debris catchment areas should be chamfered or angled to prevent debris build-up.

Occasionally within the brush wear debris are found quite large pieces of composite swarf, some measuring 3 x 0.8 mm. These are probably caused by the agglomeration of small silver particles at the leading edges of the brushes which eventually become detached. Other particles of ring material about 20 mm long and only about 5 micron in section have been found. These long particles could result in shorting across the brushes. their origin is probably due to the slip ring surface being machined by particles of work-hardened silver, or adversely orientated MoS_2 particles, in the brush. Indeed, narrow grooves up to 25 micron deep have been found.

The brush and commutator components of dc motors have shown the same characteristics identified above for slip rings, but the arcing across the contacts during air testing tends to promote the formation of hard particles. As the performance of these motors in vacuum is generally satisfactory a detailed study of the current transfer characteristics of the brushes has not been necessary.

Insulating materials must be carefully selected for strength and rigidity, particularly in coaxial disc type units. Although surface cracks have been found in ceramic discs, presumably formed during vibration testing, more serious structural cracks have been found in polymeric discs. The example shown in Figure 16 has cracked near a metallic insert sleeve. In one instance we found that the electro deposited silver had cracked across the ring.

Figure 16. Cracked slip ring disc

Surprisingly these defects had not caused any noticeable departure from the specified performance but obviously they suggest that a failure could eventually occur.

Materials used in motor stator and rotor laminations have been known to exude a fluid during vacuum testing which leaves behind a powdery deposit. This phenomenon requires further study.

In one motor a securing screw had disturbed a joint between two laminations causing the stator to twist, resulting in a misalignment of 0.5 mm.

5.4 Ancillary components, assembly and handling techniques

Some bearing off-load devices use stainless-steel release cables. In some cases it has been found that these can assume a permanent deformation during storage which, when the system is released, may result in the cable not fully releasing. Positive cable retaining springs should be used whenever possible.

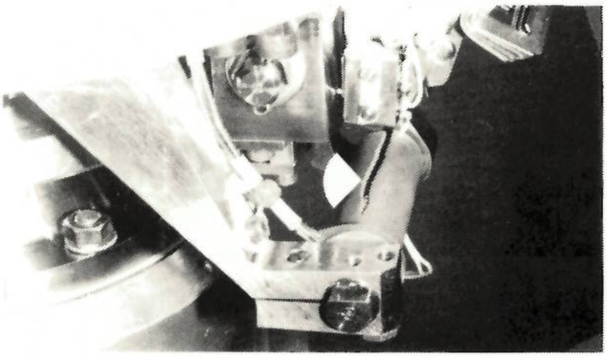

Figure 17. Ruptured MAE heater sheath

One type of release mechanism employing memory alloy elements had been tested satisfactorily in ambient air conditions, but when the heater was energised in vacuum at -60°C, with what was assumed to be the correct power input, the difference in thermal transfer resulted in localised over-heating and rupture of the outer sheath, as shown in Figure 17. Silicone compounds were released which contaminated the mechanism and the vacuum testing facility.

There have been several examples of the reduced thermal transfer in vacuum not being fully appreciated, creating higher temperatures and larger gradients than were expected. This is critical for items which are very sensitive to differential thermal expansion and where small clearances are required. For example the periphery of a slip ring disc had come into contact with the brush block assembly, and axial movement during a thermal test resulted in seizure.

One disturbing feature found during dismantling that sharp edges on components have resulted in abrasion of cable insulation. The holes shown in Figure 18 are used as guides for power slip ring cables but the sharp edges had cut through the insulation and the particles removed had been trapped between two radial surfaces causing slight misalignment.

Figure 18. Sharp edges and insulation debris

Regrettably there have been many examples of cable damage due to poor handling and assembly techniques. When cables are tied together as a group it must be remembered that during long periods of thermal cycling at extreme temperatures, particularly in high-current cable looms, they can relax and take up permanent deformations which can result in cables interfering with rotating components.

There is unfortunately frequent evidence of poor handling techniques. Finger prints, which can initiate corrosion, have been found on precision bearings, and several items of flight standard equipment have been received at ESTL with many particles of cable insulation, potting compound residues, metal swarf, etc, adhering to critical areas. It is essential to use the correct type of powder-free plastic gloves during handling, as woven cotten gloves have proved to shed fibrous particles and some are porous to skin perspiration. Constant vigilance and attention to detail during mechanism assembly and handling is just as important as any other phase of the design and development of a successful mechanism to ensure that high standards are maintained.

6. CONCLUSIONS

Thermal vacuum testing of spacecraft mechanisms has proved to be essential in assessing their reliability. It also offers a unique opportunity to assess the characteristics of a system under realistic operational conditions. Where it has been possible to load the mechanism by an inertial load which approximates that experienced in flight, valuable data has been obtained on the real interactive torque which will be transmitted to the spacecraft. Detailed examination of mechanism components after a test has proved to be of great value in assessing the condition of all items and only in this way has it been possible to identify possible failure modes otherwise undetectable.

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