A POST-FLIGHT TRIBOLOGICAL ASSESSMENT OF THE HUBBLE SPACE TELESCOPE SOLAR ARRAY MECHANISMS

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ABSTRACT

The tribological components, contacting surfaces and lubricants utilised in the Solar Array Drive (SADM), Primary Deployment (PDM) and Secondary Deployment (SDM) mechanisms of the -V2 wing of the Hubble Space Telescope Solar Array (STSA) were assessed after return to Earth, to determine suitability and effectiveness in their applications. The majority were found to be in good condition, with no evidence that any modification in mechanism design or the method of lubrication would have been beneficial. Otherwise, the main findings were: a worn anodised layer on PDM gears; corrosion on some PDM bearings; solid lubricant depletion on the clamping surfaces of the SADM offloading devices; surface damage on unprotected locating surfaces in the SADM; depletion of the solid lubricant on the SDM inboard actuator gears; surface distress on gear bores and spindles of the 3rd stage of the motor/gearhead. The two booms of the SDM inboard actuator revealed radial marks of variable intensity and width at the contacting interfaces of the inner and outer elements, their nature and variation along the boom providing an insight into possible modes of boom failure.

Keywords: anodised gears, solid lubricants, offloading devices, bearings, motor/gearhead, booms.

1. INTRODUCTION

Three prime mechanisms, namely Solar Array Drive Mechanism (SADM), Primary Deployment Mechanism (PDM) and Secondary Deployment Mechanism (SDM) were utilised in the Hubble STSA -V2 Wing (their locations being shown schematically in Figure 1). Their retrieval, after 3.5 years of flight operation, provided ESTL with a unique opportunity to carry out detailed assessments of the post-flight condition of tribological components and their solid and liquid lubricants. Such information is of importance and relevance to future missions and the main points of interest, for each of the three mechanisms, are now summarised. Full details are contained in Reference 1.

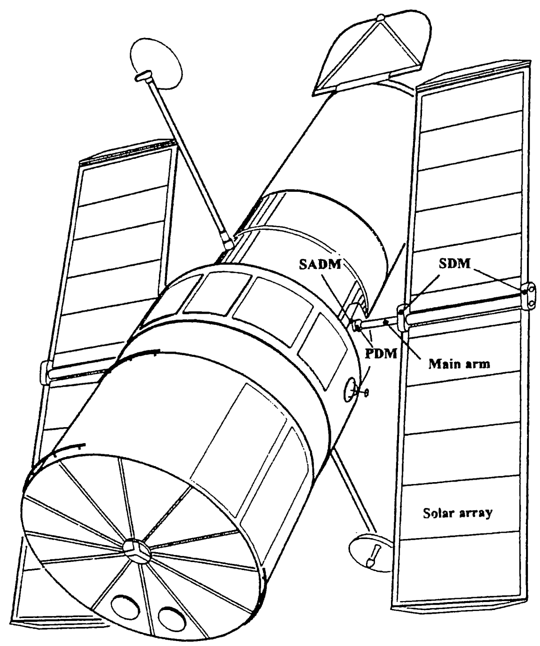

Figure 1. Schematic diagram of the Hubble Space Telescope showing the locations of the SADM, PDM and SDM.

2. SOLAR ARRAY DRIVE MECHANISM (SADM)

The SADM enabled the solar arrays to rotate to their optimum position with respect to the sun. Offloading devices (OLD) were used to clamp the shaft to protect the oil-lubricated bearings from launch vibration forces, and a solenoid brake was used to prevent jitter during operation. Further details of the mechanism are in Reference 2.

2.1 Offloading Device (OLD) flange

Several surface marks were present, their locations corresponding to the contact positions of the offloading and locking device clamps (comprising a "rocking lever" and two "tabs"), formed during pre-flight testing,

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as well as from flight application. Surface profilometry was used to fully assess the extent of the marks, revealing that some surface roughening to a maximum depth of 2 microns had occurred, consistent with normal clamping operations. Some lubricant (burnished MoS_2) is also present on the titanium alloy flange, although it is depleted.

Roughened black marks (Figure 2) were present on the locating interface between the OLD flange and the fixed bearing flange, concentrated at four positions approximately 90 degrees apart, consistent with wear caused by contact and low amplitude motion at this interface.

Figure 2. Roughened black mark on the OLD flange/ bearing flange interface of the SADM.

2.2 Offloading and locking devices

The offloading and locking devices comprised nominally identical pairs of Memory Alloy Element (MAE), Manually Activated and Manual Locking Devices. Marks, corresponding to those on the OLD flange clamping interfaces, were observed on the titanium alloy tabs and rocking levers. Although not all of these devices were used in the actual mission, these marks indicate that extensive pre-flight tests of the various locking devices occurred. In general, the burnished MoS_2 solid lubricant applied to the clamping surfaces and latch/lever interfaces of the offloading and locking devices was depleted, although remnants of the film remained (Figure 3).

Roughened black marks, a potential source of particulate contamination, of similar appearance to those on the OLD flange, were visible at the locking lever flange/mechanism housing interface. The pivot bearings (lined bushes on a central shaft) were in good condition, with a small amount of debris or transferred material, generated by wear of the bush liner, present.

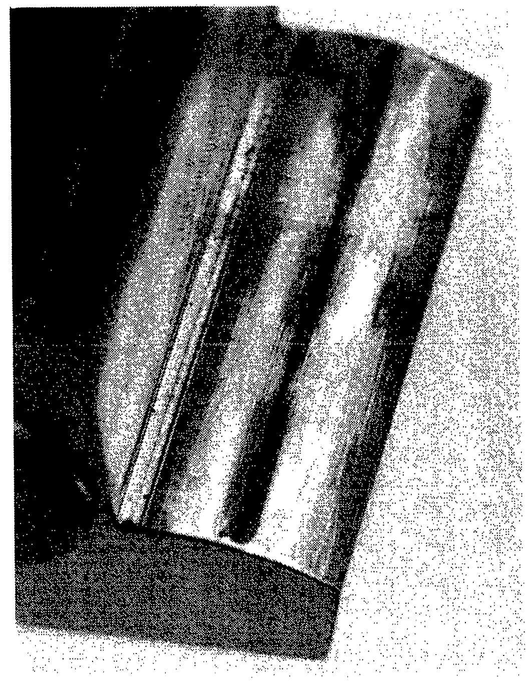

Figure 3. Clamping mark on the rocking lever of a typical SADM offloading device. The lubricant is depleted at the clamping interface.

2.3 Bearing pair & mounting flanges

A pair of angular contact ball bearings (type FAG 5500458E), manufactured from 440C stainless steel, comprising an upper rigidly mounted (fixed) bearing and a lower bearing attached to a flexible membrane (preload 80N) were used. The bearing rings were fitted on flanges and were received as an assembly. The mean torque of the floating bearing was 25gcm. An oil film, fully wetting all surfaces, was still visible on the ball track, raceway grooves, lands and balls, which were all in good condition and were well within their operational duty requirements. There was no evidence of lubricant degradation.

When assessing the effectiveness of the oil creep barriers, which did not contain a UV fluorescent indicator, it proved to be difficult to detect any visual evidence of oil creep or to determine if the creep barriers had deteriorated. Examination of the oil reservoir from the inner ring of the flexibly mounted bearing revealed an oil meniscus in the corner between the flange base and side wall, and three small oil drops were visible on the flange. This reservoir had slightly distorted. Both the inner and outer ring reservoirs had cracked at one of four countersunk securing screws but remained securely held in position. With these exceptions, there was no evidence that the lubrication system and creep barriers had not been fully effective.

The mounting flange of the inner raceway of the fixed bearing showed roughened black marks corresponding to those observed on its locating surface in the OLD flange, and thus show that these components were in moving contact at some stage of their life.

2.4 Solenoid brake

Marks, consistent with normal wear and light duty, were present on the brake blocks (silver/copper/MoS_2 composite) and on the mating surface (silver brake ring), indicating that the materials were well within their lifetime requirements, with some of the original machining marks still visible in the worn region.

3. PRIMARY DEPLOYMENT MECHANISM (PDM)

The Primary Deployment Mechanism (PDM) was responsible for the deployment of the main arm through 90 degrees and was mounted on the Solar Array Drive Mechanism (SADM). The PDM comprised a motor coupled to a single stage planetary gearbox driving lever arms which rotate a trunnion at the inboard end of the main arm. A full account of the engineering and operational details is given in Reference 3.

3.1 Tribological assessment of the PDM gears

The motorised gears, of tooth module 1mm and width 8mm, comprised a central sun gear (PCD 60mm), three planetary gears (PCD 42mm) and a ring gear (PCD 144mm), manufactured from aluminium alloy and treated by the Ematal process to produce a hard anodised surface layer of 8 to 10 microns thickness. These gears generally exhibited tooth wear consistent with relatively light duty. However, some gear teeth showed roughened black surface marks (Figure 4).

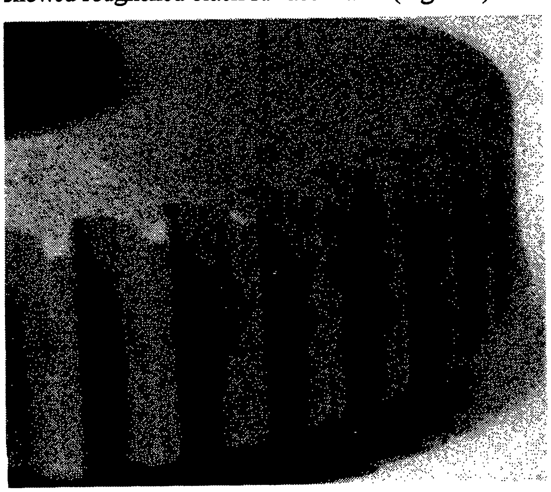

Figure 4. Planetary gear from the PDM showing blackened teeth.

These marks were located in groups of a small number (2 to 3) of teeth at positions corresponding to the stationary meshing during vibration testing and/or launch, or in the operational position. The marks revealed compacted, dark, friable material on an adherent base layer, probably oxidised aluminium partially covering the underlying, shiny, surface, and non-contacting laser surface profilometry confirmed exposure of the aluminium.
Some qualification tests, which did not incorporate vibration testing, were conducted at ESTL (Ref. 4) and showed that the Ematal surface treatment successfully protected the underlying aluminium under normal operational motion and stresses. If the protective anodised layer is breached, then the possibility of static adhesion cannot be discounted. A suitable lubricant coating (eg sputtered MoS_2) or an anodising treatment incorporating PTFE would provide some additional protection, but would need qualification in appropriate vibration tests.
The manual drive override gear system consisted of a titanium pinion and spur gear lubricated by Tio-lube 460, a resin bonded MoS_2 coating. The Tio-lube coating was intact with only mild wear on all the teeth. One tooth showed a more pronounced mark attributable to lubricant depletion, most likely as a result of contact during vibrational motion.

3.2 Tribological assessment of the PDM ball bearings

The bearings were outer race relieved, angular contact bearings (type SEB20 and EB50), manufactured from 52100 bearing steel and fitted with TiC (titanium carbide) coated tungsten carbide balls and outer-race-riding lead-bronze cage. No additional lubrication was applied to the rolling elements. The bearings were located at the primary and secondary lever arms, motor shaft, centre shaft, manual drive and main arm trunnion. All bearings were manually rotated before disassembly to give an indication of their condition. For this type of solid lubricated bearing, no torque abnormalities were observed, the torque being typically less than 3gcm, peaking to 6gcm, but the primary lever arm bearing appeared more hesitant than expected.
Inspection revealed corrosion on the exterior surfaces of several bearings, most extensive (Figure 5) on the external bearings, ie the main trunnion and lever arm shaft. A few small spots of corrosion were also present on the raceways and on the ball tracks of some of the bearings. Unprotected, clean 52100 steel surfaces are at risk from corrosion unless stored and used in a controlled environment (low humidity or inert gas purge) but this may not be achievable throughout the bearing lifetime. Some method of surface protection is therefore appropriate, or the use of 440C bearings considered (but even this material can be made to corrode (Ref 5)).

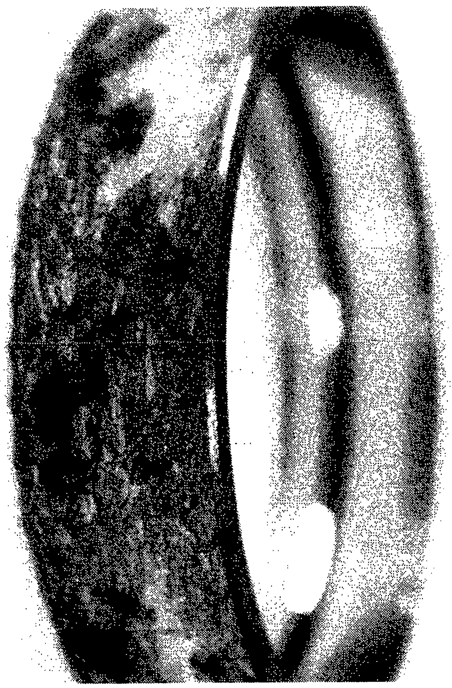

Figure 5. Lever arm shaft bearing from the PDM showing extensive corrosion on the outside diameter.

In general, from a tribological viewpoint, the internal surfaces of all the bearing raceways, balls and cages were in good condition, with no evidence of excessive wear or (with the exception of the primary lever arm) any other features suggesting unsuitability in their application. The ball running tracks showed some very mild frosting consistent with normal micropitting wear. Axial marks, composed of loosely adhered debris, were present on each side of the ball track, extending over more than half the width of the ball groove, consistent with axial ball movement induced by pre-flight vibration testing or launch. Unevenly smeared dull material on the balls and mild wear in the cage pockets indicates cage wear had transferred a loosely adhered film to the raceways, confirmed by using Energy Dispersive X-ray analysis. The cage thus provided some lubrication, although, without extensive running-in, this method of lubrication is unlikely to be as effective and predictable as a predeposited film such as lead or MoS_2.

The appearances of the balls were not identical, due to the variable nature of the transfer process through normal ball loading distributions and ball dynamics. A surface feature, with the appearance of a network of very fine lines, was evident on some balls from the main trunnion and the manual drive bearings. Examination, using a Scanning Electron Microscope, showed that these marks appeared to be fine surface cracks in the TiC coating (Figure 6). No delamination, or wear, of the TiC was found.

Figure 6. SEM image of fine surface lines on a TiC coated ball from the manual drive bearing.

The bearing used in the primary lever arm showed a relatively wide ball running track, which was located towards the centre of the ball groove, and some small indents on the ball dam, indicating that the bearing had at some time experienced radial loads, suggesting that a radial or deep groove bearing may have been more appropriate.

4. SECONDARY DEPLOYMENT MECHANISM

The SDM (described in Reference 6) is responsible for unrolling the solar arrays from their storage drum, by means of booms stored in an inboard and outboard actuator driven by a tandem dc motor/gearhead.

4.1 Stowage drum, brackets, bearings and associated components

The spar tube bearings, type SBB 3TAR49-62-71, 440C steel lead ion-plated with lead-bronze cages, were torque tested. Mean values of 200 to 250 gcm were measured, in air, with a 40N preload applied. On disassembly they were found to be in good condition with evidence of adequate transfer of the lead lubricant. Some roughened black marks were evident in the bore of the fixed (inboard) bearing, corresponding with marks on the unprotected titanium alloy mounting shaft of the spar tube, concentrated on one side, consistent with vibration during ground testing. The sliding (outboard) bearing interface showed some lubricant (Molykote - MoS_2 applied by a proprietary process involving baking) depletion on the anodised aluminium sleeve.

The end brackets supported the cushion roller in two spherical bearings (type RSTVV10-M50 with two flanged SFR4 bearings). A friable pale brown deposit, shown in Figure 7, was noted on the outboard spherical bearing and on the corresponding bracket end cover, and this deposit is believed to originate from outgassing products from the fibre/resin cushion roller.

Figure 7. Spherical bearing from SDM outboard cushion roller support bracket. A light-coloured deposit is apparent on the surface.

4.2 Inboard actuator

The inboard actuator, supplied by Astro, USA, was disassembled at ESTL by MMS personnel, and the constituent tribological components investigated. Prior to deployment the two booms are stored as separate elements in four cassettes, driven by the tandem motor/gearhead, located in the outboard actuator, through the torque tube, and a gear train.

A small quantity of steel wear debris was present in the cassette housing, this debris most probably originating from rubbing contact between the boom elements. The cassette rollers and their bearings were in good condition.

The cassette bearings were lubricated by means of transfer from RT/duroid 5813 cages. All of these bearings rotated freely in the hand, and several representative bearings were disassembled and examined. They were found to be in good condition, and a transferred uneven film of lubricant was present on the races and balls, which is entirely normal in this type of bearing and lubricant combination. A minor build-up of debris was noted in the unshielded (on one side) outer bearing of the idler gear assembly.

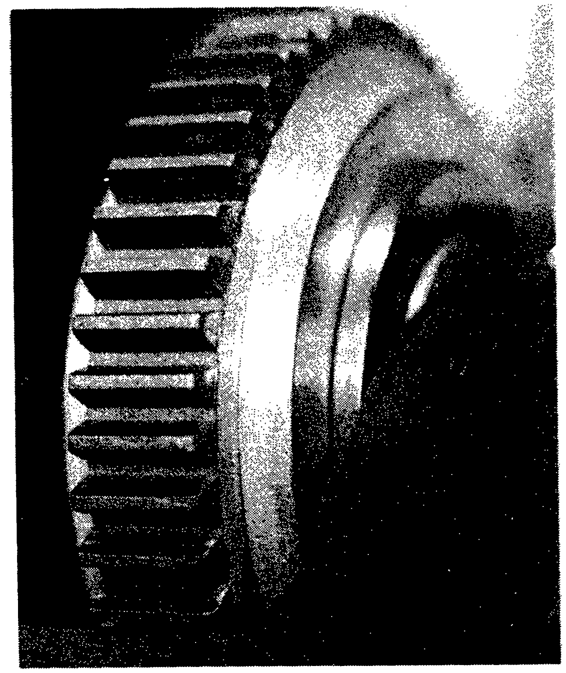

Figure 8. Large idler gear from the SDM inboard actuator. Severe lubricant depletion is evident on the gear teeth.

Wear of the surface coating (Lubeco bonded MoS_2 film) was observed on all of the gear teeth, on all gears, but there was adequate lifetime margin. Figure 8 shows the coating to be depleted but there was no evidence that the anodised layer had been worn through except on the input pinion which showed slight tooth profile distortion.

The torque tube bearings (SR6) lubricated by Braycote 601 grease were in good condition with no evidence of grease degradation.

4.3 Booms

The boom elements are of particular interest in view of the failure of one wing to retract due to boom distortion. Each (upper and lower) boom consisted of a tube formed by two (an inner and outer) "U-shaped" elements. The curvatures of the elements opposed each other, and the open ends of the inner element were restrained within the outer element.

Surface marks were observed on virtually the complete lengths of the boom elements, and can be attributed to rubbing between the inner and outer elements, in part due to a rippling effect slightly deforming the straight sides (which had sharp, raised edges) of the inner boom element. Figure 9 shows corresponding parts of the upper boom elements held open within a clamp, the polished outside face of the inner element at the left with the unpolished inside face of the outer element on the right.

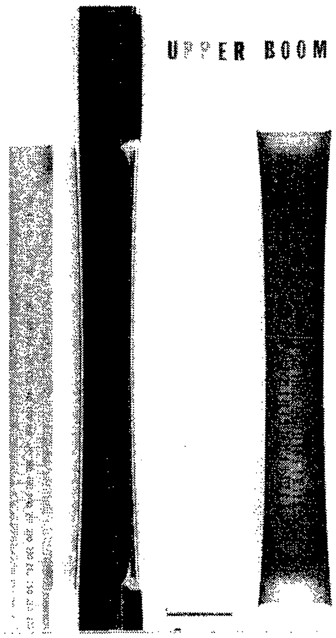

Figure 9. Typical marks on both the inner and outer boom elements.

The positions, number and width of these radial marks are variable along the lengths of the elements and provide evidence which suggests that the booms were subjected to twisting motion (due to thermal movement and/or vibration) while deployed, with maximum twist about two thirds (from the deployed end) along the length. A detailed photographic survey has been made over the full boom element length (Reference 1).
Other components such as guides, tip clamps, collars, microswitch contacts, etc., showed evidence of contact, in the form of minor scuffs, scratches and transferred solid lubricant consistent with their duty, with no evidence of lubricant depletion, surface damage or material degradation to suggest that any design modifications were appropriate.

4.4 Spreader bar

This mechanism was used to compensate for any changes in boom length caused, for example, by thermal effects. The mechanism comprised two boom extension pieces, one of which was affixed to each boom, linked by a steel tape and a compensator and spring assembly within the spreader bar. Fork ends at each end of the spreader bar were free to slide in a flanged bearing and roller arrangement in order to provide length adjustment.
The sliding contact area between the flanged bearing and the boom extension piece was lubricated by bonded MoS_2 (Molykote), and has worn to expose the underlying aluminium alloy substrate, which is itself worn (Figure 10) at the fixed fork end where the boom extension was found to be twisted through about 10 degrees. These findings suggest the use of harder materials and more adherent, durable sputtered lubricant films. The roller was also worn, with some deformation of the sliding face and flange. The exposed areas of the solid lubricant coating were duller and lighter in colour than areas masked by the steel tape or bolt heads.

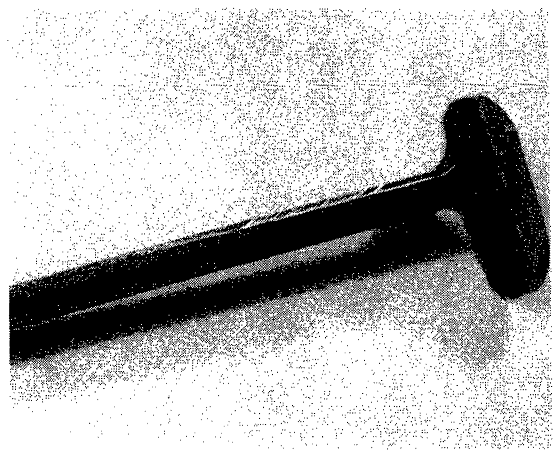

Figure 10. Wear of coating on boom extension piece.

4.5 Tandem motor/gearhead

The gearhead and one of the motors (Figure 11) were disassembled at ESTL. Two dc motors (with brushes manufactured from Boeing compound 046-45, based on MoS_2) are tandem coupled to a 3-stage planetary gearhead using stainless steel gears. The carrier plates and gear spindles of the 1st and 2nd stages are a sintered ceramic/metal composite, those of the 3rd stage are stainless steel. Braycote 601 grease was used in the gearhead and in the shaft bearings of the gearhead and torque tube. The motor bearings are lubricated by RT/duroid 5813 cages.
The motor brushes and commutator were in good condition, the remaining brush lengths and the low amount of wear (to a maximum of 7 microns) on the commutator confirming the motor was well within its life expectancy. Only a fine sprinkling of black brush wear debris was found within the brush housing. A possible source of particulate contamination which could migrate to the commutator was identified within the motor housing where part of the magnet material had a very rough texture in which crystalline deposits were embedded, some of which could be dislodged to provoke a coarse powder. The motor bearings were in good condition, but relative axial motion had caused severely blackened marks on both the rear bearing and its locating bore in the motor housing, suggesting a protective lubricant film or sleeve would have been appropriate.

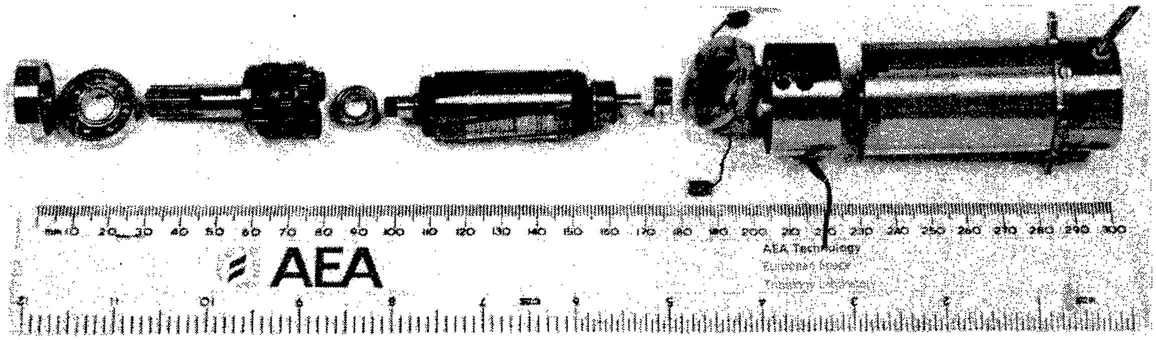

Figure 11. Components of tandem motor/gearhead, with one dismantled motor.

Dark brown discolouration of the grease lubricant was evident on the gear teeth, end faces of the gears and on the spindles of the 1st and 2nd stage carrier plates, but still appeared to adequately wet the tooth contacts. The discolouration is believed to result from wear debris generated by the end faces of the gears rubbing on the carrier plates and at the gear/spindle interfaces, and there was no evidence to suggest degradation of the 601 perfluorinated grease. Some steel wear was present on the gear teeth, but it was not considered to be significant as all the teeth profiles remained in good condition.

The 1st and 2nd stage gear bores and carrier plate spindles were in good condition, with a lightly adhered transfer of spindle material to the bores. Of concern, however, was the surface distress evident on the 3rd stage gear bores and steel spindles, proving the grease had not been fully effective in preventing wear between similar materials. A contributory factor would have been the difference in hardness, typically measured at around 390 (Vickers, 500g load) on the gear and 910 on the spindle.

The grease-lubricated output shaft bearings were in good condition, the grease appearing slightly yellow in colour.

ESTL previously performed a life test and disassembly of a similar mechanism, and the findings (Reference 7) were consistent with those found during examination of the actual flight model.

4.6 Connector brackets and bolts

The silver coated bolt, used to fasten the bracket, exhibited discolouration of the exposed threads and end tip. Some wear of the silver coating on the bolt threads was also noted.

5. CONCLUSIONS

The assessment of the STSA mechanism components confirmed that the majority were in good condition, confirming that their design, the materials used and their lubrication systems were satisfactory for their intended purpose with adequate lifetime margin. Some problem areas identified, and the implications for design modification, were:

SADM:

Solid lubricant depletion was observed on the titanium alloy clamping interfaces of the offloading and locking devices, and the use of a more adherent sputtered MoS_2 film is recommended.

An oil meniscus, believed to represent oil creep, was found in the corner of the shaft reservoir flange of the flexibly mounted bearing, and the use of an ultra-violet indicator in anti-creep fluids is recommended so that both effective application, and subsequently their effectiveness, can be verified.

Roughened black marks at some unprotected flange locating interfaces were consistent with wear caused by contact and low amplitude motion, and lubrication (preferably by solid thin film, eg sputtered MoS_2) is recommended at all close-tolerance locating surfaces which may be subject to vibration motion.

PDM:

The Ematal surface treatment applied to the aluminium alloy gears which experienced only rotational motion was intact, but was not successful in preventing substrate wear on teeth subjected to vibrational motion and stresses. The lifetime of such gears could be extended by lubrication (eg., sputtered MoS_2) but would need qualification in vibration tests.

Corrosion was present on the outside diameters and bores of most of the bearings, and some spots were visible on the ball grooves of some bearings. Protection of all such 52100 steel surfaces is recommended. Internally, the bearings showed features consistent with lubricant transfer from the cage, and relatively mild duty. In bearings with lead-bronze cages, a pre-deposited solid lubricant film is recommended and/or

adequate running-in to establish minimum torque and torque noise.
The use of angular contact bearings is not considered to be ideal for the lever arm application.

SDM:
Some of the idler gears in the inboard actuator showed severe solid lubricant depletion on the teeth, suggesting the use of a more adherent film such as sputtered MoS_2.
The actuator bearings were generally in good condition although steel debris was found in one unshielded bearing, and it is recommended that all solid-lubricated bearing are shielded.
Marks observed on the inner and outer boom elements, resulting from mutual contact and small movements of the elements (which had sharp, raised edges), provide an insight into possible modes of boom failure. A small amount of steel debris in the cassette housing is believed to have originated from sliding contact at the boom element interfaces and this may have been reduced if the inner face of the outer element had been polished.
Lubricant discolouration was found in the motor gearhead, but the lubricant appeared to wet the tooth contacts and there was no evidence of lubricant degradation, with only minor wear of the gear teeth evident. Wear at the steel interface between the 3rd stage gear bores and mating spindles could limit the useful life of the mechanism, suggesting that a self-lubricating liner would be appropriate. Surface damage on the rear motor bearing and its housing could be alleviated by a sliding sleeve or by a solid lubricant. Potential sources of particulate contamination such as motor magnet materials should be sealed.

6. ACKNOWLEDGEMENTS

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SESSION 8

ACTUATORS AND DRIVES