CRYOGENIC MOTOR ENHANCEMENT FOR THE NIRISS INSTRUMENT ON THE JAMES WEBB SPACE TELESCOPE

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ABSTRACT

Initial testing of the JWST NIRISS Dual Wheel Mechanism showed unsatisfactory life from the motors used to drive the individual wheel components. An investigation[1] uncovered that the internal friction had increased due to wear at the lubricated interface between the motor gearhead planetary gears and the planet gear retaining pins, reducing output torque. Work was undertaken to improve the life of this interface. Several design options were selected for development. A successful redesign was qualified with a larger gearhead, modified to use ball-bearings for planetary gear support. To further enhance life, all internal lubrication was changed to sputtered MoS_2. PGM-HT cages were also employed for planetary and motor rotor bearings.

1. INTRODUCTION

The Fine Guidance Sensor (FGS) Instrument is part of NASA's James Webb Space Telescope (JWST) and consists of a Guider optics module and a Near Infra Red Imager and Slitless Spectrograph (NIRISS) optics module. The FGS is provided by the Canadian Space Agency with COM DEV International as prime contractor (CSA Contract 9F006—3-197). The NIRISS dual wheel mechanism enables unique capabilities to JWST by providing the flexibility of rotating its optical elements including broad-band and cutoff filters through multiple positions to view different aspects of NIRISS' field of view. NIRISS' unique capabilities include a non-redundant aperture mask that gives the telescope its highest resolution, a full-field spectroscopic mode that is tuned to find the highest redshift objects, and a high signal-to-noise single object spectral mode that is optimized for exoplanet characterisation.

The Dual Wheel (DW) consists of two wheels, the Filter wheel and Pupil Wheel both of which are driven by independent Geared Motors with planetary reduction gearheads mated to a common structure.

During the flight qualification, the DW failed during the life-test phase not meeting the expected number of cycles. The design life of the motor gearhead was determined to be the limiting item. The current paper follows on from a paper[1] presented at ESMATS in 2013. This earlier paper detailed the investigation undertaken to identify the mechanism or mechanisms involved in the premature stoppage. Design options were then provided to address these mechanism(s).

Presented herein are details of methodology and implementation of enhancements to the motor design to improve expected life. Increased interest in the science capabilities of the NIRISS instrument led to a revised lifetime goal of 142000 output gear rotations, a more than 5X increase from original requirement. This paper discusses the qualification of the updated design though analysis, build and testing of Development Models (DM) and Engineering Model Life Test Units (EM-LTU) and Flight units. EM-LTU build and test spanned all of 2013. The Flight build and test was completed by December of 2014.

2. DESIGN UPDATE PLANNING AND DOWNSELECT

NIRISS Dual Wheel Failure Review Board

The NIRISS Dual Wheel is depicted in Figure 1. The bottom image of Figure 2 represents the motor design reviewed at the Failure Review Board (FRB)[1]. The top image of Figure 2 depicts the motor design ultimately selected for flight.

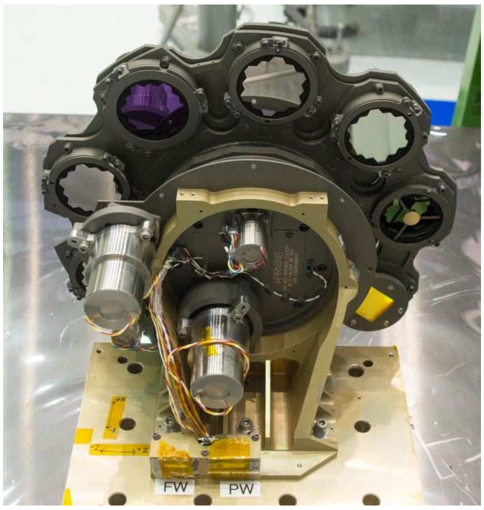

Figure 1: NIRISS Dual Wheel

The key lifetime limitation of the Dual Wheel was determined to be the geared motors and specifically

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the pin interface in the gearhead[1]. The FRB determined that the excessive wear and eventual seizing at the planet gear and pin interface was due to the loss of lubrication, high stresses and tight clearances. From the FRB finding an extensive set of design options were developed and evaluated to address this failure mechanism.

A set of possible design changes and process flow was down selected for further study from the FRB options list. The selection decision was based on several parameters; greatest potential for increase on expected life, compatibility with the DW interfaces, lowest development risk and ease of implementation. Constraints such as volume, mass and power were addressed during this assessment. Two design alternatives were ultimately selected for development. Each alternative had distinct design differences but each also had some common enhancements identified.

Common Design and Process Updates:

- Increase gearhead diameter to 1.5” from 1.25” to accommodate larger planet gears;
- Change the motor retainer from Stainless Steel to PGM-HT;
- Planet pin material changed to 440C from tungsten carbide
- Apply sputtered MoS2 to planetary bearing seat in cage and planet bearing mounting shaft (backup lubrication), as well as gearhead bearing retainers;
- Change to sputtered MoS_2 for all gear and bearing surfaces including output pinion and
- Update selected process procedures by performing additional reviews and adding mandatory inspection points.

Key design enhancements specific to Option 1 (FV-1):

- Utilize Vespel^{TM} SP-1 custom bushings installed between the planet gear and the pin; and
- Apply sputtered MoS_2 dry lubricant on the planet gear inner diameter and planetary pin.

Key design enhancements specific to Option 2 (FV-2):

- Installation of a radial deep groove bearing to interface between the planet gear and the pin.
- Apply MoS_2 dry lubricant on the planet gear inner diameter (contingency measure).

Increased Size of Gearhead

Increasing the gear head size from 1.25” to 1.5” was calculated to decrease the contact stresses inside the motor bearings and at planet gear interfaces by 40% over the heritage design.

This stress reduction was predicted to increase lubrication film life by a factor of ten on its own. This was an important change made to address the root cause of the failure.

Figure 2: Pupil Wheel Motors – Enhanced Design (Top) and Original Design (Bottom)

This increase in gear head size needed to be accommodated with the existing motor interfaces on the Dual Wheel. An interface spacer was designed to transition between the larger gear head and DW interface. A longer pinion shaft length was required.

Spacer Design:

1. Transition from interface for 1.25” gear head to the 1.5” gear head size using Ti6Al4V for CTE match to Dual Wheel.
2. Moved from a 4 point interface to 3 point mount for with an offset of the interface for clearance with the Dual Wheel mounting bracket.
3. Accommodate a tapped hole to allow for backlash adjustment during motor installation.

3. DM TESTING

A Development Model (DM) test program was undertaken to verify design parameters for the polymer bushing option proposed for the EM-LTU Option 1 to limit wear in the planetary gear head system. The polymer of interest was Vespel^{TM}, SP-1 grade, a well documented polymeric bearing material in terrestrial and space applications. Vespel^{TM} is a proprietary Dupont thermoplastic resin in the polyimide family (related to Kapton^{TM}).

A test program was developed to evaluate the wear of the Vespel^{TM} bushing in the gearhead application. Thermal distortion impacts were investigated for the polymeric bushing clearances and drag in the gearhead. Two phases of design and testing were performed to produce a Development Model for Option 1. The first phase involved Vespel™ Bushing dimensional testing. The second was for a Development Model (DM) design and test.

Vespel™ Bushing Testing

The first tests on the road to realizing an Option 1 design were Development Model level tests aimed at addressing the potential issues with the use of Vespel™ SP-1. Risk involving manufacturability, stability and Coefficient of Thermal Expansion (CTE) impacts over temperature were mitigated during these test sets.

The tight tolerances of the inner and outer bores were required for the bushing manufacture and were a concern due to the material properties of filled polymer. Positive results were obtained from the manufacture of 10 bushings all within tolerance and small scatter of the key dimensions.

Once the manufacturability was confirmed, the cryogenic stability of the bushings was investigated. This test involved cryogenic cycling of the manufactured Vespel™ SP-1 bushings to determine the level of distortion of the bushings and if a subsequent final machining step would be required.

Overall the results indicated the polymer bushings to be stable after exposure to the cryogenic cycling. There was some scatter to the results with some samples showing better stability than others. This finding flowed into the build procedures with bushings being selected post cryo cycling.

Note: During testing it was determined that due to the hydroscopic nature of the polymer material, measurements were required to be performed with the bushings dry.

Development Model Testing: Ambient and Cryogenic Wear Test

A wear test was run to provide a quick assessment of the Vespel bushing design and identify if there were any major issues early in the program. A representative gearhead was assembled with flight-like parts and tolerances at the key interfaces. The motor was an off the shelf unit from CDA with the gear-head built up with flight-like planet gears, planet pins and polymer bushings. All critical interfaces had MoS_2 dry lube applied to key parts as per the flight design process.

The test was setup was as per Figure 3. The apparatus included a side load mechanism and torque brake for test loading conditions. The purpose of the test was two-fold; one to check that the bushing to pin clearance did not close going to operational temperature and the second to evaluate the wear performance of the Vespel™ bushing design.

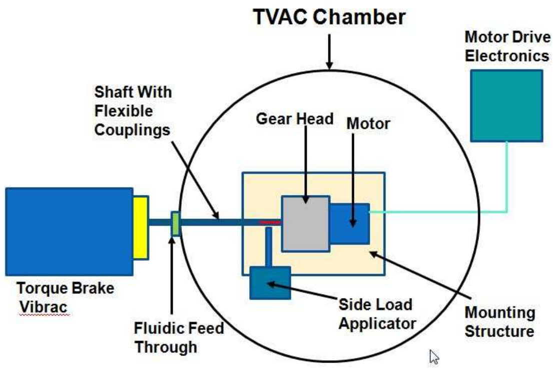


Figure 3: Cryogenic Vacuum Chamber Test Setup

The performance of the DM gearhead was successfully demonstrated with no key issues arising. There was a small issue with the power dissipation of the off the shelf drive motor which caused large temperature fluctuations in the test. The temperature excursions did not invalidate the test as the pin/bushing clearance test was performed at operational temperature. The wear test actually surpassed the life test requirement.

Post Test Inspection

Post test disassembly and inspection showed distinct wear of the bushing on both the outer and inner bearing surfaces, indicating the bushing rotated within the planet gear bore as well as in the planetary gear pin. Metallic particulate was observed in the bushing bores (likely from end-face wear of planet gears). MoS_2 transfer to the bushing at the planet gear interface was evident. An image of a bushing, pre and post test, is given in Figure 4.

Figure 4: Pre / Post Wear Test Bushing Condition

4. ENGINEERING MODEL-LIFE TEST NIT (EM-LTU) DESIGN AND TESTING

The two engineering model units, FV-1 and FV-2, were built to represent both selected motor design options. As mentioned earlier, the FV-1 key design characteristic was Vespel™ SP-1 custom bushing at the pin interface with the FV-2 option having a radial deep groove bearing at the pin interface. The Dual Wheel requires two slightly different motors, one for pupil wheel and one for the filter wheel. The FV-1 and FV-2 units were both designed and built as Filter Wheel configurations as the Filter Wheel motor would be the worst case due to pinion gear size and pinion shaft length.

The planned manufacture and test flow was as per Figure 6. The EM-LTU testing was originally formulated as a 'competition' between the two design options but testing subsequent to the release of the plan proved the competition and down-select to be unnecessary as the first option tested (FV-2) met requirements without issue. Only FV-2 completed the full test campaign; this was a rationalized decision by the Project Team to expedite PFM motor production. The grayed portion of Figure 6 represents the planned testing that was not performed on FV-1.

Geared Motor Assembly

As per the FRB findings, process flow changes and additional MIPs were included in the builds to ensure repeatability of the builds and to increase confidence in the assembly process. These process updates and MIPs were witnessed by NASA and procuring agency QA personnel.

The builds were performed as per standard CDA processes including visual and mechanical inspections as well as baseline testing with additional updates agreed upon with the project team. Once the geared motors completed the builds through the product assurance and quality program they were released for EM-LTU testing.

Ambient Motor Performance Testing

The assembled motors went through a standard set of ambient tests at different stages of the build and test campaign to assess motor health. These tests are performed in a dry nitrogen purge environment when there is any motor rotation as per MoS2 dry lubricant requirements. The full suite of tests was not completed at every stage but a key subset of tests was. Those tests included; Backdrive Torque, Minimum Current, No-Load Response Rate, Winding Resistance and Holding Torque. Tests such as backlash, end play and dimensional inspections were completed at two stages, one prior to release for testing and post test inspection. See Table 1for standard table of motor test results.

Vibration Testing

Vibration testing of the two units was completed in a flight-like configuration with the use of the development model Dual Wheel along with engineering model interface spacers.

Qualification vibration levels and durations were used for testing the EM-LTU motors with the input spectrum being developed from instrument level vibration test results and the baseline specification. Figure 5 provides a view of the setup and input spectrum.

No motor issues were raised during the vibration testing and the motors were tested to verify performance prior to commencing the cryogenic cycling portion of the test plan. All parameters were found to be consistent and in specification.

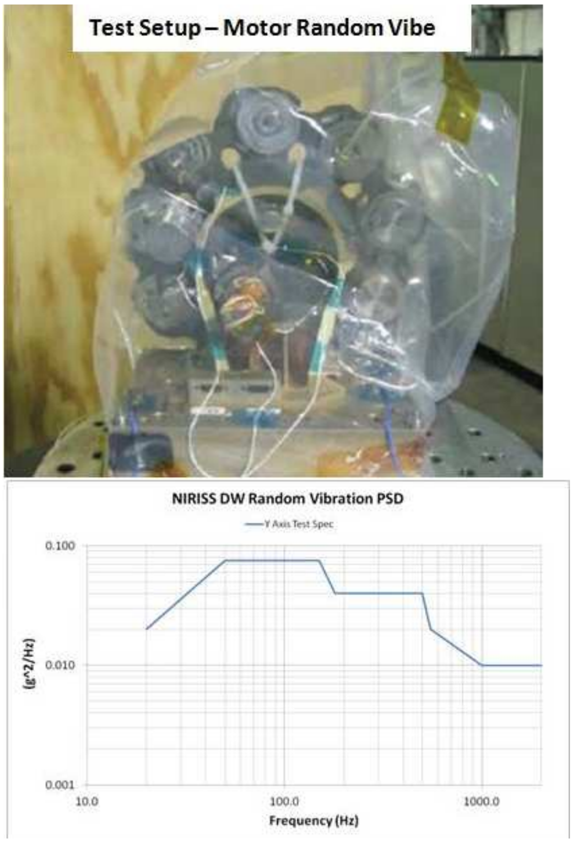


Figure 5: Random Vibration Setup

Thermal Cycle Testing

Thermal cycling was performed to test for material and CTE related issues. Eight total cycles were performed from ambient temperature of 294 K, one to survival temperature of 25K and seven to operational temperature of 35K. The thermal cycling was performed using a different setup from the TVAC performance testing, so only seven cycles were performed in that setup with the final cycle completed during the cryogenic performance. No motor related issues were raised during this testing with post-test performance being consistent and within specification.

Note: Vibration and cryogenic cycling tests were performed concurrently as the test setups allowed for multiple motors to be tested. Cryogenic performance / life motor testing can only be performed in series as the test setups allow for a single motor. The FV-2 unit (bearing on pin) was selected to be tested first as the team consensus was that it had greater potential to achieve the life requirements.

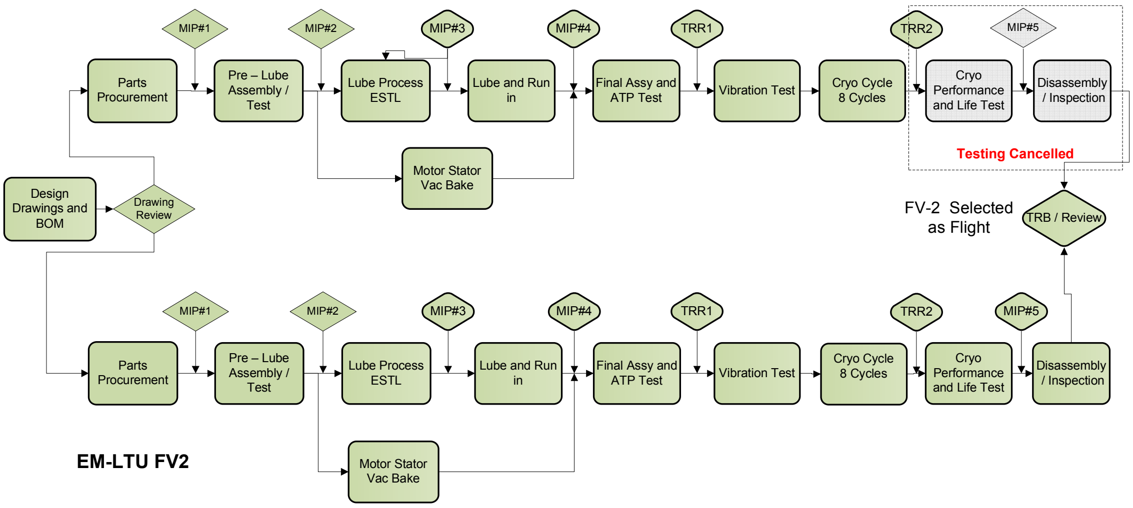


Figure 6: EM-LTU Test Flow

Table 1: Baseline Motor Performance Results

Post Assembly and Pre-Vibration Functional Tests							
STATIC MOTOR TESTS AT 25 DEG C. UNIT TEMPERATURE (CLEAN ROOM)				**GEARHEAD TESTS AT 25 DEG C. UNIT TEMPERATURE (CLEAN ROOM)**			
Description	**Units**	**Value**	**Serial Number:0740**	**Description**	**Units**	**Value**	**Serial Number:0740**
EXCITATION-CURRENT CONTROLLED	ADC	0.1 NOM.	0.100	EXCITATION - VOLTAGE CONTROL	VDC	50 NOM.	50
HOLDING TORQUE- A/C	oz-in	9 MIN.	10.500	PULSE RATE	PPS	60 NOM.	60
HOLDING TORQUE- B/C	oz-in	9 MIN.	10.500	SYNCHRONOUS SPEED	RPM	15.6 NOM.	15.625
DCR PHASE - A/C	ohm	475 / 525	477	DIRECTION OF ROTATION	-	CCW	CCW
DCR PHASE - B/C	ohm	475 / 525	477	BACKDRIVING TORQUE - CW	oz-in	7.5 MAX.	6
INDUCTANCE - A/C	mH	-	2.94E2	BACKDRIVING TORQUE - CCW	oz-in	7.5 MAX.	6
INDUCTANCE -B/C	mH	-	3.06E2	AXIAL PLAY AXIAL PLAY AT 32 OZ REVERSING LOAD	INCHES	0.001 MAX.	0.0004
DETENT TORQUE	oz-in	0.6 MAX.	0.55	BACKLASH AT 15 OZ-IN REVERSING LOAD	ARC-MIN	-	43
HI POT. WINDING TO CASE (PRIM.) @ 500 VRMS	mArms	2 MAX.	1.5E-1	GEARHEAD NO LOAD RESPONSE RATE	PPS	-	296
INSULATION RESIST. WINDING TO CASE (PRIM.) @ 500 VDC	Mohms	100 MIN.	196GOhms				
DYNAMIC MOTOR TESTS AT 25 DEG C. UNIT TEMPERATURE (CLEAN ROOM)				**INSPECTION AT 25 DEG C. UNIT TEMPERATURE (CLEAN ROOM)**			
BEMF AT 3600 RPM - A/C	Vrms	171 / 209	179	WEIGHT	OZ	-	14
BEMF AT 3600 RPM - B/C	Vrms	171 / 209	179	DIMENSIONAL INSPECTION PER ICD	-	ACCEPT	ACCEPT
EXCITATION - VOLTAGE	VDC	50 NOM.	50	WORKMANSHIP	-	ACCEPT	ACCEPT
NO LOAD RESPONSE RATE	PPS	275 MIN.	305	IDENTIFICATION MARKING	-	ACCEPT	ACCEPT
DIRECTION OF ROTATION PER DRIVE SEQUENCE	PPS	CCW	CCW				

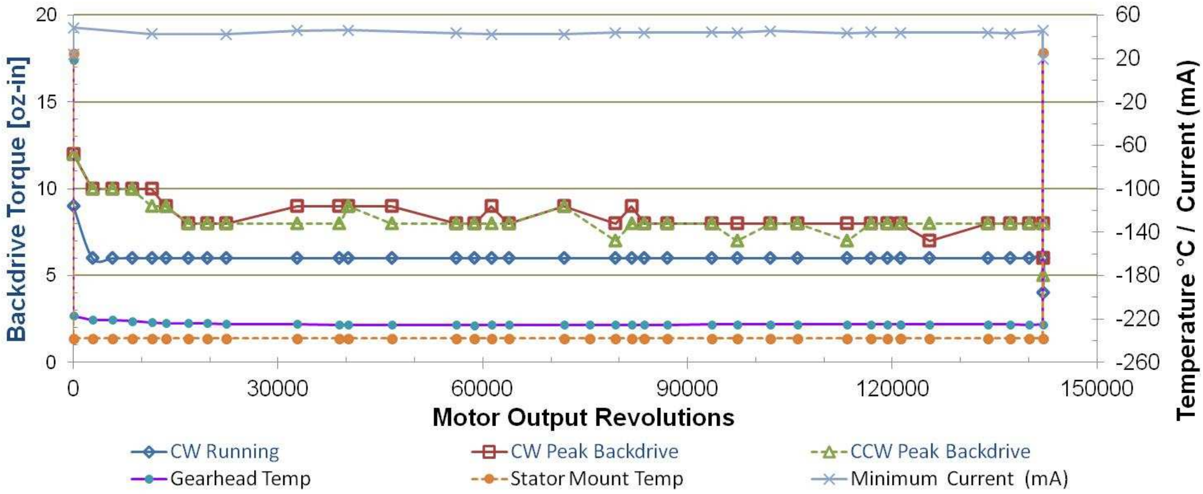


Figure 7: Motor Test Results, Lifetest

Cryo Performance Testing

Cryogenic performance testing was completed on the FV2 unit. The test setup allowed the performance testing to flow directly into life test of the unit Life Testing. Life testing of FV-2 was carried out per the test plan with the torque load in the test setup reduced from 2.5 in-lb (28.2 N-cm) to 1.0 in-lb (11.3 N-cm). The higher torque load was demonstrated to increase the minimum drive current above its specification limit. Before testing commenced, it was also necessary to relax the 7.5 in-lb (84.7 N-cm) maximum back drive torque limit due to the added torque required to overcome the side load applied to the LTU test motor. Figure 7 provides a summary of test data. 142000 revolutions were completed as required with the motor still functioning nominally; the project team declared the testing successful and decided to halt further testing of EM-LTU FV-1 (polymer bearing).

EM-LTU Disassembly

FV-2 was disassembled using CDA assembly tools in the CDA clean room facility. The gearhead was removed from the motor after two applications a vacuum heating process to soften the epoxy used as thread-lock. The gearhead and motor were then further disassembled into their respective lower level components.

Prior to disassembly, the actuator appeared in good condition upon recovery from the vacuum chamber. The motor pinion appeared in good condition with the expected amount of wear evident on the MoS_2 lubrication.

EM-LTU Disassembly and Inspection

The FV -2 motor was disassembled for inspection after the life test. Prior to disassembly, the actuator appeared in good overall condition upon recovery from the vacuum chamber.

Upon disassembly, there was considerable debris observed (as expected) within the gearhead. Visually, most particulate found resembled MoS_2 debris shed during gearhead rotation. The majority of deposits were found on the motor interface to the gearhead. Relatively light deposits were observed on the end faces of the planetary gears and almost no deposits were found in the planet gear pin holes upon teardown of the cage assembly. The planet gear bores were found to be relatively clean except for MoS_2 particulate observed at the retaining rings.

The disassembled gearhead was visually examined for wear as well. The cage (housing the planetary gear system) displayed minor score marks at both upper and lower bearing journal locations. All other areas of the cage exhibited little evidence of wear. The cutouts where the planet gears rotated had no marks, indicating that the planet gears did not contact the cage.

Looking to the gear teeth of the gearhead, the wear in general on the tooth surfaces of the gearhead components looked to be relatively even and limited to the lubricant layer. Very little visual evidence was found that metal-on-metal contact had occurred at the stage of life the test motor was taken to. Figure 8 provides images of the typical wear on the teeth of the planetary gears.

The teeth of the planet gears exhibited relatively even wear. The dark patches were indicative of tooth contours in the gear teeth that existed prior to the application of the dry lubrication. Small particulates of the lubrication were observed. The green arrows of the Figure 8 highlight lubrication wear patterns that could be matched to those of the mating internal gear.

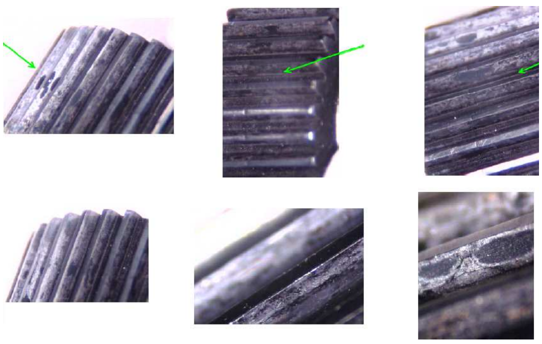


Figure 8: Planetary Gear Tooth Condition Set 3

Where the lubrication was worn there appeared to still be a thin layer left. This was confirmed by later inspection at ESTL. The bore of the planet gears looked good with the majority of the applied lubrication intact. Relative motion between the planet gear bore and bearing OD appeared minimal. The axial faces of the gears were all in good condition, indicating there was no rubbing occurring against the carrier EDM surface during gearhead operation.

The condition of the bearings was generally very good after they were examined post life test. Figure 9 depicts the condition found for the front carrier bearing of the gearhead assembly. Lubricant in the bearing looked good as indicated by the ball and bearing raceway. The picture on the lower right row of the figure shows the bearing OD. All pictures on the top row show the bearing bore. The light scuff marks in the bore matched to those found on the cage journals.

The condition of the planet gear bearings was of great interest. These bearings were found to be in very good condition after test. The bearings were generally free of visible debris and the balls, raceways and PGM-HT retainers were all in good condition. The balls were smooth and free of any scratches, dimples or dings. The bearing outer diameters (OD) were all free of major marks. The OD exhibited a slight lubrication transfer from the bore of the planet gears. The bearing bores (ID) were relatively smooth and showed greater lubrication transfer (to the pin) than occurred on the OD.

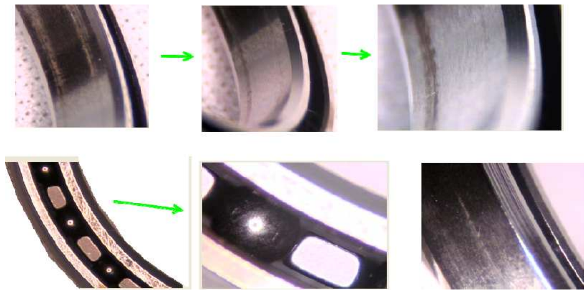


Figure 9: Front Carrier Bearing

The axial faces of the inner ring showed many scratches. These marks were found to be from assembly at the bearing vendor (not from rubbing against the planet carrier). It was also observed that the chamfer on the inner ring exhibited discoloration similar to what was observed during dry lubrication processing of the gearhead. Refer to Figure 10 for images depicting the typical condition of these bearings.

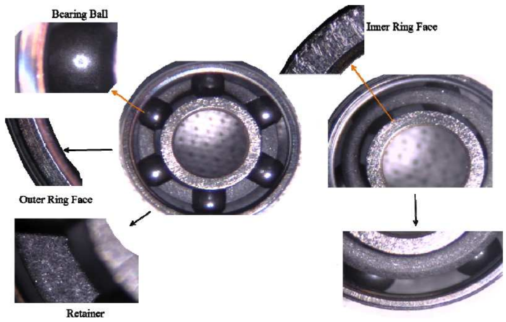


Figure 10: Planet Gear Bearings (Set 1) General Condition

The planet pins were generally in good condition when they were extracted from the carrier assembly. They displayed even wear over the contact patch with the planet bearings. There was no exposure of the base material but the lubrication was more worn at the bearing contact area to indicate there was some degree of slippage (rotation) at that interface. ESTL evaluation classified the state of the lubricant to be severely depleted in the wear areas. There were also indications of minor motion along the axis of the pin. The pins all exhibited a darker separation between the two bearings and also at the ends where they were supported in the planet carrier. The lubrication at the ends was lighter which indicates that the pins might have rotated in the pin bores of the carrier (cage). Typical conditions of the planet retaining pins were as depicted in Figure 11.

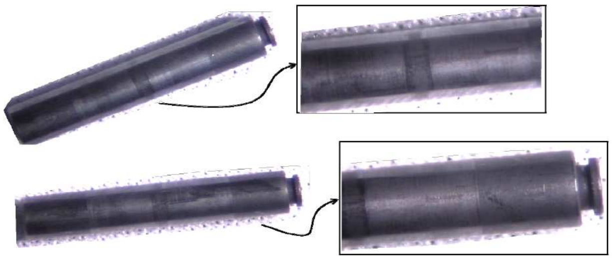


Figure 11: Planet Gear Pins, Set 1

Inspection of the motor core revealed very little debris or wear. Closer inspection revealed a minor amount of particulate (later found as MoS_2), consistent with dry lubricant from the bearings, deposited on the stator bore of the motor. Some cracking was noted in the end potting that was test induced. The affect was deemed minor as no loose or un-bonded epoxy was noted other than where damage had been induced by rotor contact during extraction. This was confirmed by probing the intact material with a dental pick.

As expected, the motor pinion (sun gear for planetary system of gearhead) displayed the highest degree of wear in the motor/gearhead system. This gear engages simultaneously with all three planet gears in its role as the 'Sun Gear' of the planetary gear train.

Figure 12 provides images of the wear found on the pinion. In general, the lubrication was greatly depleted on the gear contact patch of the pinion teeth but there was no evidence that the underlying metal had started to wear.

The motor bearings were found in excellent condition after disassembly. Both bearings were clean and free of visible debris. The balls, ring raceways and PGM-HT retainers showed even lubrication wear and transfer. Both the bearing bore and OD were in the as-assembled condition and showed no scuff marks or scoring. There was no relative motion evident between the bearings and their respective journals. Refer to Figure 13 for images of the motor bearings.

Debris was swabbed from 3 areas during the motor tear down and a SEMS/EDX analysis was performed at NASA GSFC on particles recovered from each of the three swabs. MoS_2 was identified as the main constituent of all particles examined. Iron bearing entities were found attached to some of the largest MoS_2. The entities were understood to be AISI 400 series stainless. Figure 14 provides a typical view of particles recovered by swabbing.

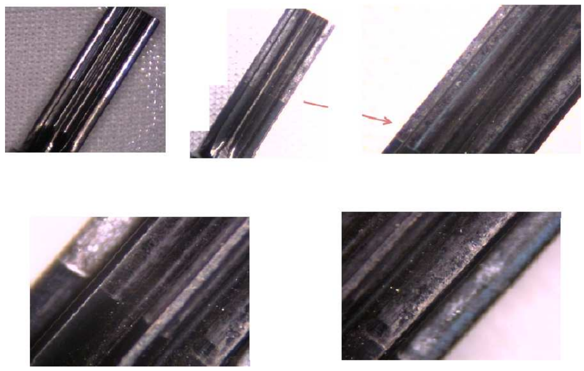


Figure 12: Motor Pinion Tooth Condition

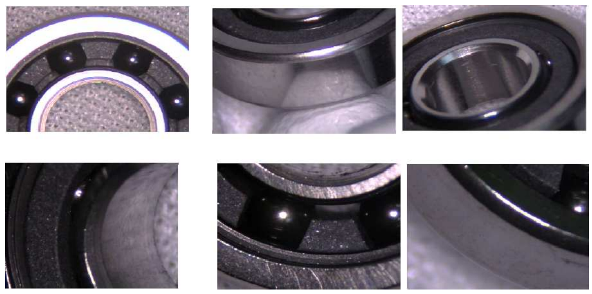
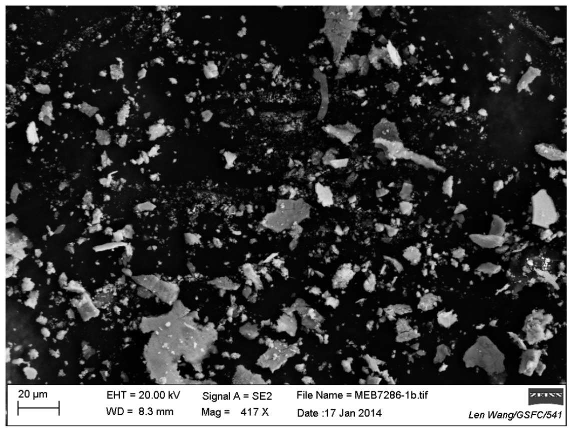


Figure 13: Motor Bearing Condition



Enlarged view of the residues from swab sample 1. They are MoS2 flakes

Figure 14: Typical MoS2 Lubricant Flakes from Swab Samples

5. FLIGHT ENHANCED MOTOR BUILD AND TEST

As mentioned above, the selection of FV-2 for the flight design was made after successfully completing the EM-LTU test campaign. One unit of each flight configuration was build and tested; the FX-1 for the Pupil Wheel and FW-9 for the Filter Wheel. The flow of the flight build and testing is very similar to the EM-LTU with the exclusion of life testing.

Environmental Testing

Vibration tests were carried out similar to EM-LTU but using the acceptance test level and duration. Eight temperature cycles were also performed on the flight motors between ambient and cryogenic (35K). Test results were as per Figure 15. Motor results were in family with those of the life test unit. Flight motor ambient testing at specified intervals between environmental tests were consistent with no issues raised.

Cryogenic Performance Testing

Operational temperature performance testing was completed for both motors with all test results falling within specification limits.

Torque spikes were observed in the backdrive trace data for the Pupil Wheel motor (FX-1). Further run-in of the motor was completed (<5% of expected motor life) to confirm stable performance and the motor was accepted for flight by the project team.

Note that the thermal gradient within the cryogenic test setup (motor to thermal sink) was improved during GSE modifications for testing of the flight motors. The 20K gradient between motor case and the platen was reduced to about 5K. This can be seen by the resistance difference of the windings observed from FV-2 and FX-1 data of Figure 15.

Lessons Learned

A. For such cryogenic complex mechanisms, early engineering life testing would greatly reduce program risks in the later phases.
B. Torque traces obtained by backdriving motors are invaluable to characterize drive train stability over motor life.
C. Sputtered MoS_2 application generates less debris and potentially could have benefitted earlier cryogenic motor designs.
D. Thermal characterization of GSE should have been better investigated prior to commencing EM activities.

Acknowledgement

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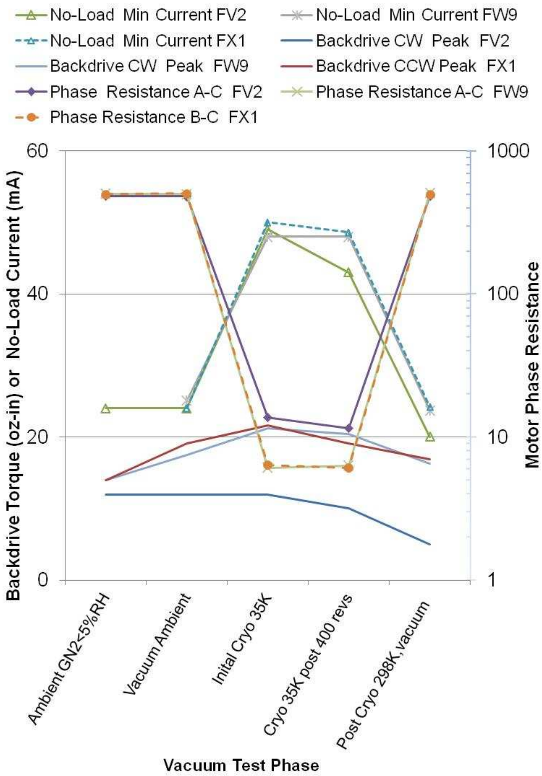

Figure 15: PFM Motor Test Data

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Keywords: Mechanism, Dual Wheel, Filter Wheel, Stepper Motor, Life Test, Gearhead, Dry Lubrication, Vespel™ SP-1, MoS_2, Vacuum, Cryogenic, JWST, FGS, NIRISS.