Test Validation of the Repair to the Space Station Solar Alpha Rotary Joint

Curtis Allmon*, Will Wilkinson* and Stu Loewenthal*

Abstract

The Solar Array Alpha Joint Lubrication Interval Test (SARJ LITE) test rig was built as a method to evaluate the performance of the grease repair on the Starboard SARJ of the International Space Station (ISS). The on-orbit SARJ was temporarily parked after receiving significant damage on one of its race ring surfaces as a result of inadequate lubrication (high dry contact friction) and unaccounted for roller traction kinematics. In a scaled down rig, flight-like roller bearings were preloaded and cycled on a nitrided 15-5 race surface. Grease was added to the track and with instrumentation monitoring performance, trending data will be extracted and used to determine lubrication intervals for both Port and Starboard ISS SARJ's. The grease lubrication was found to be effective in eliminating the high friction that contributed to the on-orbit race damage.

Introduction

The ISS is powered by eight solar arrays that track the sun for optimum power generation. Each Solar Array is mounted to a Beta Joint that provides a degree of rotational freedom and, further inboard, a cluster of four arrays is mounted to SARJ, one starboard and one portside, providing an additional degree of rotational freedom (see Figure 1). The Alpha and Beta joints by design provide continual year round tracking of the sun. This paper covers the ground testing used to determine lubrication intervals for the Space Station SARJ's. Included is an overview of the SARJ, a description of the on-orbit anomaly that led to the greasing of the SARJ, a thorough description of the test rig used to determine the intervals for relubrication, and a summary of the performance to date, and the plan forward.

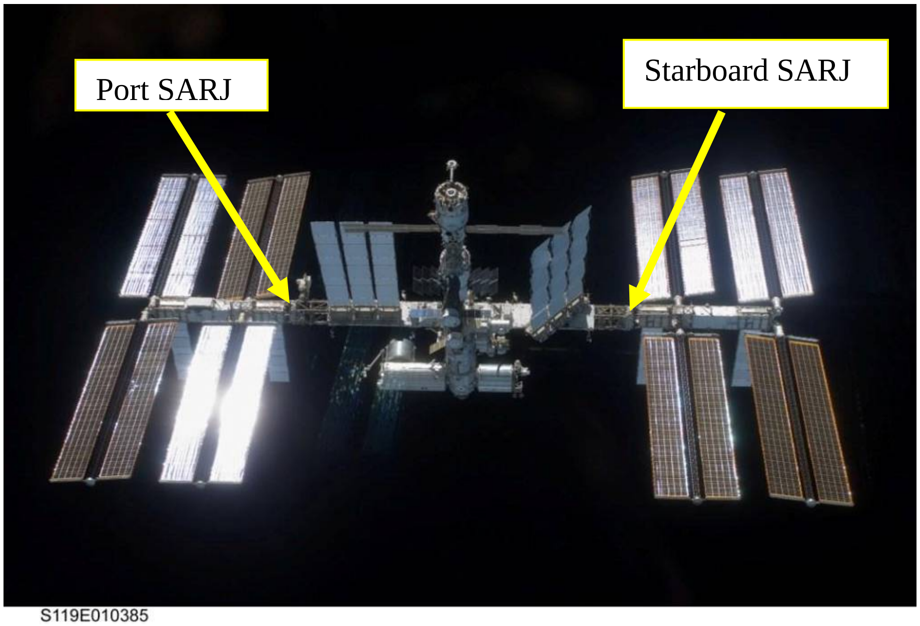

Figure 1: Space Station on-orbit

* Lockheed Martin Space Systems Company, Sunnyvale, CA

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Background

The Space Station utilizes two SARJ's, a Port and a Starboard, whose primary purpose is to rotate the outer most truss segments and allow the solar arrays to track the sun. Sun tracking is achieved through rotation of two orthogonal joints, the Alpha and the Beta. The loss of a SARJ would mean significantly reduced rotation of the solar arrays as the Beta joint would then be the only joint left; power harnessing would be significantly reduced.

Each SARJ consists of 12 trundles, 2 race rings, and 2 drive motors called DLA's (Drive Lock Assembly). The trundles are the bearing assemblies that allow one race ring to rotate relative to the other. The DLA is the motor that drives the ring using a pinion gear that engages the race rings bull gear. In primary operation, the trundles and DLA's are mounted to the inboard side and the outboard race ring is driven. In its redundant mode, or outboard operations, the trundles and DLA's are flipped and mounted to the outboard side and the inboard race ring is driven. The redundant mode of operation is only used if there is a failure or issue with the inboard mode of operation.

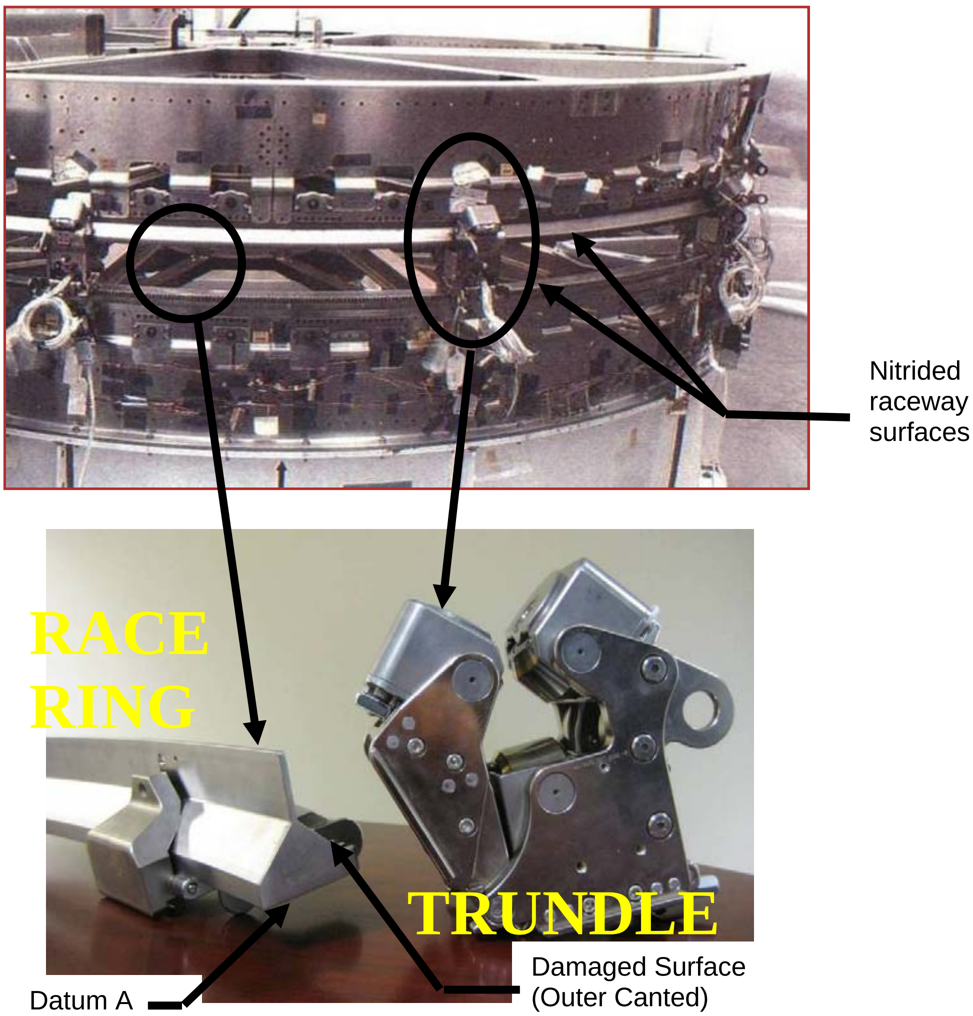

Figure 2: SARJ with blowup of a trundle and a race ring segment

Each trundle bearing assembly consists of three rollers that are made of 440C with an ion-plated gold coating. The DLA assembly consists of two trundle-like bearing configurations called followers, which also each consist of three 440C gold-coated rollers. The rollers between the trundle and the followers differ in several minor respects such as contact width and edge radius. Although the follower rollers have a slightly larger overall width, their contact width is slightly less due to their larger radius. Both the trundles and the followers have a datum A roller that rides on the bottom surface of the race ring (see Figure 2) that is different than the other two rollers. The datum A roller is wider and also has a different taper angle. Its corresponding surface on the race ring was also different than the other two surfaces as it was ground and the other two surfaces were not.

In the fall of 2007, an increase in the drive current was observed on the Starboard SARJ. After further monitoring, it was decided to park the joint in order to prevent any further damage. The Starboard SARJ had only been operating for approximately 5 months compared to the Port SARJ, which had been operating nominally for approximately 14 months. Shortly thereafter, an EVA ensued, which included an inspection of the ring. It was then discovered that a significant amount of damage had been done to the outer 45 deg canted race surface with debris being observed in high quantity on much of the adjacent hardware all around the race ring.

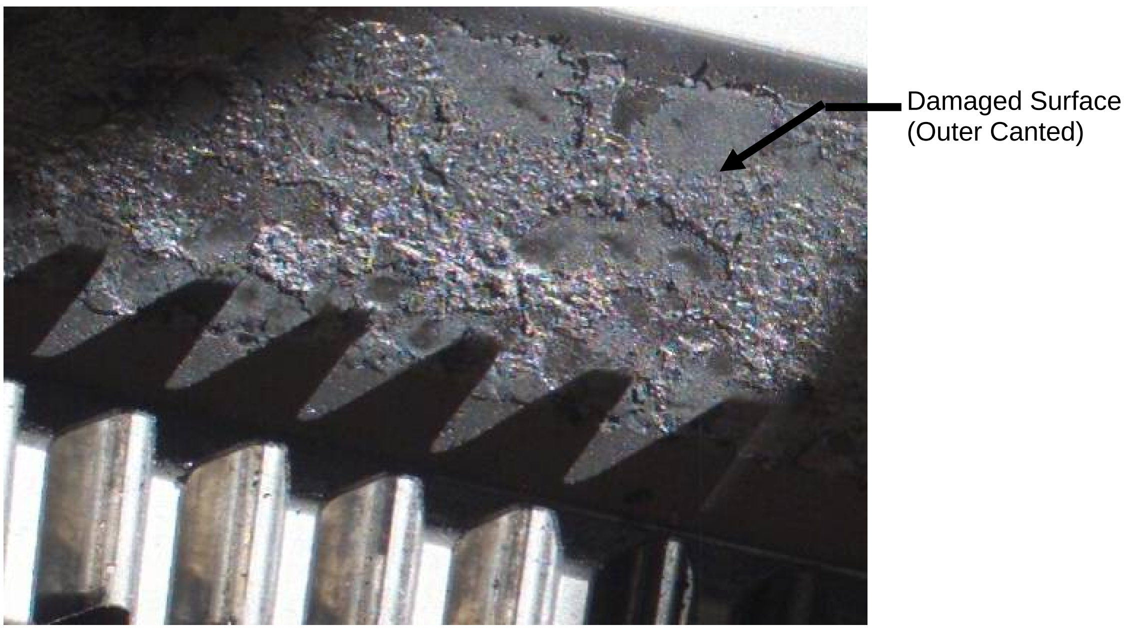

Figure 3: Damaged on-orbit SARJ race ring

A root cause investigation was then initiated. A fault tree was built with all conceivable possibilities of cause being included. Each item was closely reviewed and rated on likelihood based on results from data review, analysis, test, and on-orbit inspection. It was determined that roller mistracking coupled with high surface friction from dry roller contact was the root cause of the failure. The high contact stress due to roller edge loading as a result of mistracking caused the roller to spall the nitride case. Mistracking is the result of the rollers being slightly misaligned (<0.5 deg) relative to the race as shown in Figure 4. A side friction force is generated at the roller/race contact since the rollers are slipping slightly as they roll. The side force creates a tipping moment about the camber pivot axis. This in turn causes the roller edge to dig into the race as illustrated in Figure 4. The details of the failure investigation are discussed in a companion paper (Reference 1).

A subsequent EVA inspection of the Port SARJ revealed traces of grease on the race surfaces. It was discovered that the trundle bearings had most likely leaked out a sufficient amount of grease to adequately lubricate the ring surfaces and prevent the rollers from edge loading and causing the damage to the race surface. A review of the differences between the Port and Starboard SARJ's had revealed that the Starboard SARJ never had a thermal vac test performed, which may have created the environment for the Port SARJ trundles to leak some grease.

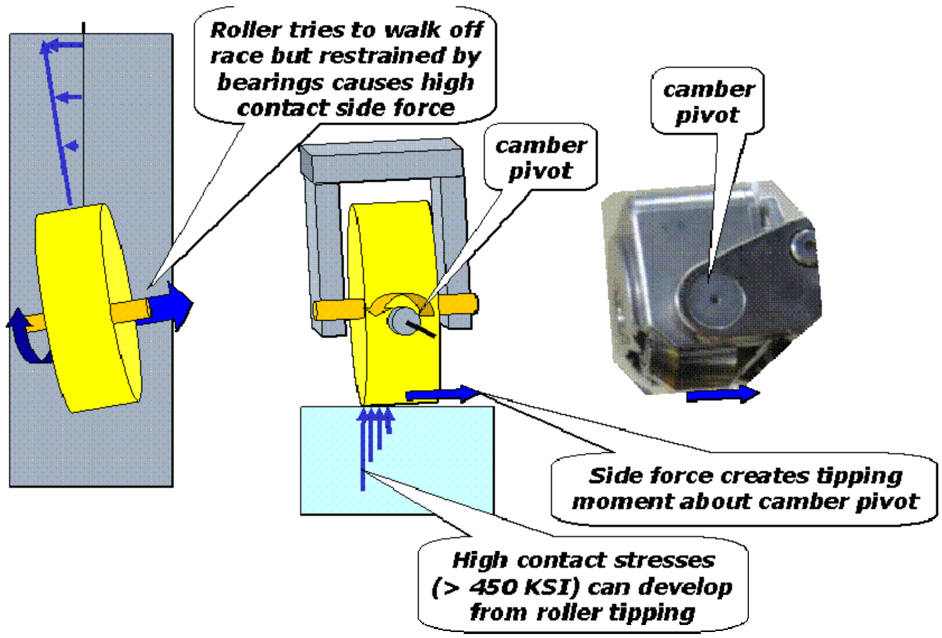

Figure 4- Mechanics of mistracking causing tipping and edge loading

As part of the recovery effort, both the Port and Starboard SARJ's were greased using Braycote 602 during mission STS-126 Nov 2008. Since then, the Port SARJ has been under continuous operation with nominal performance while the Starboard SARJ remains parked except for an occasional test run for evaluation. Several questions remained unanswered including: a) at what rate would the damaged ring continue to degrade after greasing during normal auto-tracking (continuous operation), and b) at what time intervals would relubrication operations be needed for both joints? Furthermore, how long could the relubricated damaged ring last before a transition to outboard operations be required?

Rig Design

These unanswered questions led to the need for some additional ground testing. It was decided that a high-fidelity test rig dubbed the SARJ LITE (Lubrication Interval Test) would be created to determine lubrication life on the SARJ. This was accomplished by building a scaled-down version of the flight SARJ that simulated flight trundle bearing kinematics such as mistracking along with flight roller and race geometries/materials.

Its purpose was threefold. First, to use the rig to damage the test plate to generate flight-like race damage. Secondly, to test for ring durability by making sure running on the damaged surface doesn't lead to catastrophic breaks in the ring; and thirdly, to determine grease relubrication intervals that would reveal how often an EVA is needed to relubricate the rings. The SARJ LITE data in addition to data from other component test rigs are being used to steer decisions for future Space Station operations.

In the on-orbit configuration, 12 sets of trundle rollers and 2 sets of DLA follower rollers ride on the race ring surface. With the race ring diameter being nearly 10 feet (3 m), it was decided that a full-scale test rig would not be feasible so a smaller size was chosen to be compatible with a thermal chamber but the spacing between trundle rollers would be maintained. The DLA follower rollers were left out due to their significantly reduced preload that lessened the likelihood of their contribution to ring damage. A configuration of three equally spaced rollers was chosen for the rig. It was additionally decided that since each trundle assembly has two different roller types, a wide and a narrow, two different race tracks would be utilized to run simultaneous tests, one for the wide and one for the narrow. The rig was setup so each track and preload system was independent of the other and could be run by itself or in parallel with the other. The preload system initially used a stack of Bellville washers to achieve the desired preload (roughly 13.3 kN (3,000 lb)). After analysis of the roller support structures (called spiders) however, it was determined that the spiders had sufficient compliance and were soft enough to act as the Bellville stack themselves, so the Bellville washers were taken out of the design. Instead of modeling the trundle assembly, which includes a cluster of three rollers, the test rig simply used a single test roller backed with a support roller (see Figure 5). The preload was to be set with an individual preload bolt for each test setup, evenly distributing the load between the three rollers.

Roller geometry was maintained close to flight with the exception of the taper angle, which was increased to accommodate the reduced size of the test plate. The camber axis was also included in the test trundle design. The camber axis was intended to allow the roller to tilt, which causes the roller to lay flat against the race ring. However, it was this very camber feature that ended up contributing to the race damage by allowing the roller to tip and initiate the damage to the ring. A feature was added to the rig design to lock the roller housing at a particular camber angle. The roller was then maintained with edge loading for extended periods during attempts at damaging the race in a flight-like manner.

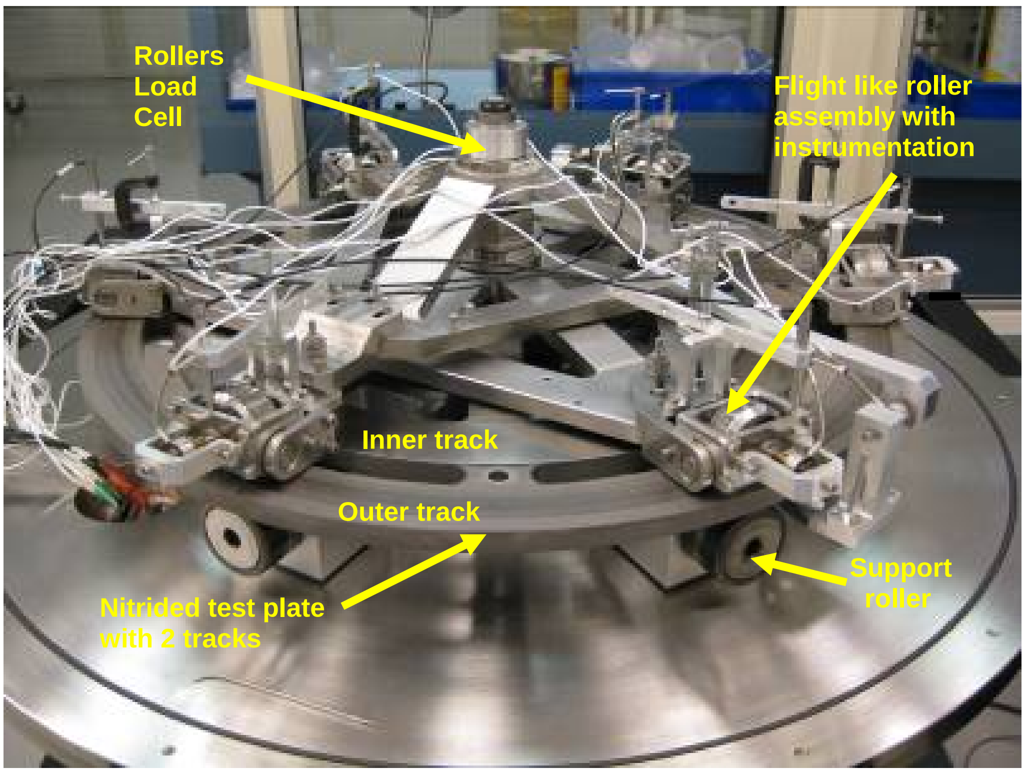

Figure 5- SARJ LITE Rig (vacuum chamber cover not shown)

Adjustment of the mistracking angle was another feature built into the rig (see Figure 6). The mistracking element was important because it played into the root cause. Some of the rollers from actual on orbit trundles were measured and found to have a certain amount of mistracking built into them due to tolerancing buildup. This data was used to aid the final setting for the lube life test. Additionally, since the rig would be used to cause initial damage to the plate, a roller adjusted to a high mistrack angle could quicken the damage runs. The mistracking was set using a known zero, which was achieved using instrumentation that defined a perfect alignment of the roller relative to the track. An LVDT as shown in

Figure 6 was used to aid in defining the motion required to obtain a particular mistrack angle. Once the angle was achieved, the three fasteners holding the bearing mount to the spider were tightened. This process was performed on each bearing assembly.

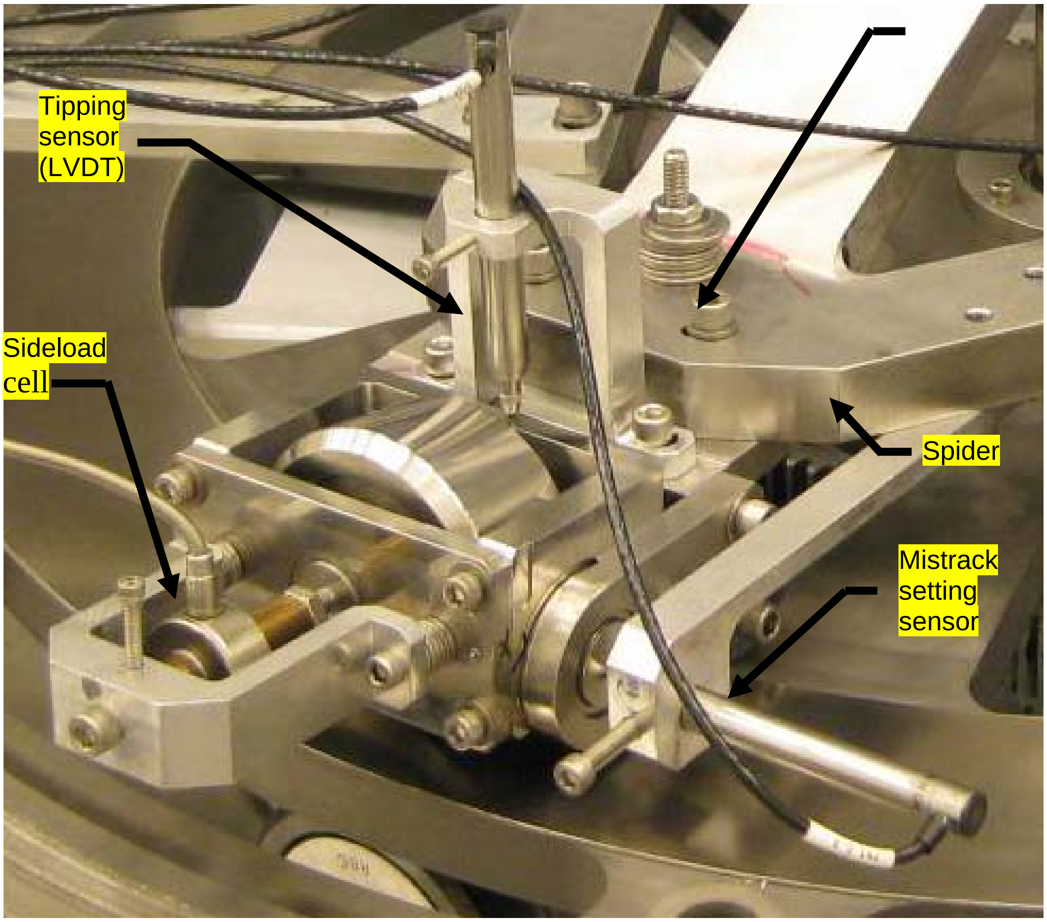

Figure 6: Test roller with its respective instrumentation

Pre-Test Damage Phase

The first task was to damage the outer track to simulate the damage condition of the on-orbit Starboard race. This race had significant pitting both across the track and along the entire circumference. The nitrided layer was broken through and only islands, remains of the surface, were left with the majority of the nitride case turned into debris (see Figure 3). It was originally thought that the rig could be used to damage the test plate using hardened rollers and purposely mistrack them to high angles to induce tipping, or even to pin them to maintain an extreme tipped state. The damage runs were made initially with only the three outer track rollers engaged so the entire inner spider, including its rollers, was disengaged. Difficulty was encountered when attempting to spall the test plate. The rig was then reconfigured (see Figure 5) with extensions added to the inner spider, which allowed all six bearing assemblies to run on the outer track and double the number of stress cycles the ring would see. This helped speed up the damage but the damage was confined to a narrow region (see Figure 7).

It was suspected that the roller tipping was too high (see Figure 8) to propagate the damage across the track. So the tipping angle was reduced to get more roller contact across the width of the track. Early results looked promising as some additional spalling was observed, but over time roller and track wear became the dominating factor (see Figure 7). Wear simply produces debris that eventually becomes pancake-like in appearance. It differed from the on-orbit pitting and spalling observed. The 440C rollers would wear at the tips (see Figure 9) where the contact was made and become dull and a trough would gradually form on the track.

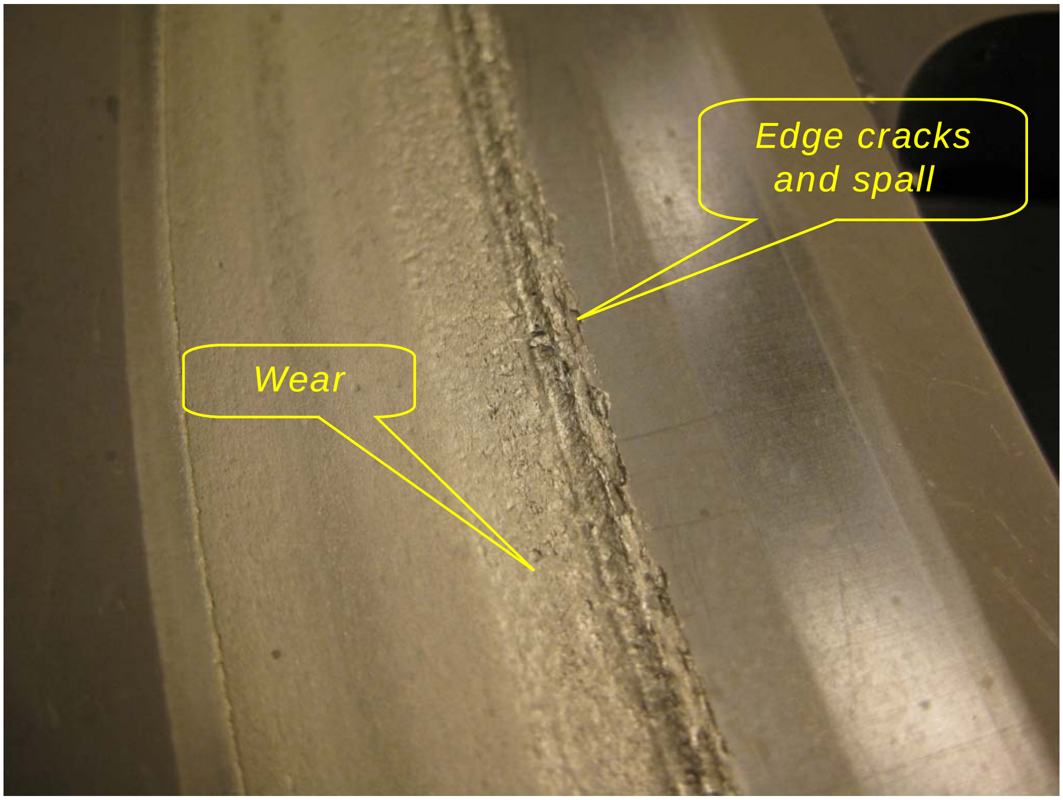

Figure 7: Example of damage generated on outer track

Additional attempts were made using alternate tip angles, mistrack angles, and preloads, with mostly wear being created. Harder tool steel rollers were also implemented but they also began to wear and lose their edge over time.

It seemed that no matter what the configuration was, the result was more of the same. It was later determined using a comparison of samples that the on-orbit case hardened nitride layer had more subsurface defects (porosity, etc.) than that of the test plate. Although the test plate was nitrided at the same vendor as the flight race rings, its superior metallurgical structure made it less susceptible to damage. This was perhaps the key factor for our inability to damage the test plate.

Other techniques for damaging the race had been pursued and some looked promising. These methods included EDM'ing, etching, pressing pins, and use of a friction stir welder. The friction stir welder at JSC used a single roller on a linear path and could cause damage on a single chord. Sixteen chords would cover the entire plate. The initial damage was done with a mistracked and tipped roller. The stir welder would then be radially offset inward for more damage passes and the process of shifting inward repeated until a strip of nearly 5 cm (2 in) was produced (see Figure 10). Once the damage runs were complete, the plate was shipped to Sunnyvale and mounted onto the test rig.

Figure 8: Tipped roller

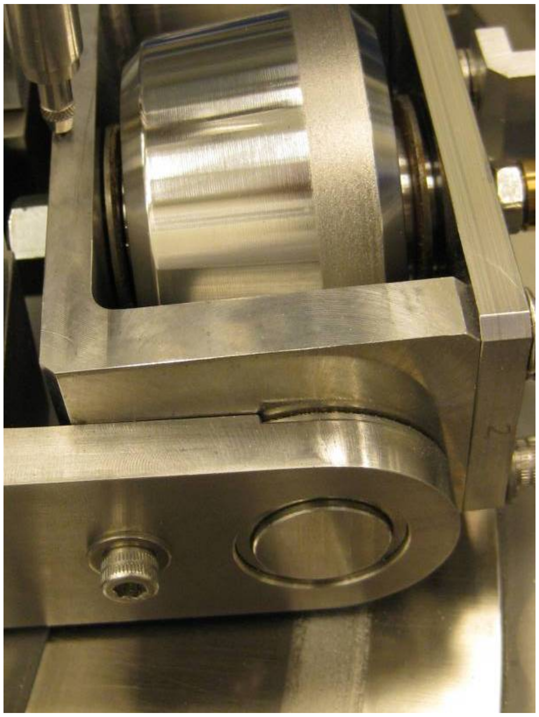

Figure 9: Roller and track wear

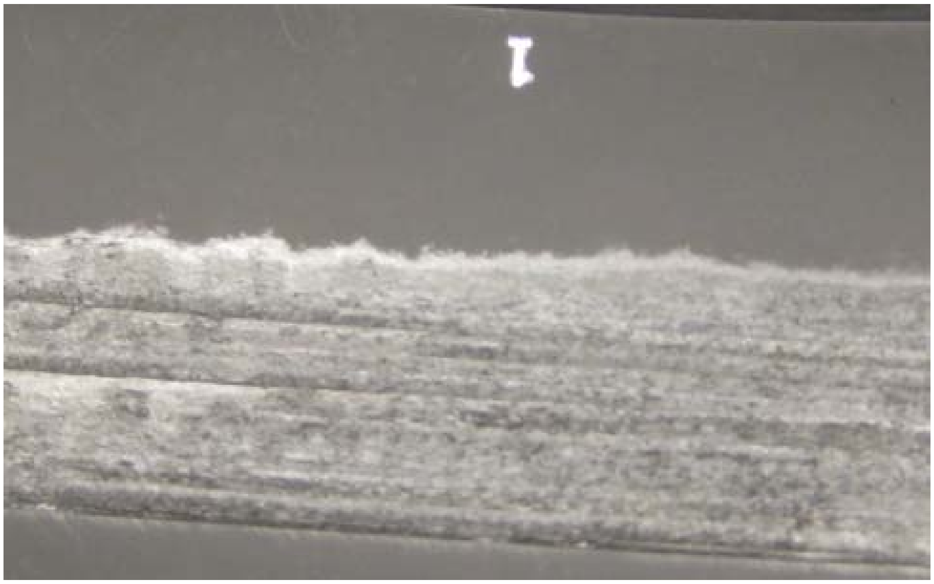

Figure 10: Damaged Outer track before test start

Test Results

Ring Durability

The first task was to determine if the damaged flight race could suffer a structural failure if continued on-orbit operation was resumed. It was decided to run the previously damage test plate dry to bound the problem. This was in line with the test philosophy of doing ring durability testing prior to the main test for lubrication life.

The ring durability test was started with the rollers set at flight-like mistrack angles based on measurements made on flight trundles at NASA MSFC. LVDT's were set up on the rollers to monitor tipping and the load cells in line with the roller axis were set up to monitor sideload. Unfortunately, due to the sensitivity of the load cell and the higher drag in the bushings through which the bearing shaft rides, the exact friction values couldn't be extracted from the data. The load cell data however, was still very useful for monitoring trending of the sideload of each roller. With the preload set at a flight-like value, roughly 4 kN (900 lb) per roller, the test was started.

Initial testing was performed with no lubrication in order to characterize the track dry. It was also performed at ambient pressure to create a baseline to which data could be compared to during the transition to vacuum. The sideload values were high relative to the later runs with grease. Also, edge loading was observed upon examination of the tracks but no tipping was evident. It was decided to limit the amount of dry running to preserve the Datum A track so as to ensure a flight-like surface for the lubricated portion of the test. The surface was run on just long enough to obtain some wear but not long enough to cause damage since the on-orbit datum showed minimal signs of damage.

After approximately 16 equivalent flight months of testing, the previously damaged outer track showed no significant structural degradation other than generation of additional surface wear debris and a deeper groove under the edge of the tipped roller. The test results showed that structural damage even at the high stresses associated with tipped rollers and dry running would not jeopardize the structural integrity of the SARJ.

Lubrication

Grease was then added to the track using a grease gun similar to the on-orbit gun and in similar quantity. A single bead of the Braycote 602 flight grease was added to the center of the track around the entire circumference. The test was restarted at ambient pressure for more data and then the lid was put on the fixture and the chamber taken to vacuum. The grease effect on the track was an immediate reduction of close to 50% of the sideload as expected. After a short period of time, the grease was pushed out of the way and the sideload increased and then stabilized (see sideload drop at 6000 revs in Figure 11).

Another important variable was the test speed. The test speed needed to be fast enough to perform the test in a reasonable time frame but slow enough to ensure a flight-like test environment. Running too fast could cause the track to starve itself of grease and that is exactly what was observed during initial grease runs.

As shown in Figure 11, the sideload friction levels climbed back to the pre-grease levels after only a few thousands revs at 1 rpm. This test speed is approximately 20X faster than flight. Based on previous SARJ coupon testing, it was known that speed affected grease performance so it was clear that the speed would have to be reduced in order to allow the grease to produce a flight-like affect. The test rate was then lowered to 0.4 rpm at roughly 17000 plate revs. The sideloads then started to drop. The track was then re-greased and the sideload dropped even more as expected. They remained reasonably stable until at about 21000 revs when an operator error inadvertently switched the test speed back to 1 rpm. Figure 11 shows that the sideloads continued climbed again until about 29000 revs when the speed was reduced back to 0.4 rpm which lowered the sideload once more. Clearly there was a direct connection between surface speed and grease effectiveness. The explanation for this is that the grease needs sufficient time to flow back into the contact between roller passes after being pushed to the side (see Figure 12). The time required is a function of the length of travel, which is significant for our test rollers being relatively wide. This grease flow phenomenon is relatively well documented, e.g., see Reference 1. Further observations allowed determination of the 0.4 rpm to be the threshold at which the lube life test should be performed. It provided an approximate 8 to 1 test acceleration factor, which was tolerable as 3 years of on-orbit data could be gathered in just over 4 months.

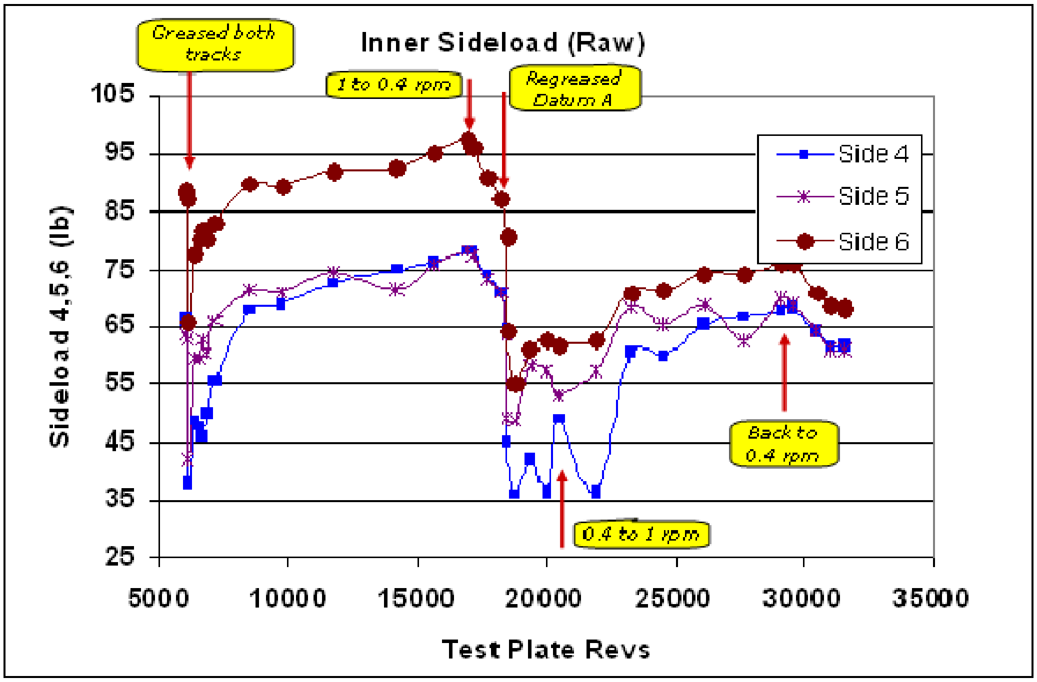

Figure 11: Datum A sideload friction data showing the benefit of grease and low test speed

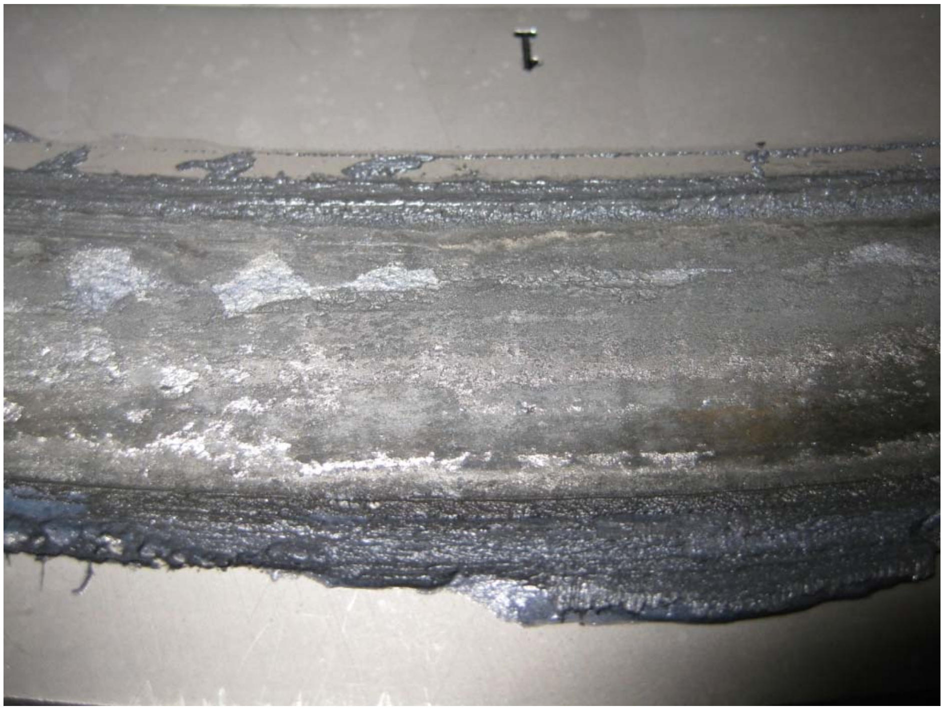

Figure 12: Damaged Outer track with grease

Lubrication Interval

The goal of the lubrication interval portion of the test was to determine how long the SARJ could run without needing a resupply of grease. Each relube would mean an additional EVA, which is added risk and cost to the Space Station program. Data for sideload, tipping, drag torque, temperature and preload was gathered and plotted against time. The sideload friction data (as shown in Figure 13) provided the most relevant feedback to aid in determining the need to relubricate as an increase would indicate a drying track. As shown, the sideload curve remains flat with no sign of any significant trend increases after 125,000 total revs on the damaged outer track and nearly 95,000 revs on the Datum A track at the time of this writing. This is equivalent to about 3.5 years on-orbit since the last greasing. The local up and down variations in side load appearing in Figure 13 closely follows the temperature of the load cell mounting structure, which is also plotted. Apparently, the differential thermal expansion of the mounting structure alters the load cell reading since the load cell is so stiff.

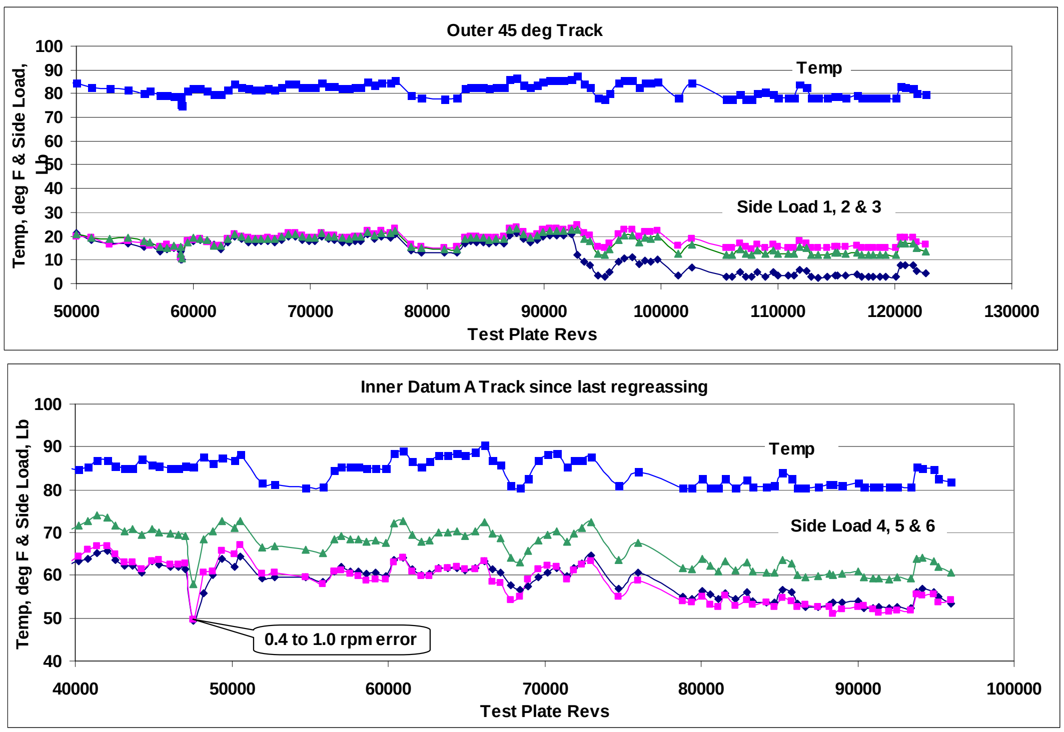

Figure 13: Sideload vs. test plate revs

Roller tipping angle and roller drag are also indicators of increased friction and the lubricant drying out. As shown in Figure 14, the tipping LVDT curve and drag torque curve for the outer track is also relatively flat over time. This indicates that the grease is still effective. However, the drag on the inner track seems to be increasing (more negative) slightly at this point and will continue to be monitored.

This is consistent with intermediate visual inspections of the tracks where the outer track remains relatively well greased throughout its entirety. The voids and pits in the damaged outer track were filled with the grease as the rollers plowed through the track, thus creating a reservoir and perhaps allowing the roller to track interface to remain somewhat wetted (see Figure 12). On the other hand, the inner track looked relatively dry as the grease had been pushed out of the way, leaving only a thin film of oil that would be sufficient enough to keep the roller interface wet. The inner track does show a propensity to dry out faster than the outer track.

This portion of the test is still young and as it progresses, data will continue to be collected and monitored for shifts and changes. The outer track has passed the 3.5 year on-orbit mark since the last lubrication and the inner track is closing in on three years. Testing will likely continue to mid 2010.

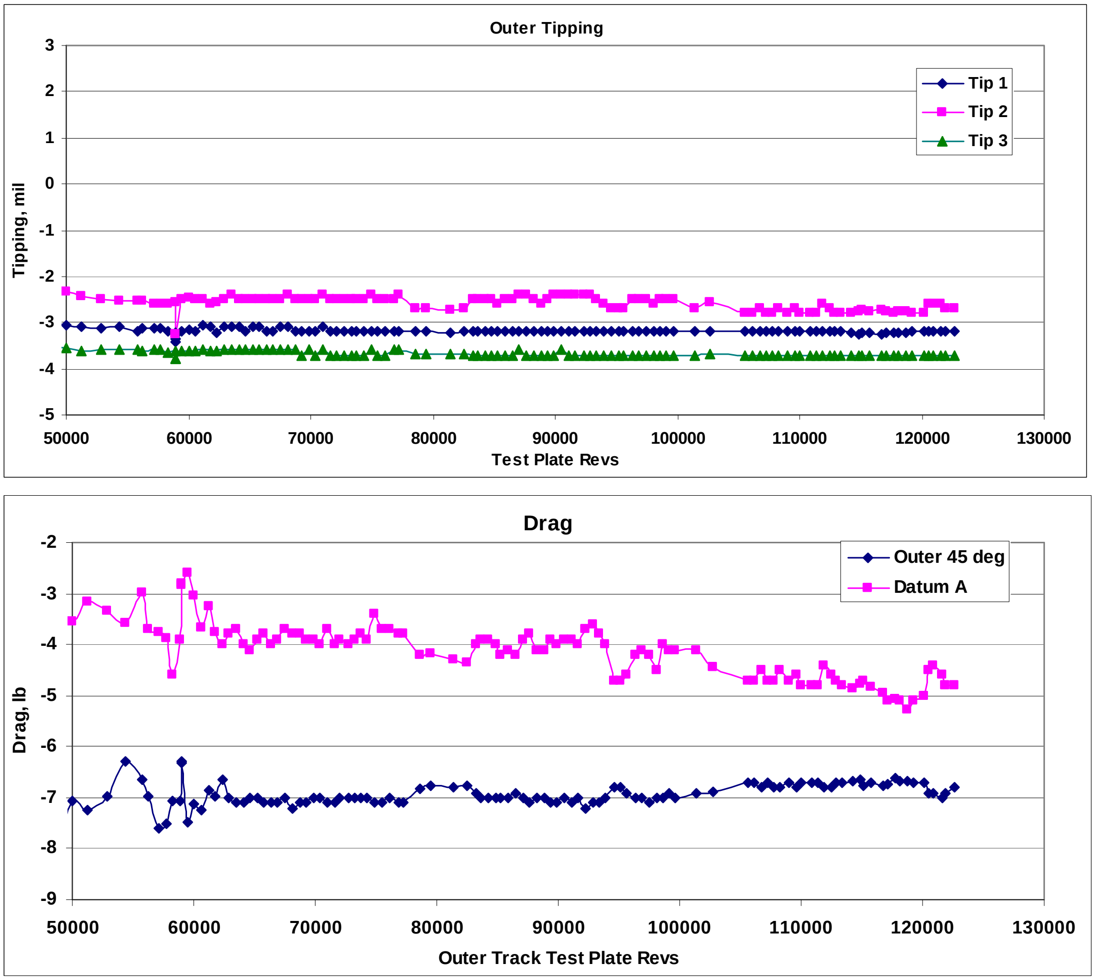

Figure 14: Tipping & drag vs. revs

Conclusion

A test rig was developed that closely simulates the roller/race contact conditions of the SARJ trundle rollers. The test plate was artificially damaged to represent the on-orbit damage race. The test results show that grease lubrication is an effective way of combating the high friction that led to roller tipping and high edge contact stress that led to the on-orbit failure. On-orbit relubrication intervals in excess of 3 years are reasonable based on the data generated to date. The authors would like to acknowledge the contribution from the experts at Boeing, NASA, NESC, and ATK in the design and formulation of test requirements for the SARJ LITE rig.

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