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Root Cause Investigation of the Starboard Solar Alpha Rotary Joint Anomaly on the International Space Station

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Abstract

The Solar Alpha Rotary Joint (SARJ) is a single-axis pointing mechanism used to orient the solar power generating arrays relative to the sun for the International Space Station (ISS). Approximately 83 days after its on-orbit installation, one of the two SARJ mechanisms aboard the ISS began to exhibit high current draw. Later inspections via Extravehicular Activity (EVA) discovered that the case hardened steel race ring on the outboard side of the joint had extensive damage to one of its three rolling surfaces. A far-reaching investigation of the anomaly was undertaken, comprising metallurgical inspections, coupon tests, traction kinematics tests, detailed bearing measurements, and thermal and structural analyses. The investigation found that the race ring damage had been caused by high bearing edge stresses that resulted from inadequate lubrication of the rolling contact. The profile of the roller bearings and the metallurgical properties of the race ring were also found to be significant contributing factors.

Summary

Review of the certified design and previous qualification tests, in addition to extensive new testing and analysis led to identification of the root cause. Many lessons learned were discovered during the 18 month investigation. With careful attention to design, verification and operational considerations, failures of the type observed on the starboard SARJ mechanism can be avoided.

The SARJ is depicted in Figure 1 below. The inboard and outboard sides of the SARJ are structurally connected by twelve Trundle Bearing Assemblies (TBAs), which are mounted to the inboard race ring. Each TBA package includes three tapered roller bearings that support the outboard race ring. The driving torque for the joint is provided by two Drive Lock Assemblies (DLAs), which also include support rollers that interface with the outboard race ring. The TBA and DLA rollers are made of 440C steel and are coated with a thin layer of ion-plated gold, intended to serve as a lubricant. The SARJ race rings are 10 foot diameter 15-5PH forgings, which are case-hardened using a nitriding process. It is this nitrided case that was observed to be fractured and missing from the parent material of the race ring during on-orbit inspections. Figure 2 is a photograph taken by a crewmember during an EVA inspection of the starboard SARJ mechanism. It shows extensive damage to the outer rolling surface of the outboard race ring, as well as an accumulation of fine particles of debris that had been liberated from the race ring surface. The other two rolling surfaces of the starboard SARJ race ring were observed to be largely intact, as were the rolling surfaces on the port SARJ.

The root cause investigation took place over the course of one and a half years and drew on the work of experts from across the country, including NASA civil servants, aerospace contractors and members of academia. The tests, inspections and analyses they performed during that investigation focused heavily on the complex tribological interactions between the trundle bearing rollers and the outboard race ring of the SARJ. Of particular importance is the role of the camber pivots that support the rollers in each of the TBAs. These pivots, designed to give the trundle bearings compliance to accommodate thermal-structural

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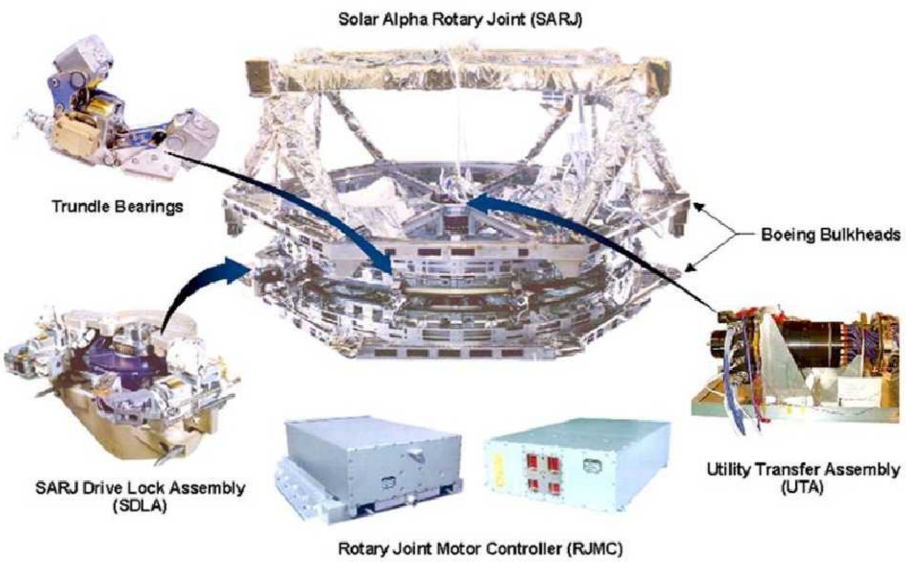


Figure 1: Solar Alpha Rotary Joint (SARJ)

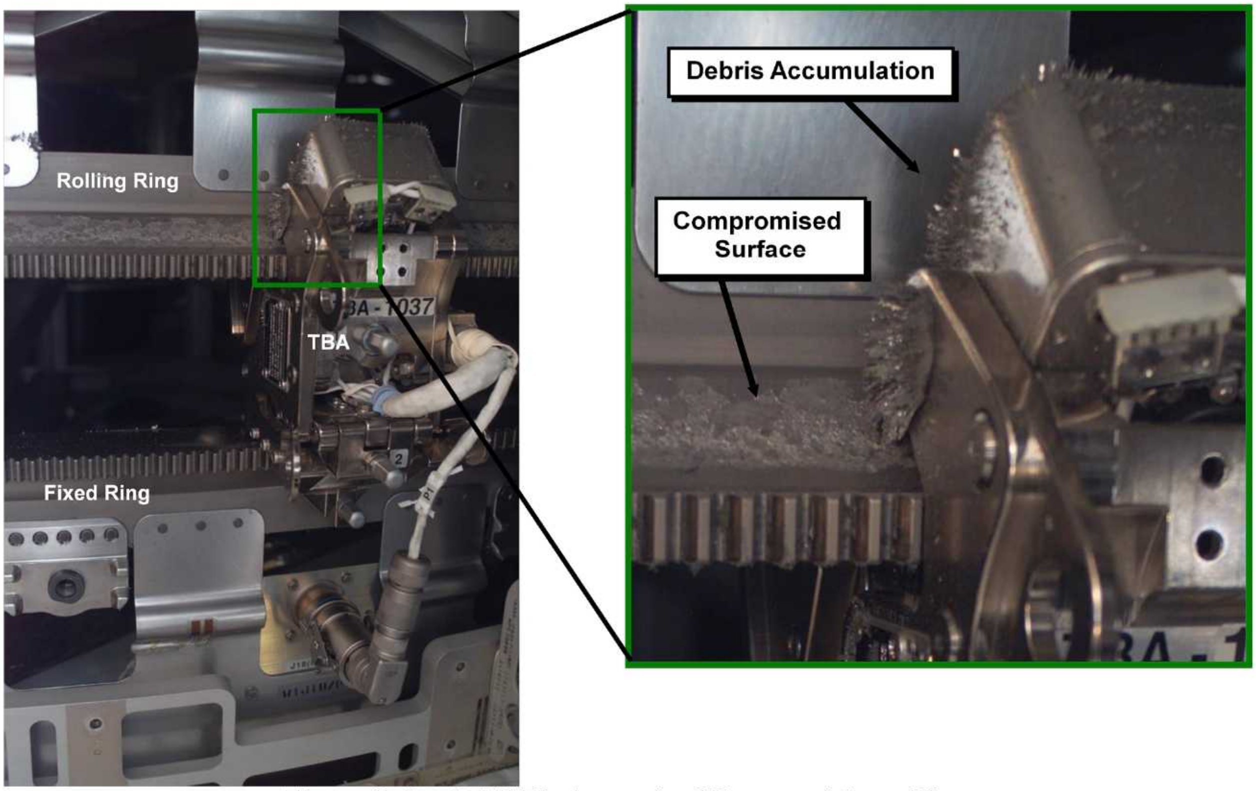


Figure 2: On-Orbit Photograph of Damaged Race Ring

distortions, also allow the rollers to tilt when subjected to thrust loads. The camber pivots are visible in the photograph of a trundle bearing shown in Figure 3. Roller thrust loads, which were generated due to lack of adequate lubrication and small angular misalignments of the TBA rollers, created a moment about the camber axis. The overturning moment resulted in an asymmetrical loading of the normal roller bearing contact with the race ring, giving rise to subsurface stresses that exceeded the yield strength of the race ring core material and ultimately caused the brittle fracture and spallation of the nitride case.

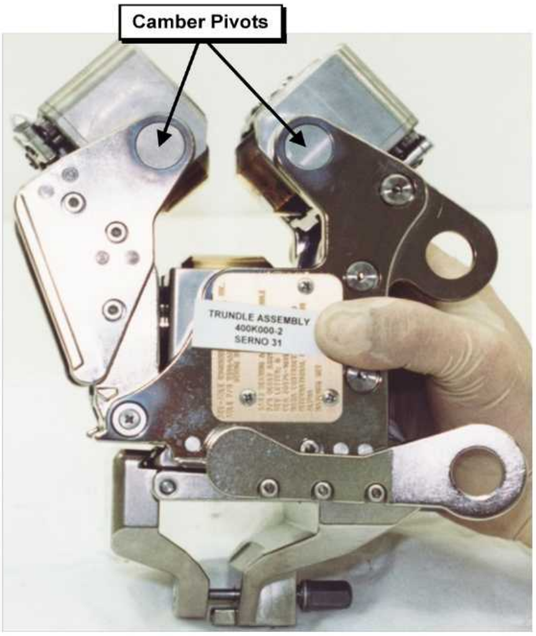
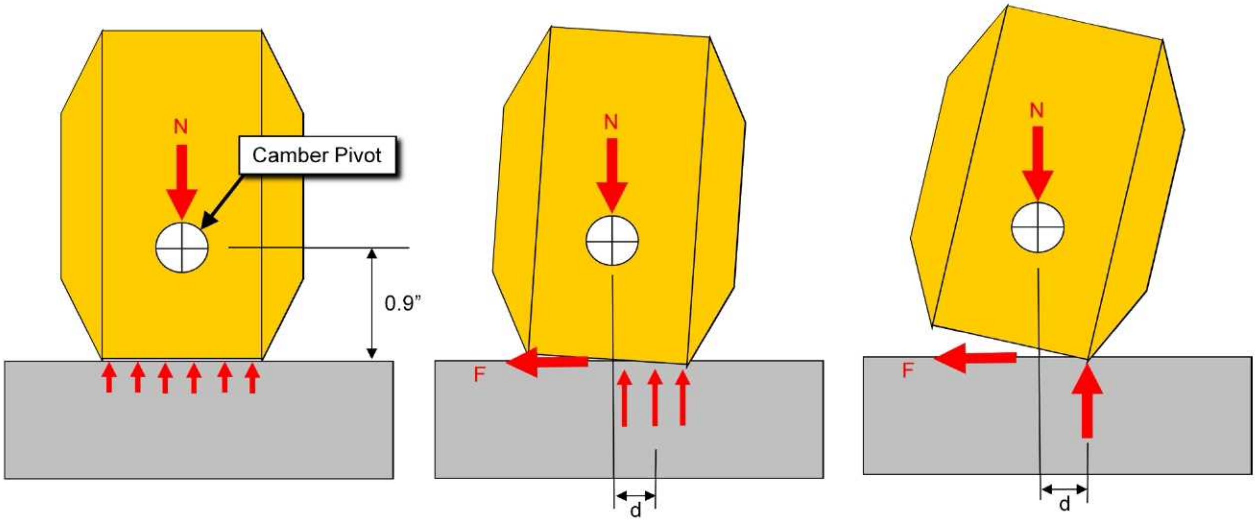


Figure 3: Trundle Bearing Assembly

Figure 4 illustrates the mechanism by which thrust loads lead to asymmetric roller loading. Analysis and detailed TBA inspections show that although the starboard SARJ trundle bearing rollers remained within the regime of stable tilting, the resulting stresses were sufficient to cause the observed damage to the race ring.



Pure Normal Contact

Stable Camber Tilt

Unstable Camber Tilt (Tipping)

Figure 4: Trundle Bearing Roller Stability

The starboard SARJ failure mode was made possible by an increase in the coefficient of friction of the rolling contact between the rollers and the race ring. The choice of gold for the SARJ application and the processing timeline of the hardware contributed to the breakdown of the lubricant system. Traction testing of rollers using flight-like materials demonstrated that the lubrication provided by the thin gold film on the rollers was not sufficiently durable to prevent high thrust loads.

The root cause team further found that the bearing edge stresses were exacerbated by the flat, un-crowned profile of the TBA rollers. The roller geometry made the system sensitive to non-hertzian effects, which gave rise to high pressure points at the edges of the rollers during the initial run-in period of the mechanism. These high pressure points are visible in the contact stress profile of the TBA rollers shown in Figure 5.

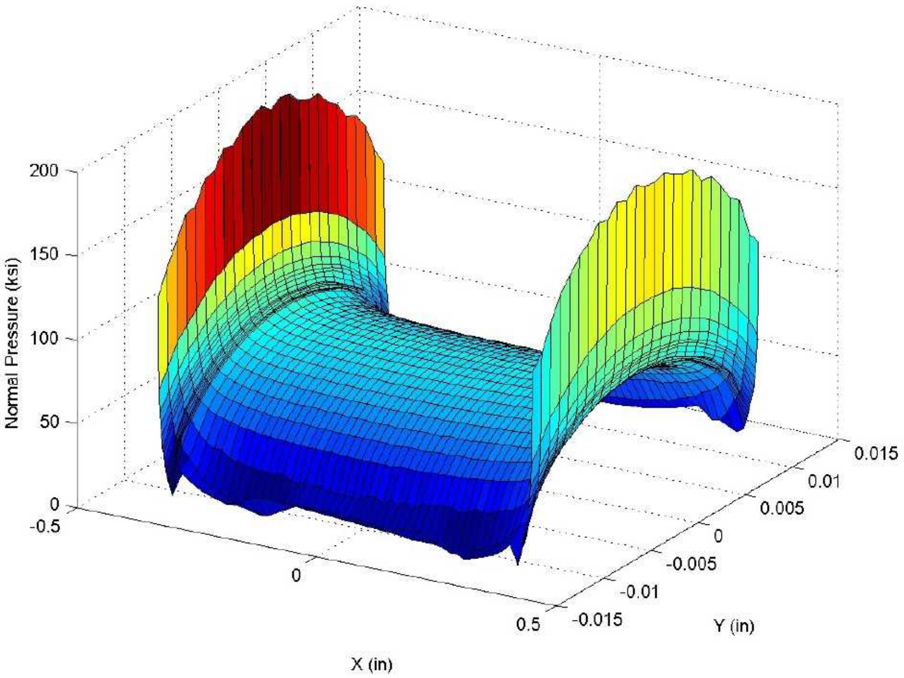


Figure 5: Contact Stress Distribution for Trundle Bearing Roller

Metallographic inspection of the starboard SARJ race ring material also revealed an unusually high concentration of discontinuous intergranular separations (DIGS) when compared with similar nitrided specimens. Subsequent tests using a variety of specimens suggest that the presence and concentration of these DIGS may play an important role in the susceptibility of the race ring material to the type of damage observed in the starboard SARJ.

The damage sustained by the starboard SARJ highlights the importance of sound design and verification practices in the development of rotating space machinery. The non-hertzian contact mechanics of the roller bearing to race ring interface proved to be a crucial detail of the system. Special attention should be given to such effects in the design of bearing systems. The SARJ exhibited high vulnerability to damage during the initial run-in phase of the mechanism's life. The risks incurred during this period can be mitigated through the use of adequate lubrication, crowned rollers, detailed screening of the nitriding process, and the implementation of a pre-flight run-in period. The addition of these elements to the operational plan for the SARJ forms the basis for the continued successful use of these mechanisms in flight.