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TRIBOLOGICAL CHALLENGES IN HARMONIC DRIVE ACTUATED SPACE ROBOTIC ARMS

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ABSTRACT

The use of harmonic drives in space robotic manipulators can be explained by its compactness, high levels of torque density and zero backlash properties. Nevertheless, the extreme conditions of the orbital space present extreme tribological issues that directly affect the actuator reliability, accuracy and service time. This review integrates current articles (2022–2025) on environmental impacts on lubrication, wear caused by friction and tribological failure mechanisms within Space robotics applications by utilizing Harmonic Drive. Specific focus is on contributions of vacuum, thermal extents as well as dynamic impact loads experienced during on-orbital service provision and capturing of non-cooperative targets. The comparison of dry and wet lubrication strategies is done critically in terms of wear resistance, damping capability and failure susceptibility. The review identifies important shortcomings in the existing methods of modelling, with the necessity to merge environmental tribology and actuator dynamic simulations to provide dependable mission planning and failure alleviation.

KEYWORD

Harmonic drive, tribology, wet lubrication, space robotics, vacuum environment, actuator reliability

INTRODUCTION

Robotic manipulators operating in space are increasingly being tasked with contact intensive tasks including satellite docking, active debris removal and capture of non-cooperative objects [1-4]. As opposed to free flying inspection missions, such missions include inevitable impacts and uncontrolled transfer of impulse by the manipulator joints [5-7].

Harmonic Drives have been extensively used in space robotic arms because they have high reduction ratios, compact geometry and high positioning accuracy [6-8]. Nevertheless, in docking or debris capture, impact loads are directly coupled to the gear transmission and tribological performance is a very important factor in determining how long actuators will survive. In this regard, the choice of lubrication strategy is not just a wear reduction problem but a major wear impact load control tool [9].

MECHANICAL VULNERABILITIES OF HARMONIC DRIVES

Harmonic drives are based on the elastic deformation of a thin walled flexspline to provide the torque. This allows compact and lightweight actuation, but it causes susceptibility to impulsive and overload conditions [10-12]. Ratcheting is one of the worst failure modes that happen when the impact induced torque is greater than the flexspline buckling threshold causing teeth disengagement and uncontrolled transmission error [10-11].

These transmit bursts of torque well beyond the usual operating levels in cases where sudden momentum exchange and a misalignment of contact during satellite docking or debris capture can occur [5-7]. In these circumstances, the capacity of lubrication system to dissipate energy comes out as a determining factor in inhibiting ratcheting and structural deformation.

TRIBOLOGY DRIVEN FAILURE MECHANISMS UNDER IMPACT LOADING

The tribological behaviour is directly involved in the way the impact loads pass through the Harmonic Drive. Friction and lack of damping lead to abrupt stress wave transmission to the flexspline teeth that hastens the wear and enhances the likelihood of ratcheting [12-14].

Both experimental and analytical observations have consistently indicated that under transient loading lubrication degradation results in higher torque ripple, focal heating and damages on the surface [10, 15]. These effects are magnified in the impact dominated operations and tribology is a primary failure driver and not a secondary performance driver. The key tribology related failure modes, reasons why they occur and the environmental factors are summarized in Table 1 and one can get a clear picture of how the lubrication and the operating conditions influence Harmonic Drive reliability in space [5-8, 15-16].

Table 1: Tribology driven failure mechanisms in harmonic drive actuators under impact load.

Failure Mechanism	Tribological Cause	Operational Consequence
Ratcheting	High friction + impact torque	Permanent transmission error
Tooth wear	Inadequate lubrication	Reduced positioning accuracy
Flexspline fatigue	Repeated frictional heating	Crack initiation
Torque loss	Lubricant degradation	Reduced load capacity
Stiction / cold drag	High lubricant viscosity	Actuator stall during start-up

Figure 1 Schematic of tribology driven failure mechanisms in Harmonic Drives, showing ratcheting, excessive wear, torque ripple, surface adhesion/galling and friction induced heating under environmental stressors like vacuum, temperature extremes and impact shocks.

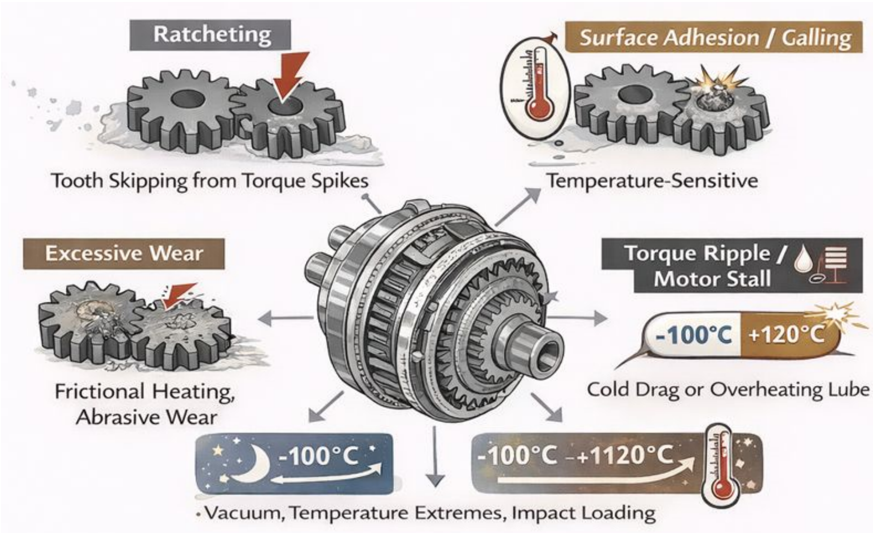

Figure 1: Tribology-driven failure mechanisms in harmonic drive.

LUBRICATION STRATEGIES FOR IMPACT DOMINATED OPERATIONS

The major difference between dry and wet lubrication strategy used in the Harmonic Drives is their capacity to absorb impact energy during docking and to acquire events [13-14, 17].

Dry Lubrication: MoS_2 dry lubricants offer low friction and environmental stability which indicate that they can be used in long term, low impact operations [18-21]. Nonetheless, dry lubrication has insignificant viscous damping, i.e. impact energy flows virtually directly to the gear teeth and flexspline [11]. Consequently, dry lubricated Harmonic Drives are more prone to ratcheting and surface fatigue at times of debris capture.

Wet Lubrication: Hydrodynamic damping is provided by grease based lubrication systems, which is important to damp impulsive loads at the gear mesh [9-10]. This viscous damping causes impact forces to be distributed over extended time period during satellite docking or during debris capture and peak contact stresses are reduced as well as the risk of flexspline buckling and ratcheting failure is far lower [10, 17].

A variety of studies prove that the application of variable joint damping (which is closely related to wet lubrication behavior) can significantly decrease the impact forces to be passed to robotic joints [17]. Wet lubrication is therefore found to be the best tribology approach to use in Harmonic Drives with the space missions of impact dominated space missions although wet lubrication is more complex to model and long term stability.

A straight study of the sustainability, wear, shock load and impact energy dissipation between dry and wet lubrication is summed up in Table 2 indicating the excellent aptness of wet lubrication in the impact prone operations [18-24]. Figure 2 shows that dry lubricants provide vacuum stability but no impact damping, whereas wet lubricants provide hydrodynamic damping with temperature dependent viscosity.

Table 2: Comparison of dry and wet lubrication in harmonic drive under space impact loads.

Tribological aspect	Dry lubrication	Wet lubrication
Wear characteristics	Higher wear under repeated impacts	Reduced wear due to lubricant film
Impact energy dissipation	Minimal damping capability	High damping, absorbs impact energy
Response to shock loads	Direct transmission of impact	Attenuates impact forces
Suitability for docking / capture	Limited	Highly suitable

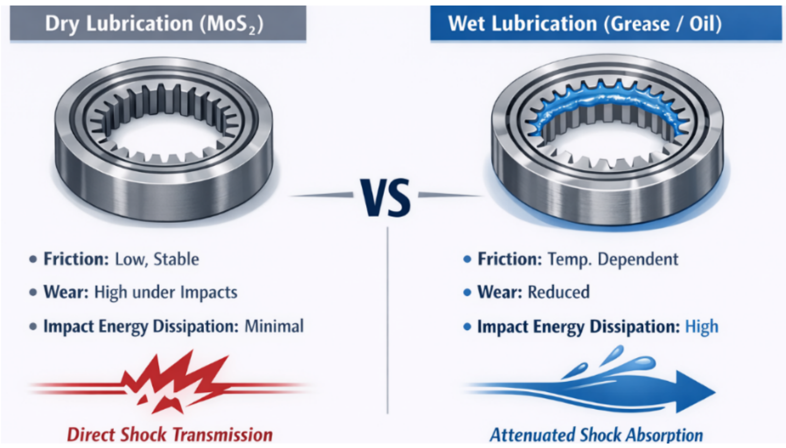

Figure 2: Dry vs wet lubrication in harmonic drive actuator under impact load.

MODELING AND SIMULATION OF TRIBOLOGICAL EFFECTS

In order to model the tribological behaviour accurately in dynamic actuator models, tribological behaviour should be integrated in the prediction of harmonic drive survivability during docking and capture. It has been suggested to use hybrid reliability models and analytical formulations of friction to explain the torque dependent friction and accumulation of wear and transmission error [10, 12, 15].

The recent research on space robot dynamics highlights that joint damping has a leading role in restraining vibrations and stress spread during contact occurrences caused by impact [8, 25]. Nevertheless, the vast majority of existing simulations continue to ignore the effect of damping of joints as a fixed factor, missing the effect reducing benefit of wet lubrication [13-14]. Dynamic models which include lubrication dependent damping are therefore necessary to make realistic predictions of the actuator failure thresholds during docking and debris capture.

CONCLUSION

The reliability of Harmonic Drive actuated space robotic arms depends critically on tribological performance, especially in missions where the major effects involve impact, like docking the satellite and catching space debris. Under impulsive loading the major failure mechanism is still friction induced wear and ratcheting. Although dry lubrication offers environmental robustness and low friction, it does not have the energy dissipation properties needed in impact mitigation. Wet lubrication on the other hand provides better hydrodynamic damping and this will reduce the peak impact loads and the survivability of the actuators is greatly increased during the docking and capture manoeuvres. The development of the wet lubrication based damping models into dynamic simulations in the future should be a priority so that the failure can be predicted properly and the design of the next generation space robotic manipulators can become effective designs.

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