Failure Analysis of International Space Station Control Moment Gyro

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ABSTRACT—The US Attitude Control system of the International Space Station (ISS) includes four Control Moment Gyros (CMGs) that provide a micro-gravity environment for science payloads. On June 8th 2002 a CMG suffered a hard failure after approximately 1.5 yrs in operation. This paper presents an overview of the design, heritage, on-orbit failure, and corresponding root cause analysis of an ISS CMG. A discussion of telemetry data analysis conducted and methods to produce significant results are presented. A description of the suspected modes of failure and corresponding analysis are also given.

Keywords: International Space Station, Control Moment Gyro, Tribology

NOTATION

τ_S	Torque applied through shaft due to ball of load P skidding (in.-oz.)
fmu	Friction coefficient between ball and raceway
P	Load on ball that is skidding (lbs.)
E	Pitch circle of bearing (in.)
w_b	Ball group rotation (Hz)
w_i	Shaft Rotation (Hz)

INTRODUCTION

The International Space Station (ISS) is currently the largest man-made object to ever orbit the Earth and represents one of the greatest engineering and integration efforts the National Aeronautics and Space Administration (NASA) has ever undertaken. The Guidance, Navigation, and Control (GN&C) system is composed of both a US non-propulsive attitude control system and a Russian thruster attitude control system. Nominal operations are conducted under US control using its four CMGs, shown in Figure 1, with the Russian system providing momentum desaturation through thruster assists. When configured for completely non-propulsive control, the CMGs provide the ISS the micro-gravity environment that is required for science payloads.

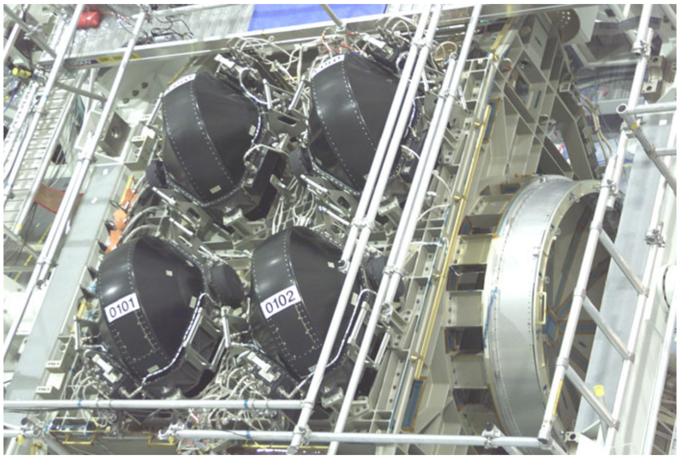

Figure 1: CMGs 1-4 Mounted on Z1 Truss

The US GN&C system uses a two-axis Torque Equilibrium Attitude (TEA) seeker controller to minimize the amount of momentum required to maintain attitude control. Due to thermal issues with external components, several of the assembly stages require a biased attitude to minimize sun exposure to specific surface regions. Analysis of the momentum necessary to maintain the required attitude envelope has shown that the momentum of four CMGs is required for much of the assembly phase. On June 8th of 2002, one of the CMGs suffered a bearing failure and is no longer operational. The failure poses a major obstacle to the ISS program and GNC subsystem as we approach a critical yearlong stage of assembly with very asymmetric configurations.

This paper describes the configuration of the ISS CMGs, historic heritage, the on-orbit failure, and corresponding root cause analysis.

CMG CONFIGURATION

The four CMGs operate as momentum storage devices that exchange momentum with the ISS through induced gyroscopic torques created by a motor-driven constant-speed momentum wheel mounted in two orthogonal gimbals. Both gimbals have torquer motors and position resolvers mounted on the rotational axis and move by use of a gear train system. The momentum wheel is mounted inside the inner gimbal and is supported by bearings mounted on both sides of the spin axis as shown in Figure 2a.

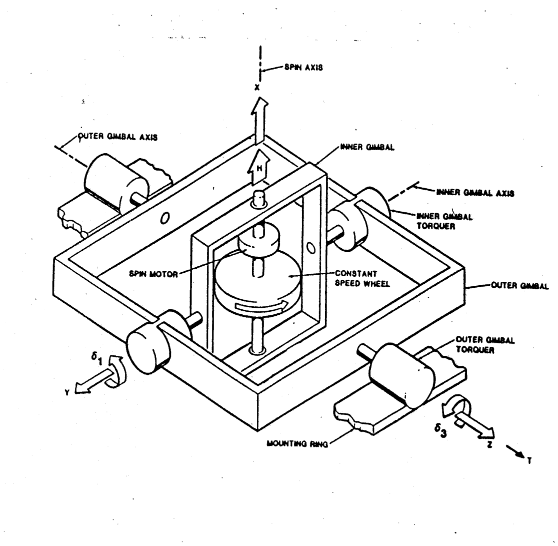

Figure 2a: CMG Gimbal and Wheel Assembly

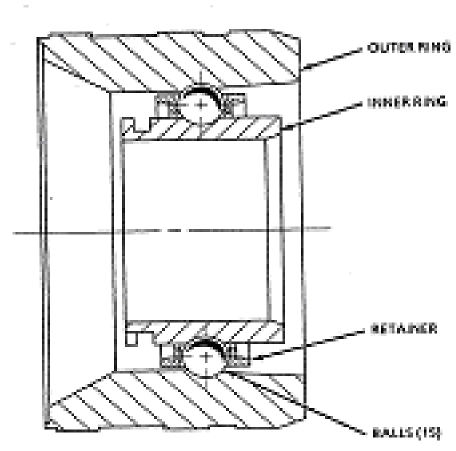

Figure 2b: CMG Spin Bearing Assembly

The Spin Motor is a low torque motor mounted on the spin axis with a control loop operating at 440Hz to maintain the nominal wheel-speed of 6600 rpm. The wheel speed resolver is mounted on the opposite side of the spin axis and provides digital wheel-speeds for downlink telemetry. The Spin Motor Commanded Current (SMCC) ranges from 0 to 1.6 Amps and nominally averages approximately 0.37 Amps. The SMCC varies from viscosity changes in the spin bearing lubricant due to thermal variations and high gimbal rates that induce radial loads on the spin bearings. The SMCC is used as a “barometer” of spin bearing health.

An accelerometer is mounted to the inner gimbal of each CMG to measure spin bearing vibrations in the radial direction. The accelerometer is used to track the unbalance of the momentum wheel during operations. Values seen on on-orbit since operations began have been between 0 to 0.04 G.

The Spin Bearings (SB), shown in Figures 2a and 2b, are Barden 107 H single roller angular contact bearings with 15 steel balls mounted in a phenolic retainer that maintains consistent ball motion. The spin bearings use a petroleum lubricant in an active dynamic oiler system. Due to the large influence of temperature on lubricant viscosity, the spin bearings must maintain an 18°C to 50°C temperature range for operations. This is accomplished using a pair of small heaters mounted around the outer race of each bearing.

DESIGN HERITAGE/HISTORIC PERFORMANCE

The ISS CMG is based on the Bendix CMG designed for use on the NASA Skylab program. The spin bearings have also been used on the Defense Support Program (DSP) satellite constellation in momentum wheels. A comparison of basic design and operational parameters that effect loading and environment is presented in Table1.

Table1: Hardware Heritage Parameters by Program

	Skylab	DSP	ISS
Configuration	Dual Gimbal CMG	Momentum Wheel	Dual Gimbal CMG
Pre-Load (Thrust loading)	40 lbs.	30-40 lbs	55 lbs.
Wheel Speed	9100 RPM	3000-9000 RPM	6600 RPM
Wheel Mass	150 lbs.	105 lbs.	220 lbs.
Max Gimbal Rate (Slew Rate)	3-4 deg/sec	N/A	3.14 deg/sec
Orbit	Low Earth	Geostationary	Low Earth

Of the three CMGs used on the Skylab station, one CMG1 spin bearing suffered a failure after 195 days of continuous operations while CMG2 showed repeated anomalous behavior. CMG2 was spun-down after the CMG1 failure and stored until the final days the of the Skylab mission. Extensive analysis and testing was conducted to determine the cause of the failure of Skylab CMG1 bearing. Conclusions from the failure investigation were:

1. The lubricant feed rate was insufficient to adequately supply the race and ball contact zone. This was due to the lubricant being centrifuged from the retainer feed holes not migrating into the outer raceway contact area.
2. Marginal oil film thickness led to a breakdown of the elastrohydrodynamic film resulting in initial metal damage. Additionally, local heat was not being properly dissipated due to lack of lubrication for thermal transfer median.
3. Heat generated from the continuation of metal damage and lack of sufficient thermal transfer resulted in exceedance of the allowable delta temperature across the bearing. This “thermal runaway” caused loss of radial clearance and quick catastrophic failure.

Modifications were made to the oiler system to increase lubrication flow into the raceway contact zone. The retainer was redesigned such that the lubricant from the flange would feed directly into the bearing outer race groove. The lubricant housing was made more redundant with addition sources of lubricant supply, which also increased overall supply rate. Ground testing on the redesigned bearing showed no signs of bearing distress and adequate lubrication in the ball/raceway contact zone after 3588 hours of operation.[1]

The DSP program uses this redesigned bearing in momentum wheels with units operating at two different rotational speeds. Two units operate at 3000 RPM and have currently exceeded 14 years of on-orbit life with no performance anomalies. Three units operate at 8000 RPM and have exceeded 10 years of on-orbit life with some anomalous behavior but without failure. These anomalies have been analyzed extensively by the Aerospace Corporation and have been concluded to be retainer instabilities. The instabilities are thought to be a result of the retainer guide surface being marginally lubricated.[2]

ON-ORBIT FAILURE SUMMARY

At the end of May 2002, the ISS was in a high solar beta inertial attitude period were the CMGs experience warmer operations due to more sun exposure. The ISS attitude was transitioned from inertial to Local Vertical Local Horizontal (high solar shade) on June 7th[1], several hours prior to shuttle docking [2]. Several hours after docking, the flight control team noted a flag that indicated the accelerometer on CMG1 had measured 0.5 Gs [3]. The CMG1 SMCC was elevated and one spin bearing temperature was beginning to rise. GN&C personnel determined that the CMG would be monitored but no immediate action would be taken. The event repeated itself twice during the next 16 hours. Then, following a 30-minute period with no ground communication, telemetry showed that the CMG1 SMCC was at its maximum value, 1.6 Amps, and the wheel-speed was decreasing [4]. After several seconds of maximum current and wheel-speed reduction, Fault Detection and Isolation software declared the CMG failed and automatically shutdown the spin motor. Following motor shutdown, normal SB drag would result in the wheel speed decaying to 0 rpm in about 12 hours. During this event, the wheel stopped 72 minutes after spin motor shutdown. Data was retrieved from the on-board data recorders to fill in the missing telemetry for analysis purposes. Astronauts aboard the station and orbiter reported hearing a sound similar to an unbalanced washing machine while vibrations could be seen in acclerometers throughout the 300 tons of mated vehicles. Telemetry data from the failure period is shown in Figure 3 with events described previously annotated.

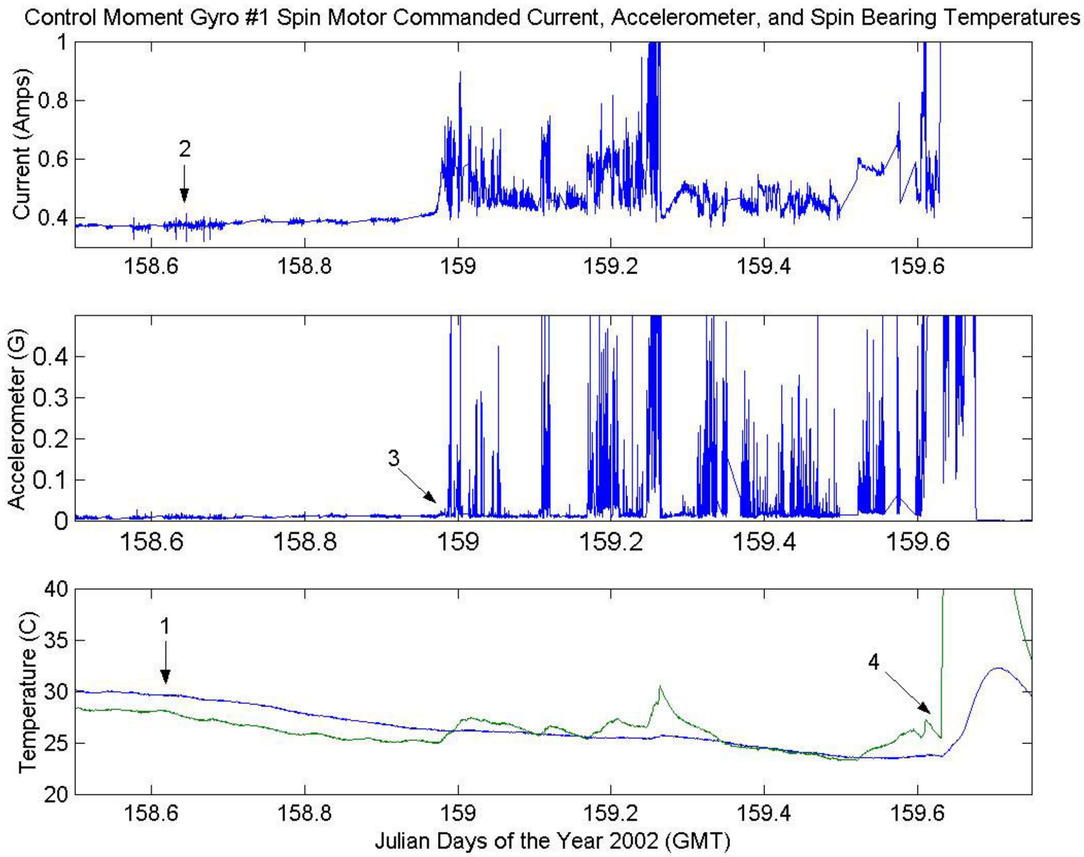

Figure 3: ISS CMG1 Failure Telemetry Data

ROOT CAUSE ANALYSIS

In the initial phases of the root cause analysis, a fault tree was developed that covered failure methods as a result of design, manufacture, assembly, and operation. A breakdown of the fault tree is provided in Table 3, with the red column being the most likely cause of failure and green being the least.

Table 3: CMG1 Root Cause Fault Tree Summary

RED	Yellow	Green
Axial Impulse compresses Belville Spring	Debris created by bearing surface wear	EA fails to supply expected current
Bearing outer race jams	Debris from external source	Spin Motor fails to develop expected torque
Transfer of ball control to outer race	Impingement by dislocated of deformed part	Debris obstructed ball motion
Excessive wear of retainer ball pockets	Unexpected loading from external source	Loss of correct race curvature or ball sphericity
Insufficient design/analysis	Thermal contraction of outer race	Rotation of sleeve in beryllium housing
Lubrication degraded	Excitation of axial resonance by external forces	Loss of alignment of two-bearing system
Jamming of outer race in sleeve	Loss of correct viscous drag forces	Impingement by debris lodged in airgap
Retainer fails from impact load of fatigue	Insufficient protection during testing	Loss of balance of Momentum Wheel
Loss of retainer stabilizing characteristics	Incorrect material selection	Loss of balance of Spin Motor Rotor
Excitation of unstable modes	Insufficient protection during operation	Loss of balance of Hall Sensor Rotor
	Lubricant leaks to unintended path	Strut fails to maintain correct clamping force
	Loss of surface wetability	Retainer exerts unexpected force on balls
	Contamination of lubricant by foreign material	Insufficient manufacturing controls
	Lubrication not delivered to ball track	Reservoir contains insufficient lubrication
	Obstruction to flow	Failure of lubrication flow
		Incorrect viscosity for operating conditions
		Debris from external sources

The root cause analysis of the ISS CMG1 Failure has been documented a previous paper, but to date has not revealed the cause of failure.[3] Failure methods due to design, manufacture, or assembly were removed as possible causes once the documentation from those phases of production was reviewed in detail and are out of the scope of this paper. The focus of this paper is to address methodologies to analyze flight data during the operations phase.

TELEMETRY DATA REVIEW

The ISS downlinks sensor data or telemetry through an S-Band Antenna at a rate of 5-0.1 Hz. At ISS assembly complete, there will be approximately 300,000 parameters being constantly downlinked at this rate. Given bandwidth constraints of the antennas, the CMG internal parameters that are available are downlinked at only 0.1 Hz. For spin bearing health and status the parameters available are accelerometer (magnitude of 110Hz), spin motor commanded current, bearing temperatures, wheelspeed, and gimbal rates (radial loading).

When compared with the spin bearing generated frequencies shown in Table 2, the downlink telemetry appears to not be of adequate rate to detect changes in the inherent frequencies. These changes in frequencies would be most apparent in the SMCC, whose telemetry Nyquist frequency is 0.5 Hz, while all bearing frequencies of interest are significantly higher. While these higher frequencies will be aliased into multiple lower frequencies, certain assumptions must be made to in order to determine the exact aliased frequency. Given the size of the mated vehicles and the several hundred thousand moving parts within the two, it was not possible to use this technique directly.

Table2: Spin Bearing Frequencies

Inner Ring Rotation	110 Hz
Retainer	46 Hz
Ball Group relative to Outer Race	46 Hz
Ball Group relative to Inner Race	64 Hz

However, the technique of analyzing frequency content proved valuable in determining likely candidates for failure and on-orbit bearing health monitoring. The use of this method with heritage data showed correlations throughout each former program.

RETAINER INSTABILITY/LUBRICATION STARVATION

Retainer instability is an unstable mode of high frequency retainer vibration that produces high-impact forces in a bearing. Retainer instability has long been the subject of research in rotating machinery due to the catastrophic impact the phenomenon can have on operational life. Historically, the Skylab bearings and DSP bearings both suffered from retainer instability due to starvation or marginal lubrication.

Retainer or cage instability is not very predictable and has never been known to cause catastrophic failure on the first occurrence. Instabilities can be sectioned into the categories of wet and dry; where wet instability is caused by the bearing being flooded with lubricant and dry instability is caused by poor lubrication at the ball-retainer contacts. Wet instability is of concern due to the higher drag torque and current required to operate with the increase in lubricant, however it typically does not cause catastrophic failure. Wet instability drag torque signature is a step change in drag torque with a slow first order decay as illustrated below in Figure 4 which shows a period of wet instability experienced by CMG4.

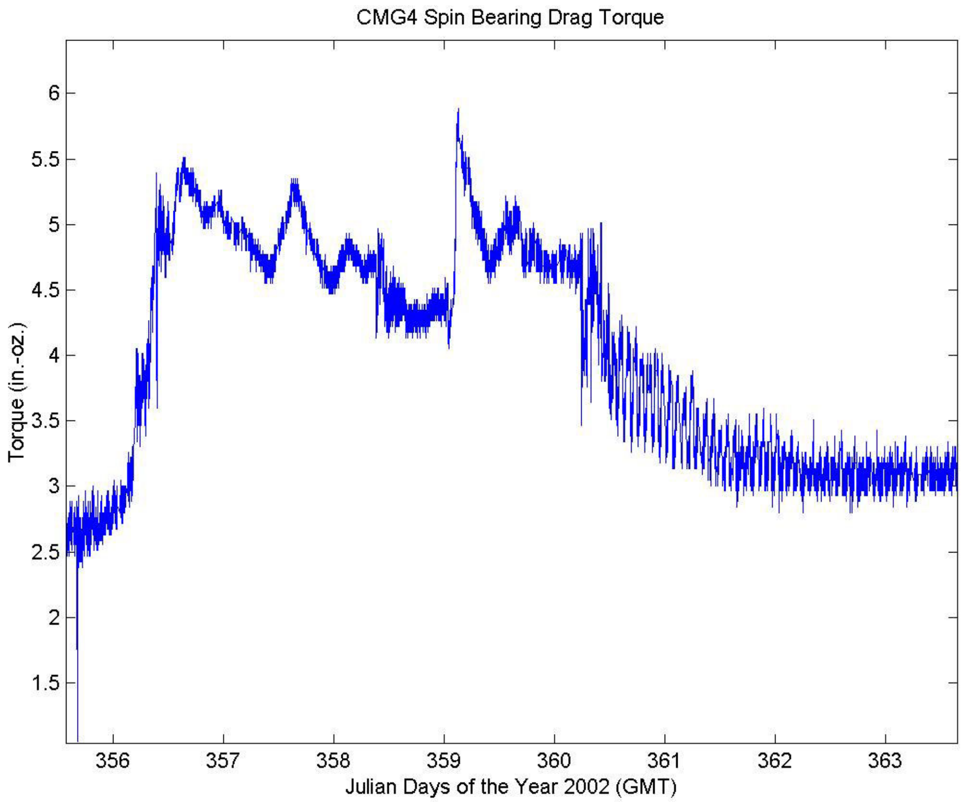

Figure 4: CMG4 Wet Retainer Instability Event

Dry retainer instability is not the primary cause of on-orbit wheel failures but rather a side effect of lubrications starvation. When the ball-retainer contacts are poorly lubricated, contact between the ball and retainer or raceway and retainer can excite instability in the retainer. Both heritage programs showed the same on-orbit characteristic, a step change in bearing drag torque of approximately 5 in-oz with a period of several minutes to almost an hour. Analysis from the Skylab program showed this anomaly to exist at 1000 to 1200 Hz, which is well above the 440 Hz spin motor controller loop bandwidth and results in the constant drag torque increase seen by the controller. The instability is relieved when the ball path changes and the balls pick up lubricant outside of their normal track, this is done either naturally as the instability persists or from large external loading. Dry instabilities will repeat as the additional lubricant is used and not replenished. Instabilities will occur more frequently and for longer periods, as the balls must travel farther from the nominal ball path to pick up lubricant. The progression to failure occurs because eventually there is no longer any extra lube available. This process can take weeks to years from the first anomalies to failure and was never seen on CMG1 prior to failure.

Ball Control/Ball Skidding

Roller bearings are designed with either inner or outer race control defined by which race controls the balls spin. This control is a function of the rotational speed of the bearing and contact angle of the balls which is a result of the dynamic pre-load. The ISS CMGs were designed with inner race control. It was shown through analysis that during periods of high gimbaling or radial loading, one or more balls in the bearing could become unstable and be controlled by either race.

Ball skidding is the phenomena that occurs when one or more balls will be controlled by the opposite race from the others. This results in the ball attempting to rotate at a different speed, which causes it to slide along the race and add stress to the retainer. If properly lubricated, ball skid will not cause damage. If the ball skid occurs on a dry surface, it will cause smearing which will degrade the surface and lead to premature failure.

When one or more balls skid along a race, the drag torque increase due to skid loading can be calculated as:

$$\tau_S = fmu * P * (E/2) * (w_b / w_i) \qquad \text{Eq. 1}$$

Where *fmu* is the friction coefficient between the balls and raceway, *P* is the ball load, *E* is the pitch circle of the bearing, w_b is the ball group rotation frequency, and w_i is the inner ring rotation frequency. For the ISS CMG spin bearing, this torque load is:

$$\tau_S = (.06) * 16 * P * (1.9/2) * (46/110) = .381P(in - oz)$$

From the bearing under nominal loading conditions with 55 lbs thrust loading due to the pre-load, the nominal load torque is 0.85 in-oz or 0.0566 in-oz per ball. For a single ball with one pound of skidding load, the load torque would be (.38/.0566)*1-lbs. or approximately 6.7 times as much torque as a ball acting normally with regards to the raceway motion. Each pound of skid load per ball corresponds with a 0.381 in.-oz increase in drag torque. Total drag torque (lube + load) for a ball skidding with between one pound of skid load and the nominal load would be 1.83 in-oz (0.329 Amps) and 5.64 in-oz (0.547 Amps) depending on the number of balls skidding. For a bearing pair with a ball skidding as above in one of the bearings, the total drag torque would be between 3.37 in-oz (0.416 Amps) and 7.15 in-oz (0.633 Amps).

Ball skidding is a low frequency event over several seconds and would be plainly visible in downlink telemetry. The bearings do not have inherent frequencies below the 46 Hz ball group rotation as their single row configuration does not allow beat frequencies to exist between the pair. Anomalies have been seen on ISS CMGs which corresponds to the amplitude and frequency described above. Figure 4 shows a period of CMG2 SMCC in which ball skid is believed to be occurring.[4] Figure 5 shows CMG1 SMCC during the period of anomalous data prior to the hard failure, the similar signature is seen.

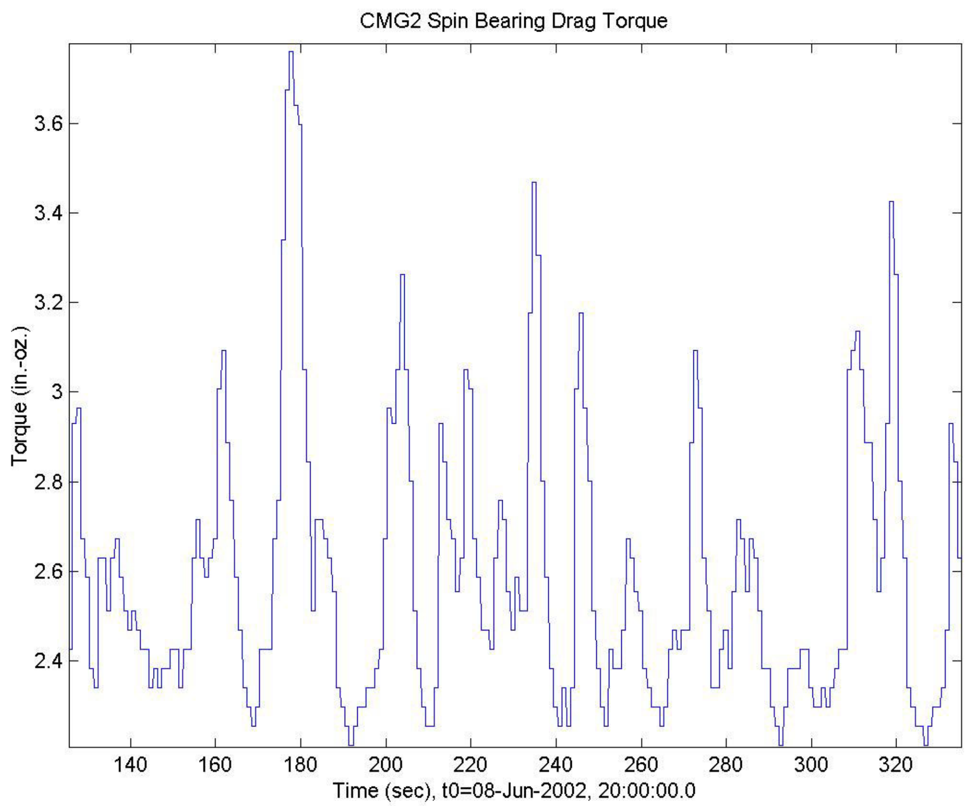

Figure 4: CMG2 Possible Ball Skid Event

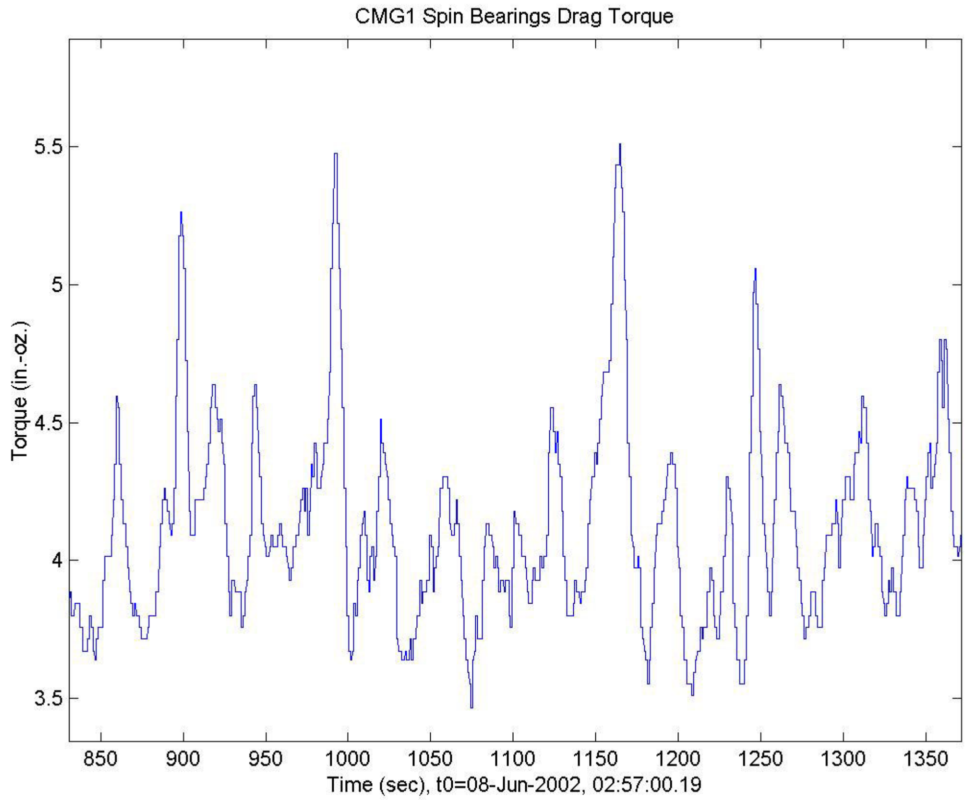

Figure 5: CMG1 Possible Ball Skid Event During Failure

CONCLUSIONS

Over the past 11 years, the largest number of GN&C subsystem failures leading to loss of spacecraft have been due to momentum wheel failures.[5] Given the predominance of this failure type on-orbit, the literature available lacks developed methodology for flight data analysis in anomaly resolution and root cause analysis. This paper presented a technique of characterizing drag torque frequency content that can be used to analyze flight data for distinct signatures of several failure methods.

NASA is currently working to gain insight into the dynamics of ball and cage interactions with regards to ball skid in the ISS CMG 107 H bearings configuration. Testing similar to that conducted by Pasdari and Gentle is currently planned to empirically define the effects of changes in dynamics pre-load and thermal environment to ball control.[6]

With failure of momentum wheels on telecommunication and military satellites on-orbit, the possibility of returning the hardware for teardown and thorough failure analysis is not feasible. The ISS CMG1 is scheduled to return to Earth aboard STS-114/ULF1, this presents a unique opportunity to gain insight into an on-orbit failed momentum wheel through such a detailed teardown. Data gained from this experience can provide the community with information to prolong spacecraft life in the design phase, diagnose potential problems early, assist in developing mitigation plans, and further develop root cause data analysis techniques.

ACKNOWLEDGMENTS

The authors would like to thank the dedicated team at L-3 Communications in Budd Lake, NJ including Charles Gurrisi, Dennis Francia, Raymond Seidel, and Mark Glowacki. The work of specialist is the fields of tribology, CMGs, and failure analysis: Alan Leveille, Jack Murphy of Boeing Satellite Services, and Stuart Randolph of GB Tech for their contributions. Thanks to Richard Swain, John Harduvel, and Michael Begley of the Boeing Company for their guidance and assistance. Special thanks to the NASA/Boeing GN&C team for providing a very significant portion of this entire root cause effort, including fault tree development, root cause analysis, tireless effort for months, and overall direction.

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