New Understanding of Hubble Space Telescope Gyro Current Increase Led to a Method to Save a Failing Gyro

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Agenda

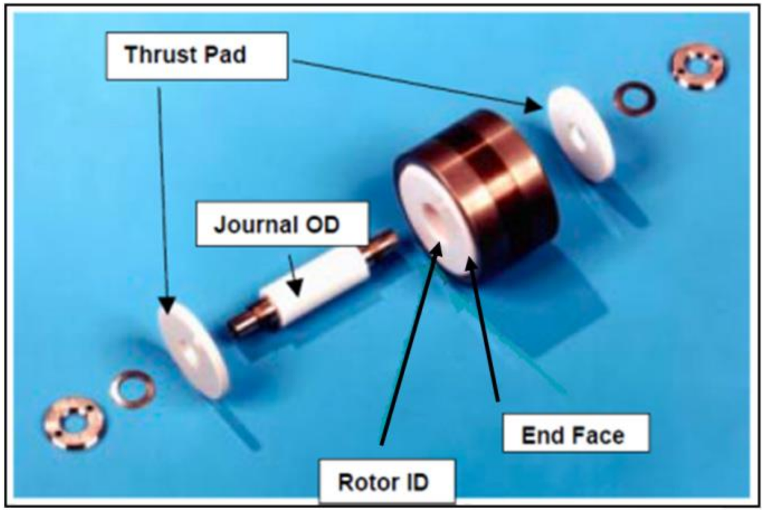
- Hubble Space Telescope (HST) History
- Gyro Configuration
- History of Gyro High Current Anomalies and Failure
- Why does gyro current increase? A problem with the long-held theory.
- Failure Review Board
- Brief Motor Theory – BDC, Synchronous, Hysteresis
- The Proposed Theory
- Proving the Theory
- Why multiple current increases?
- Saving a Failing Gyro
- Questions?

Hubble Space Telescope History

- Launched 24 April 1990
- Servicing Mission 1, conducted by STS-61, was the most complex of any shuttle mission
  - Installation of corrective optics and main camera
  - New solar arrays
  - Various instrument upgrades
- Gyros were replaced 3 times
  - Servicing Mission 1, Dec. 1993, 4 gyros replaced
  - Servicing Mission 3A, Dec. 1999, all 6 gyros replaced after 4 failed
  - Servicing Mission 4, May 2009, all 6 gyros after 3 failed

Gyro Configuration

- 2-phase hysteresis motor spins 19,200 rpm
- Gas bearings provide levitation
  - The motor is in a sealed pressurized chamber
  - The chamber floats in a fluid for 1-g buoyancy
  - Flex leads for power pass through the fluid



Gyro Anomalies and Failures

- Gyro anomalies of increasing current in steps
- High current has led to flex lead failures
- Attributed to corrosion of flex leads from interaction with buoyancy fluid
- Accelerated by heating from high current
- Later gyros have enhanced flex leads, which are plated to resist corrosion

Why does gyro current increase?

- Returned gyros have been found to have debris in the 1.27 μm gas bearings
- Current increase has been attributed to rotor restriction, increasing gas bearing drag
- This theory never explained why a gyro exhibiting anomalous high current restores back to nominal after a restart

Failure Review Board

- In the first week of November 2015, 2 gyros exhibited anomalous current increases
- A Failure Review Board was formed
  - To determine if the events were connected
  - To generate operational procedures that could potentially extend gyro life
  - I was assigned to that review board
  - This effort led to a theory that was accepted to be the root cause of gyro current increase

Hysteresis Motor Behavior

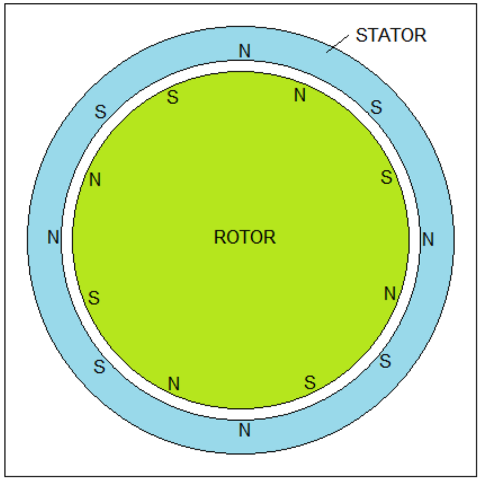
- We need to understand the hysteresis motor
- This requires building understanding
  - DC motor theory
  - Synchronous motor theory
  - Hysteresis motor theory

DC Motor

- Defined by a torque constant K_t in N-m/amp
- This must exist with a back-emf constant K_b in volts/rad/sec, which is identical in MKS units
- Commutation is a function of shaft <u>position</u> so that the relationship between the stator and rotor fields is always optimal

$$T = K_t I$$

where T is torque and I is current



Optimal Torque Phase Angle

Back-emf and Load Power

- A particular torque requires a particular current
- If the motor is spinning, more voltage is required to overcome back-emf, so more power is required
- A torque at speed means there is shaft load power; there is no load power when holding a static torque

$V_b = K_b\, \omega$

where V_b is back-emf voltage and ω is angular velocity in rad/sec

$P_{load} = V_b\, I = T\omega$

where P_{load} is the load power

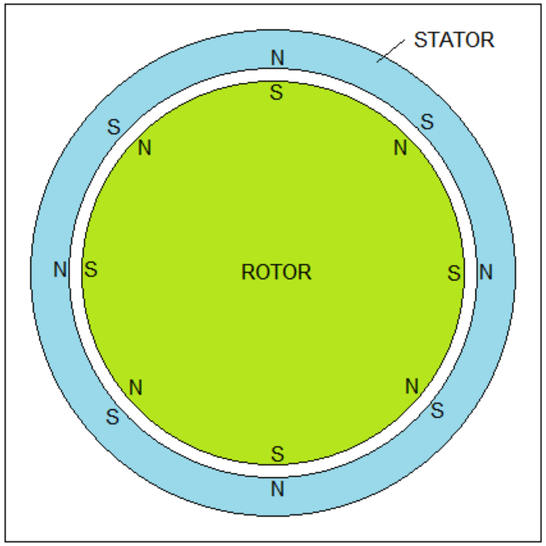
Motor Constant

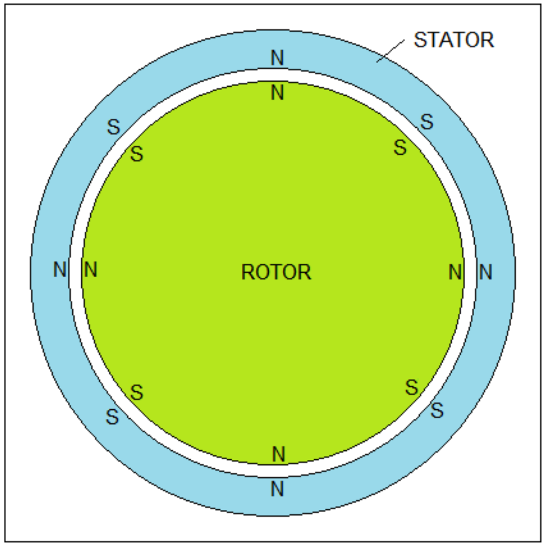
- The motor constant K_m is in N-m / sqrt(watt)
- This defines power in the winding as a function of torque, which are simply resistive losses
- Winding power does no work; it is entirely parasitic

If commutation was not set optimally

$T(\theta) = \cos\theta \, Kt \, I$

where θ = 0 degrees at the highest efficiency phase angle and θ = +/- 90 degrees at the zero torque phase angles





Zero Torque Phase Angles

Synchronous Motor

- A synchronous motor is commutated as a function of time
- Commutation angle for a synchronous motor will vary like we just discussed, based upon motor operating conditions
- In a synchronous motor, optimal torque commutation has zero torque margin.
- Therefore, less-than-optimal commutation is necessary.

Hysteresis Motor

- The rotor of dc brushless motor and a synchronous motor can have permanent magnet poles, but the hysteresis motor rotor is a ring of soft magnetic iron alloy
- The rotating (time-varying) field of the stator induces magnetic poles in the rotor material
- Consider locking the rotor while applying a rotating field from the stator:
  - Due to the hysteresis of soft magnetic material, the magnetic poles induced in the rotor will lag those of the stator field, causing a phase angle between them.
  - This results in a torque called the hysteresis torque.

Hysteresis Torque

- If we let go of the locked rotor, the hysteresis torque will cause the rotor to accelerate until it matches the stator field rotation rate (synchronous speed).
- Once at synchronous speed, the poles in the rotor will become stationary within the rotor material.
- Behavior in this state is similar to that of a synchronous motor

Why does gyro current increase?

- A restart restores the current to nominal
- It makes sense that drag torque would not be at an elevated level after the restart
- If it was not persistent elevated drag torque that resulted in an increase of current, what could possibly change that would result in increased current?

What changed to increase current?

- If not drag torque, it has to be something in the motor that would reduce torque constant K_t:
  - Stator winding or iron
  - Rotor magnetization
- What if the rotor magnetization changed?
- What can cause the rotor magnetization to change?

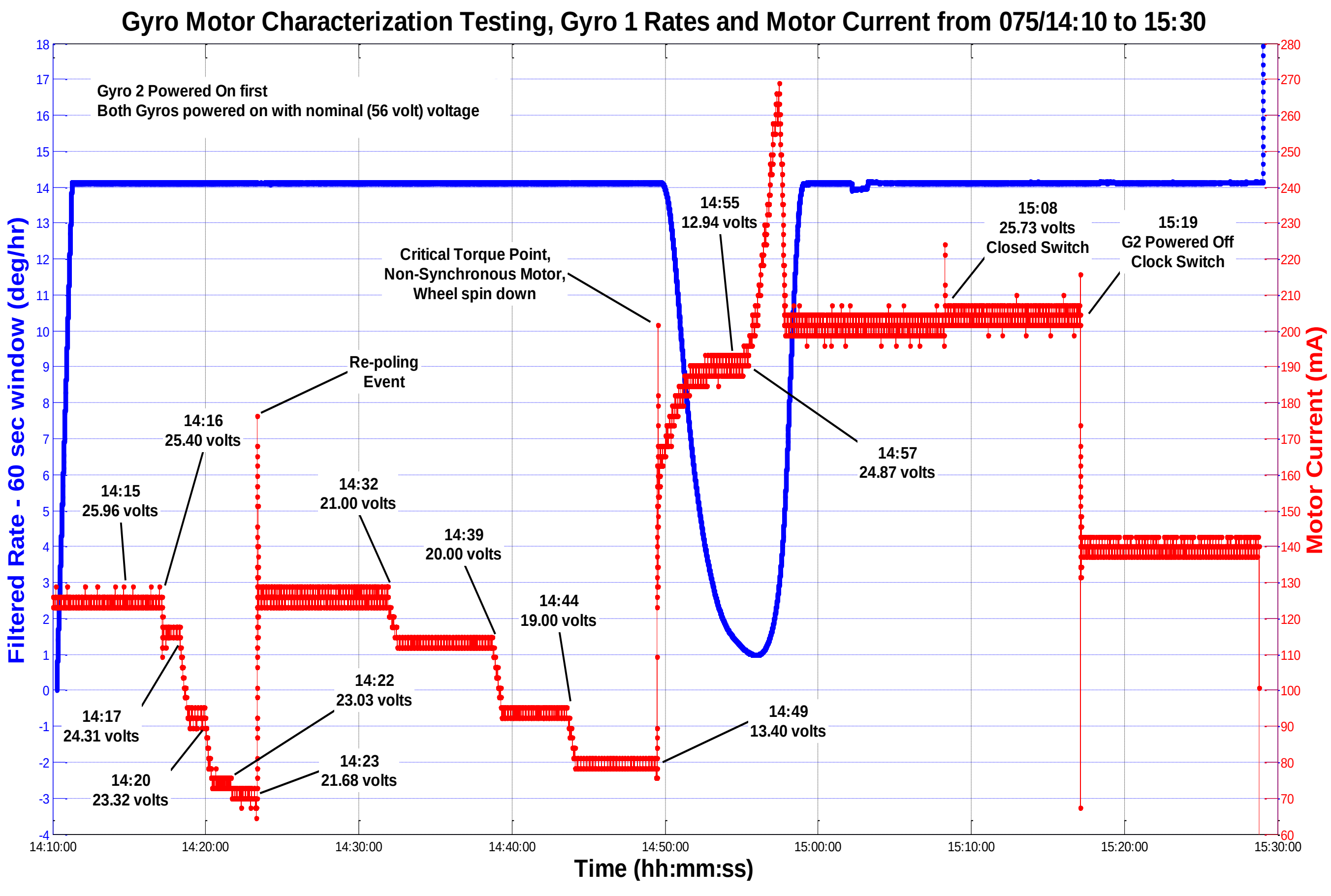
THE PROPOSED THEORY

- A momentary rotor restriction exceeded the hysteresis torque, causing the poles to move in the rotor material (as they do during startup).
- The run voltage is lower than the start voltage, so the rotating field is weaker when running than at start.
- The weaker stator field means the rotor field strength will decrease as the poles are shifted in the rotor material.
- This results in a lower K_t, so current will increase to overcome the original torque after the restriction passes.
- Lower K_b results in more overall torque capability, preventing the process from cascading.

Proving the Theory

- We utilized the HST Vehicle Electrical Systems Test (VEST) facility
- I received permission to modify the hardware to reduce voltage to the gyro
- As voltage was lowered, the motor became more efficient as phase angle increased, so voltage and current dropped
- Once the “optimal” phase angle was reached, re-poling occured, weakening magnetization, causing the current to jump higher

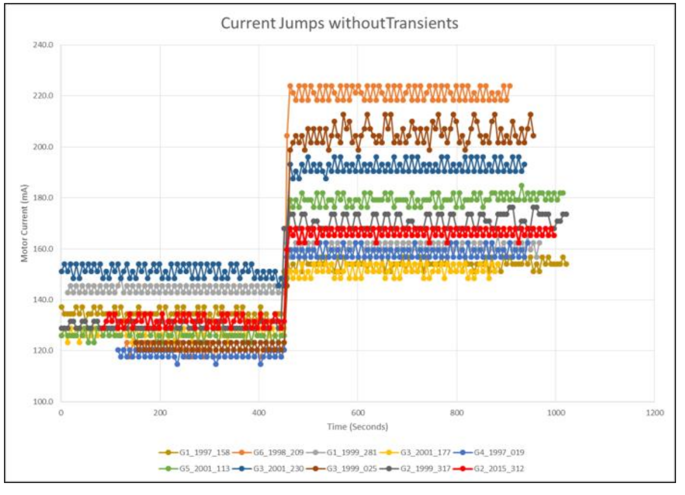
VEST Data



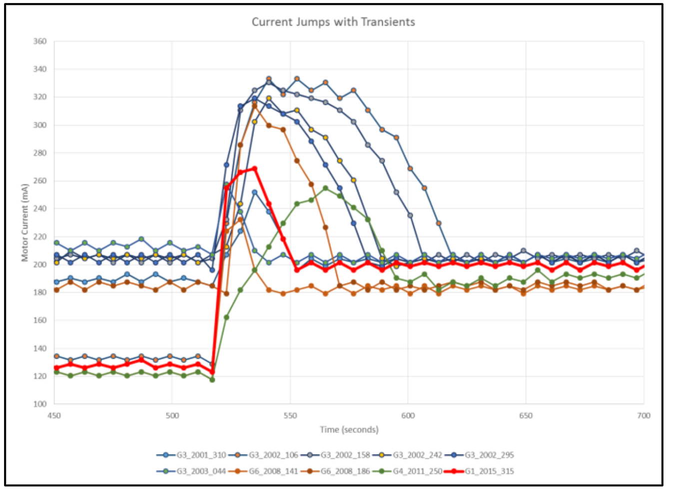
Gyro Motor Characterization Testing, Gyro 1 Rates and Motor Current from 075/14:10 to 15:30
Gyro 2 Powered On first
Both Gyros powered on with nominal (56 volt) voltage
Filtered Rate - 60 sec window (deg/hr)
Motor Current (mA)
Time (hh:mm:ss)
14:15
25.96 volts
14:16
25.40 volts
14:17
24.31 volts
14:20
23.32 volts
14:22
23.03 volts
14:23
21.68 volts
Re-poling
Event
14:32
21.00 volts
14:39
20.00 volts
14:44
19.00 volts
Critical Torque Point,
Non-Synchronous Motor,
Wheel spin down
14:49
13.40 volts
14:55
12.94 volts
14:57
24.87 volts
15:08
25.73 volts
Closed Switch
15:19
G2 Powered Off
Clock Switch

Historical Gyro Current Anomalies

- Past data shows that current jumps are not always discrete, with increased current with transients dropping somewhat after an increase, never taking more than two minutes stabilize
- It is believed that the post-current jump transients are the result of residual particles being ground up in the gas bearings after the remagnetization event.



Current Jumps Without Transients



Current Jumps With Transients

Why multiple current increases?

- Why wouldn't a single rotor remagnetization event result in a weakest rotor magnetization state and just one current increase to the worst case current?
- The historical anomalous behavior indicates that there are always multiple increases in current.
- **THE REASON:**
  1. Reducing rotor magnetization increases torque margin if motor power is dominated by load power rather than winding resistive losses
  2. Reduced rotor magnetization means a reduced back-emf constant K_b
  3. Reduced back-emf voltage V_b allows for increased current despite a fixed supply voltage, resulting in increased torque capability
- A rotor restriction event may barely slide the poles in the rotor since torque capability simultaneously increases.
- If the poles do not slide a full hysteresis cycle, magnetization will not reach it weakest state.

Saving a Failing Gyro

- The HST team accepted the new theory that weaker magnetization resulting from a rotor restriction event is the root cause of increased gyro motor current
- It was considered, but not recommended to perform a running restart to restore gyro current back to nominal since analysis showed gyro life would only increase by a few months
- If gyro current becomes high enough such that gyro failure is imminent, the HST team decided that an autonomous running restart be implemented
- The software was tested at the VEST facility, approved by HQ, and uploaded to HST

QUESTIONS?