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

17th European Space Mechanisms and Tribology Symposium (ESMATS)  
20th – 22nd September 2017

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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
• 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.
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
• 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 position 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
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 \( \omega \) is angular velocity in rad/sec

\[ P_{load} = V_b I = T\omega \]
where \( P_{load} \) is the load power
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 \( \theta = 0 \) degrees at the highest efficiency phase angle and \( \theta = +/- 90 \) degrees at the zero torque phase angles
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.
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.
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.
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?
• 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.
• 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 occurred, weakening magnetization, causing the current to jump higher
Gyro Motor Characterization Testing, Gyro 1 Rates and Motor Current from 07/14:10 to 15:30

- **Filtered Rate - 60 sec window (deg/hr)**
- **Motor Current (mA)**

- **Time (hh:mm:ss)**
  - 14:10:00
  - 14:20:00
  - 14:30:00
  - 14:40:00
  - 14:50:00
  - 15:00:00
  - 15:10:00
  - 15:20:00
  - 15:30:00

- **Motor Current Events**
  - 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
  - 14:32:21.00 volts
  - 14:39:20.00 volts
  - 14:44:19.00 volts
  - 14:55:12.94 volts
  - 14:57:24.87 volts
  - 14:59:13.40 volts
  - 15:08:25.73 volts
  - 15:19:24.87 volts

- **Critical Torque Point, Non-Synchronous Motor, Wheel spin down**

- **Gyro 2 Powered On first**
  - Both Gyros powered on with nominal (56 volt) voltage

- **Re-poling Event**

- **Closed Switch**

- **G2 Powered Off**

- **Clock Switch**
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 to 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.
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 its weakest state.
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?