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

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ABSTRACT

Throughout the history of the Hubble Space Telescope (HST) program, gyro current increases have been observed to occur, oftentimes leading to gyro failure. The explanation was that debris from the surfaces of the gas bearings, with only 1.27 μm clearance, resulted in "rotor restriction," which increased friction, torque, and current. However, the rotor restriction theory never could account for the fact that a restart of the gyro would restore the current back to nominal. An effort was made to understand this puzzling gyro behavior after two HST gyros exhibited increased current within the same week in November 2015. A review board was created to resolve these anomalies and generate operational procedures to potentially extend gyro life. A new understanding of gyro current behavior led to implementation of a method that could potentially save a failing gyro.

HST AND GYRO OVERVIEW

The legendary Hubble Space Telescope (HST) was launched on April 24, 1990. As of this writing, HST has been on orbit for over 27 years. There have been five servicing missions. No future servicing missions are planned.

HST has six gyros. Three gyros provide the necessary three orthoganol axes for highest performance pointing, with three gyros as spares. Four gyros were replaced during Servicing Mission 1 in December 1993. All six gyros were replaced during Servicing Mission 3A in December 1999, weeks after a fourth gyro had failed. All six gyros were again replaced during Servicing Mission 4 in May 2009 after three gyros had failed. This was the final servicing mission.

To improve gyro life, later gyros have enhanced flex leads, which are plated with an anti-corrosive coating. Not all the present gyros aboard HST have enhanced flex leads. Gyros returned from service were found to have debris of the same composition as the coating of the gas bearings. It was theorized that this debris was responsible for increased gyro current. Since there is a relationship between motor current and motor torque, increased friction from debris would result in additional motor torque, thus resulting in increased current. However, the rotor restriction theory did not explain why gyro current would return to nominal if the gyro was powered down and restarted. This behavior was reported to be observed by the gyro vendor long ago and was also observed during HST operations.

GYRO CONFIGURATION

Each HST gyro utilizes a 2-phase hysteresis motor that spins at 19,200 rpm. Gas bearings provide radial and axial levitation, so the motor and bearings are sealed in a chamber that is pressurized with a gas mixture. The motor rotor and the gas bearings are shown in Fig. 1. The sealed chamber floats within another chamber that is filled with a fluid that provides buoyancy under 1g operation. Delicate flex leads pass through the fluid to provide motor current.

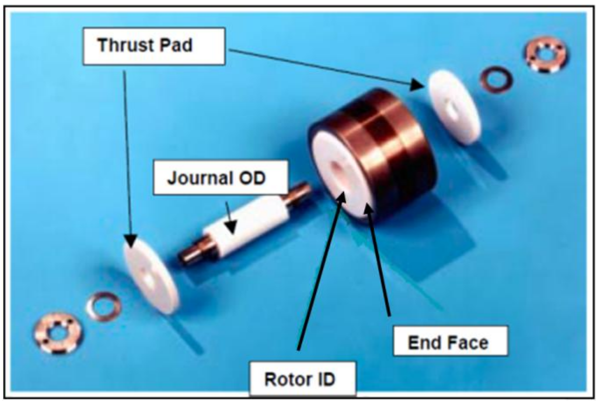

Figure 1. Gyro Rotor and Gas Bearings

PAST GYRO FAILURE HIGHLIGHTS

Early versions of the gyro suffered flex lead corrosion, eventually leading to failure. Such failures were determined to be accelerated by high gyro current heating the flex leads, thus accelerating the corrosion process until finally failing.

GYRO ANOMALY OVERVIEW

The applied motor voltage is a 960 Hz quasi-square wave for 19,200 rpm operation. Starting torque is provided by the "start voltage" of 55 volts for 30 seconds, followed by the "run voltage" of 26 volts. The lower run voltage saves power and reduces heat in the motor windings and flex leads.

At the run voltage, gyro current is nominally about 130 mA. Current may remain steady for years, but then may suddenly jump to an anomalous level. Once the current rises, it may stay at that level for some time, or it may rise again, sometimes a few times. The highest levels observed were around 220 mA. With sustained high current, a flex lead failure is more likely to occur. In some cases, a gyro was able to continue operation with flex lead failure of one phase, though failure of the other phase would shortly follow.

BUILDING UPON MOTOR THEORY

In order to make headway into understanding the cause of the HST gyro current anomalies, it is necessary to understand the behavior of the hysteresis motor. This first requires understanding behavior of the DC motor, followed by understanding behavior of the synchronous motor, leading to understanding behavior of the hysteresis motor. A short summary of motor theory follows. We will look at the similarities and differences of the three motor types.

DC MOTOR BEHAVIOR

Let us assume a brushless DC motor with a permanent magnet rotor. Though called a DC motor, winding excitation is either trapezoidal or sinusoidal. Ideally, if the motor is built such that the torque profile is sinusoidal when applying a fixed current to a winding, and if the motor had multiple phases and was sinusoidally excited, the output shaft torque would be constant if neglecting detent torque.

The optimal phase of the waveform is set by commutating as a function of shaft position. If the applied current waveform was synchronized with the torque profile as described in the previous paragraph, highest efficiency would be achieved. This would result in a relationship between motor current I in amps and motor torque T in N-m such that the defined torque constant K_t in units of N-m/amp, as in Eq. 1, is achieved operationally.

$$T = K_t I \tag{1}$$

Note:

If Kt is not in in N-m/amp, a constant is required.

This occurs when the phase of the rotor to stator is such that at any instant, the rotating magnetic poles of the rotor are always mid-point between the rotating magnetic poles of the stator, as shown in Fig. 2, resulting in maximum torque. If the commutation phase is not correctly set, the torque will be degraded.

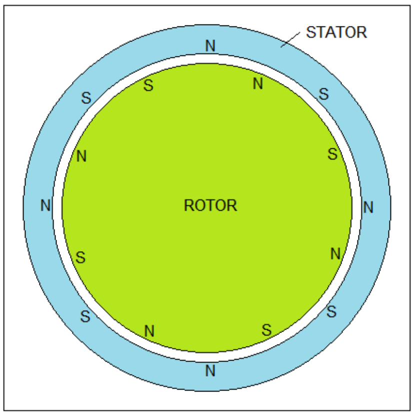

Figure 2. Highest Efficiency Phase Angle

The commutation phasing can even be set such that opposite or like poles of the rotor and stator will always be in alignment, resulting in zero torque when energized. Both zero torque rotor to stator phase relationships are shown in Fig. 3.

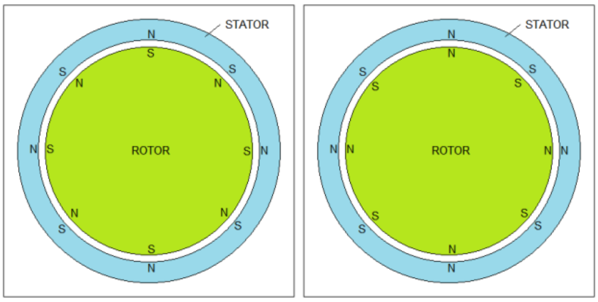

Figure 3. Zero Torque Phase Angle

If the commutation is not properly set for highest efficiency, torque as a function of commutation phase angle is defined by Eq. 2, where $\theta = 0$ degrees at the highest efficiency phase angle and $\theta = +/- 90$ degrees at the zero torque phase angles.

$$T(\theta) = \cos\theta\, K_t\, I \tag{2}$$

Another parameter is the back-emf constant K_b, which defines back-emf voltage V_b as a function of angular velocity ω in units of volts/rad/sec as in Eq. 3.

$$V_b = K_b\, \omega \tag{3}$$

Back-emf is also a function of commutation phase angle as defined in Eq. 4.

$$V_b(\theta) = \cos\theta\, K_b\, \omega \tag{4}$$

It may not seem to be intuitive, but here is an explanation of how torque constant and back-emf constant must go hand-in-hand.

If the rotor is held locked, applying current will result in torque according to the torque constant. A voltage will be applied to achieve that current, based upon the resistance of the motor winding.

If the motor is running at a speed with the shaft loaded such that the same torque exists as when static, current must be the same since torque is the same. There will be a back-emf voltage that must be overcome in order to achieve that same current. So, more power is required to maintain torque at speed, but a fixed current gives a fixed torque whether the rotor is locked or rotating.

Let's look at this from a power standpoint. The power needed to hold a static torque is according to Eq. 5, where I is motor current and R is winding resistance.

$$P_{winding} = I^2R \tag{5}$$

This is parasitic power dissipation in the winding. No work occurs. Additional power is required when the rotor is rotating with a torque. This is the power provided by the motor shaft to the load, according to Eq. 6 and Eq. 7 yielding Eq. 8, where T is motor torque and ω is angular velocity.

$$P_{load} = V_b I \tag{6}$$

$$P_{load} = T\omega \tag{7}$$

$$V_b I = T\omega \tag{8}$$

In order for the torque constant K_t to remain true from zero to any angular velocity, a back-emf constant K_b must exist in order for there to be power to perform work. Thus, both a torque constant and a back-emf can only exist together. One cannot exist without the other.

In MKS units, the torque constant and back-emf constant values are numerically the same, as follows in Eq. 9 to Eq. 11, resulting in Eq. 12.

$$K_b\omega I = T\omega \tag{9}$$

$$T = K_b I \tag{10}$$

From Eq. 1,

$$T = K_t I \tag{11}$$

$$K_t = K_b \tag{12}$$

For completeness, the motor constant, K_m in units of N-m /$\sqrt{watt}$, defines the winding power as a function of torque. There is a relationship relating the motor constant Km with Kt and R as in Eq. 13.

$$K_t = \sqrt{R}\, K_m \tag{13}$$

K_m is defined for a particular motor frame and remains virtually constant, even if the winding wire gauge is changed. A winding change only trades voltage for current and does not affect power in the winding to achieve a particular torque.

SYNCHRONOUS MOTOR BEHAVIOR

It is important to realize how a phase angle θ that is not always zero results in torque degradation as well as back-emf degradation in order to understand the operation of the synchronous motor.

How does synchronous motor behavior compare with DC motor behavior? Let's assume the same configuration DC motor, which consists of a stator with poles along with a permanent magnet rotor. There may be no physical differences, but rather just an operational difference.

A synchronous motor is commutated as a function of time rather than position. A fixed frequency may be applied that will achieve the desired synchronous angular velocity, though frequency ramping may be needed, due to inertia of the rotor possibly causing the highest efficiency phase angle being reached, resulting in the motor to stall. The excitation waveform often has a fixed peak voltage, yet the fixed excitation can result in various levels of motor shaft torque, dependent upon operational conditions.

Synchronous motor torque is a function of both current and the rotor to stator field relationship, which is not a fixed phase angle like it is when there is rotor to stator position commutation that is properly fixed at $\theta = 0$ degrees. There can be phase angles occurring between θ of -90 to + 90 degrees, defined by the possible extremes of Fig. 2 and Fig. 3. Thus, $T(\theta)$ and $V_b(\theta)$ could vary anywhere in the defined range dependent upon the phase angle θ.

If a synchronous motor is running without a load at speed, let's assume that the bearing and windage torque is negligible such that drag torque is zero. At no load, the attracting poles of the rotor and stator will be aligned as in Fig. 3, resulting in zero torque. Thus, $T(\theta)$ and $V_b(\theta)$ would be zero. Power will simply be winding resistive losses.

If we load the rotor shaft such that some torque develops, a phase angle will occur such that the needed torque occurs, and a corresponding $T(\theta)$ and $V_b(\theta)$ will occur. If we continue to load the rotor shaft, we can eventually get close to the phase angle for maximum motor efficiency, achieving close to the maximum possible $T(\theta)$ and $V_b(\theta)$, with the phasing θ close to 0 degrees, close to that of Fig. 2. In such a case, from a power standpoint, winding power and shaft power will be nearly the same as in the position commutated motor. However, no torque margin will exist if operating at $\theta = 0$ degrees. Any additional torque needed will go beyond the motor capability, so the motor will stall since any change in phase angle will result in reduced torque.

With a fixed level voltage excitation waveform, loading the synchronous motor increases its phase angle, thus efficiency, lowering current as the loading increases as a result of an increase in back-emf, reducing total power supplied, reducing power in the winding, and increasing power to the load.

HYSTERESIS MOTOR BEHAVIOR

The hysteresis motor is operated like a synchronous motor once at synchronous speed. The stator can be the same as that of the synchronous motor. The difference is the rotor. Rather than using a permanent magnet rotor as in the previous examples, the rotor is a soft magnetic material that has a wide hysteresis curve, meaning that it will be magnetized with a greater magnetization than a soft-magnetic material that has a narrow hysteresis curve.

Magnetization occurs as a result of the rotating magnetic field of the stator. If the rotor is locked and a rotating magnetic field is applied from the stator, continual remagnetization would occur in the rotor such that a rotating magnetic field would exist in the rotor material. Due to hysteresis of the soft magnetic material of the rotor, poling of the rotor will lag the applied poling of the stator, causing a fixed phase angle between the two rotating fields, resulting in a fixed torque called the hysteresis torque. Thus a difference between the synchronous and hysteresis motor is that repoling of the stator allows for a constant torque to occur, until synchronous speed is achieved. Rotor inertia is not a factor, ramping of the excitation frequency is not needed, and a stall condition will not occur. When not synchronous, there is power dissipation in the rotor, which must be present for there to be hysteresis torque.

When reaching synchronous speed, there may be some overshoot and settling. The required torque needed to maintain synchronous speed will be less than the torque required to get there since acceleration torque is no longer needed. At synchronous speed, the poles become fixed in the rotor material, and behavior becomes the same as that of the synchronous motor. At any instant, a phase angle between the rotor’s now fixed poles and stator poles will be naturally found such that motor efficiency reduces to the point necessary to reduce the motor torque to what is required for the synchronous condition.

AN INTERESTING PUZZLE

As previously stated, rotor restriction was believed to be the cause of increased motor current, but restarting a gyro results in motor current again becoming nominal. Thus, it was not believable that the torque needed to maintain synchronous speed was any different after the increased current event occurred than it was before the anomaly occurred. If the load was the same after the event, what could possibly change that would result in increased current?

There is a motor, a load, a fixed voltage waveform, but a changing current. Using process of elimination, let’s first assume that the load has not changed since operation goes back to nominal once there is a restart. The voltage is fixed, so that does not change. The only thing left is the motor. If the motor parameters changed, that could explain the current changing.

The motor components consist of a stator and a rotor. There is no reason to suspect a change in the stator winding or the stator iron. That only leaves the soft magnetic rotor. Once the motor is in synchronous mode, the poling is fixed, like a permanent magnet rotor. What could possibly happen that could change the rotor magnetization? If the rotor magnetization became weaker, K_t and K_b would reduce, resulting in a need for higher current to maintain a constant torque.

A PROPOSED THEORY

After some time of mental exercise, I proposed the following theory to explain the anomalous gyro current behavior.

Let’s assume that a rotor restriction occurred, but only momentarily. If the hysteresis torque limit was reached, then repoling of the rotor would occur. The phase angle between the rotor and stator poles can vary to increase motor efficiency as the drag torque increases, but once highest efficiency is achieved, motor torque is limited to the hysteresis torque. In effect, the magnetized poles will slide somewhat around the rotor material.

Since the original magnetization occurred at the start voltage 55 volts and the repoling would occur at the run voltage of 26 volts, a weaker magnetizing field would repole the rotor, resulting in a weaker magnetization of the rotor.

The theory so far can explain how motor current can increase due to weaker rotor magnetization caused by a momentary rotor restriction that exceeds the hysteresis torque. How can we explain the fact that gyro current increases occur in multiple steps?

If the rotor restriction was momentarily severe, one would expect a significant sliding of the poles in the rotor material. Just sliding enough for a north pole to find its way to a previous north pole would result in going fully around the hysteresis curve. One would then expect the weakest level of magnetization. The current anomaly would go from a nominal current level of about 130 mA to about 220 mA in one step.

Intuitively, a weaker rotor magnetization means a lower torque capability due to a lower K_t, leading to the conclusion that intermediate current steps should not occur, which is not the case. What is wrong with this line of thinking?

The first statement is actually incorrect. A weaker rotor magnetization does not necessarily mean a lower torque capability.

Since we wish to consider the capability of a synchronous motor at its highest efficiency phase angle, let's consider the case of the brushless DC motor, which is set to always operate at $\theta = 0$ degrees, which is the phase angle for highest motor efficiency.

Assume that we had a DC motor operating at high speed, like the hysteresis gyro motor. Suppose that most of the power is delivered to the rotor shaft to overcome bearing friction, so the resistive losses are relatively low. In such a case, the back-emf is a voltage that is close to the applied voltage. For the sake of argument, let's assume that 10% of the motor voltage is across the winding and 90% of the voltage overcomes back-emf as in Eq. 14 and Eq. 15, such that 10% of the power is in the winding and 90% of the power goes to the load.

$$P_{winding} = I\,(0.1V_{motor}) \tag{14}$$

$$P_{load} = I\,(0.9V_{motor}) \tag{15}$$

What if we now weaken the magnets such that K_t and K_b drop by 5% to 95% of their original value? So, for Case 1, before weakening the magnets, the back-emf is as in Eq. 16. For Case 2, after weakening the magnets, the back-emf is as in Eq. 17.

$$V_{bemf1} = 0.9V_{motor} \tag{16}$$

$$\begin{aligned} V_{bemf2} &= 0.95\,(0.9V_{motor}) \\ &= 0.855V_{motor} \end{aligned} \tag{17}$$

The back-emf will then drop to 85.5% of the applied voltage. Since the rest of the voltage drop is across the winding, the winding will see 14.5% of the motor voltage, following Eq. 18 to Eq. 19.

$$V_{motor} = V_{bemf} + V_{winding} \tag{18}$$

$$\begin{aligned} V_{winding2} &= V_{motor} - V_{bemf2} \\ &= V_{motor} - 0.855V_{motor} \\ &= 0.145V_{motor} \end{aligned} \tag{19}$$

Since R is fixed, current will increase by 45% as in Eq. 20 through Eq. 24.

$$I = V_{winding} / R \tag{20}$$

$$I_1 = 0.1V_{motor} / R \tag{21}$$

$$I_2 = 0.145\ V_{motor} / R \tag{22}$$

$$I_2 / I_1 = 0.145 / 0.1 \tag{23}$$

$$I_2 = 1.45\ I_1 \tag{24}$$

Despite a 5% reduction in Kt, torque capability has increased as in Eq. 25 through Eq. 26.

$$T_{motor1} = K_{t1}\ I_1 \tag{25}$$

$$\begin{aligned} T_{motor2} &= K_{t2}\ I_2 \\ &= (0.95\ K_{t1})\ (1.45\ I_1) \\ &= 1.38\ K_t\ I_1 \\ &= 1.38\ T_{motor1} \end{aligned} \tag{26}$$

So in this example, we see a 38% increase in torque capability by reducing motor efficiency.

This seems counterintuitive, but it is the result of having a fixed supply waveform, a larger power going to the load with a lesser power dissipated in the winding.

Thus, a rotor restriction that results in a torque that exceeds the hysteresis torque also results in magnetization and V_b to drop while simultaneously increasing torque capability due to additional available current that more than overcomes the drop in K_t. This explains why a momentary rotor restriction would not slide the poles very far such that magnetization would not reach its weakest level with the first current anomaly.

PROVING THE THEORY

It would have been great to have a dynamometer to load the motor and prove that at some torque level, the motor characteristics would change, resulting in a drop in K_t and an increase in torque capability. Since the gyro is a sealed system, there is no access, so controlling the load is not possible. I had no means to change the load that is the result of aerodynamic drag torque of the gas bearings. So, how can we reach the hysteresis torque to force remagnetization of the rotor? The answer is to reduce the applied voltage.

As we reduce voltage, current will also reduce. The phase angle between the rotor and stator will change, increasing the efficiency of the motor. Thus power reduces in the winding, but the power to the load via the motor shaft remains the same. Once the maximum efficiency phase angle is reached, it cannot be exceeded, so any further lowering of the voltage will result in a sliding of the poles in the rotor. As already stated, the poles will gradually reduce in magnetization, lowering K_t and K_b. Though additional current will be necessary to maintain the same torque, a lowered back-emf will result in increased current and increased torque capability.

The HST Vehicle Electrical System Test (VEST) facility encompasses HST command and telemetry software, associated electronics, and gyros. I requested permission to modify the motor driver electronics such that the applied voltage could be reduced, requiring installation of a potentiometer. Permission was granted to modify the hardware.

The gyro was oriented such that it would see a strong rate signal resulting from the earth's rotation. Gyro motor voltage and current were monitored along with gyro rate. The gyro was started with 56 volts applied, reached synchronous speed, and the applied voltage automatically lowered to the run voltage. The nominal current was measured at 125 mA at the run voltage of 25.96 volts, as seen in Fig. 4.

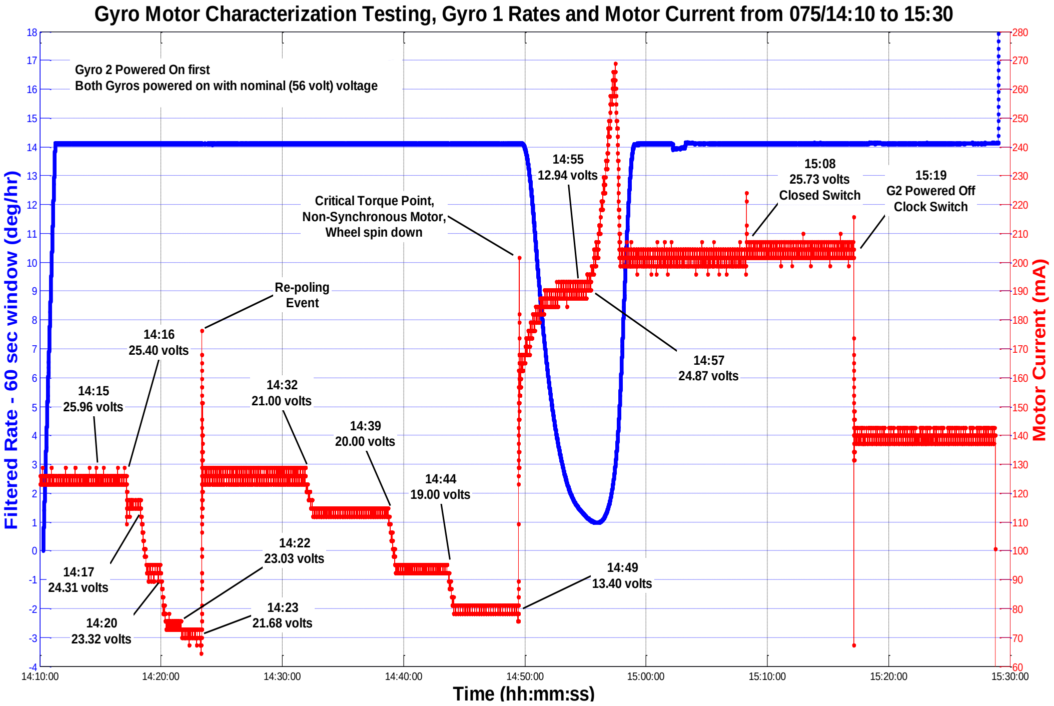

Figure 4. Gyro Motor Characterization Testing

The red plot is of motor current and the blue plot is of gyro rate. Starting at the left side of the red current plot, it can be seen that there is a downward staircase. Voltage was being adjusted downward with the potentiometer and current was following the reduction in voltage.

Each tread of a step is a stop at a particular voltage, so current remains constant on a tread. Once reaching the bottom of plot, there is a vertical jump in current, resulting in a tread that is about level with the starting tread. Thus current is a bit more than what it was when the voltage was at the initial run voltage of 25.96 volts, yet voltage has been reduced to 21.00 volts. Further lowering of the voltage resulted in another descending staircase of lowering current. The bottom of the staircase at a voltage of 13.40 volts and 80 mA is followed by vertical jump in current to 190 mA at 12.94 volts.

So, we have seen the relationship between voltage and current change twice while reducing applied voltage, meaning that K_b and K_t have reduced during these events. During the first occurrence, the gyro rate stayed constant, which is the blue plot, so torque capability had to increase in order to maintain synchronous speed, despite the reduction in K_t. This was explained as a result of K_b being reduced, thus back-emf being reduced, allowing for more current to flow, despite a reduced applied voltage.

However, we can see from the blue plot of gyro rate that upon the second instance of the motor characteristics K_t and K_b changing, the rate falls off. This means that the gyro has lost synchronous speed and is decelerating. Why wouldn't torque capability be maintained or increase like before?

As previously mentioned, it is counterintuitive that torque capability of the motor increases with a weaker rotor magnetization that has a reduced K_t and K_b. It was pointed out that the counterintuitive case will occur if the power to the load is greater than the power in the winding. So, in the second instance of current increasing after reducing voltage, after which the gyro lost synchronous speed, the motor has become so inefficient that winding power dominates, so torque capability is lost with a reduced K_t, which is the intuitive case.

Voltage was increased rather abruptly in Fig. 4 resulting in 204 mA after settling. Let's look at the data in Fig. 5 to see what happens as voltage was increased gradually. After the voltage was reduced from 13.20 volts at the lower left of the plot, there was a vertical jump to 175 mA, which is the lowest magnetization state. The gyro rate then dropped off. As the voltage was increased to 14 volts followed by 1 volt increments to 18 volts, current increased as expected, but also gyro rate was changing. Increasing voltage from 19 volts and beyond, we see current falling. However, the rotor is in hysteresis mode until it reaches synchronous speed, in which gyro rate is restored. At the run voltage, current was 220 mA. It is not clear if any magnetization has restored. Once the 3-second running restart was performed, current restored to 138 mA, so K_b and K_t were nearly restored to nominal, so magnetization was restored.

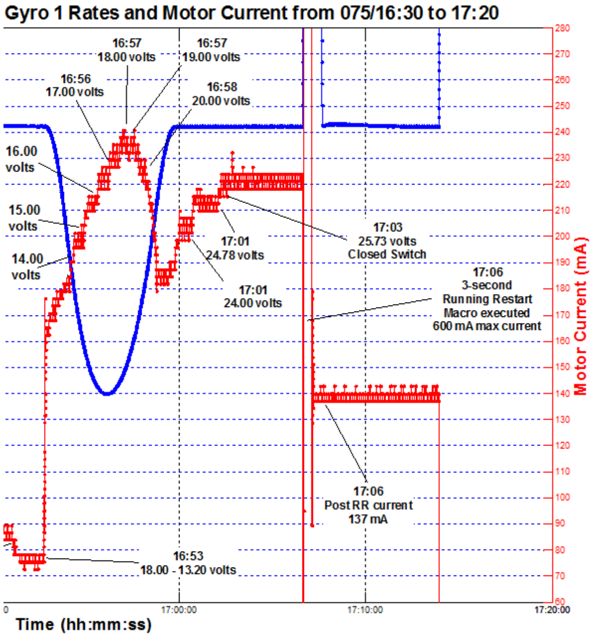
Gyro 1 Rates and Motor Current from 075/16:30 to 17:20

Figure 5. Gyro Motor Characterization Testing

The testing did show that we can take a working gyro, one that is assumed not to have any rotor restriction behavior, and operationally make it run at near the highest current observed on orbit, and then restore that current back to near nominal. This testing proves that gyro current can change, despite applied voltage and bearing friction being nominal.

Looking back at HST data of current anomalies, it was found that in most cases, the current jump was a discrete jump, as shown in Fig. 6. Sampling of data occurred once per second. In other cases, the current jumped to a new level, but then reduced to a stable level, a transient period never taking more than 2 minutes to level out, as shown in Fig. 7. In those cases, it is believed that rotor restriction is not momentary but is rather short term, though the hysteresis torque is only reached momentarily, followed by a continuing increased drag torque that drops back to nominal torque in no more than two minutes. It is believed that particles in the gas bearings are being ground up during the transient period.

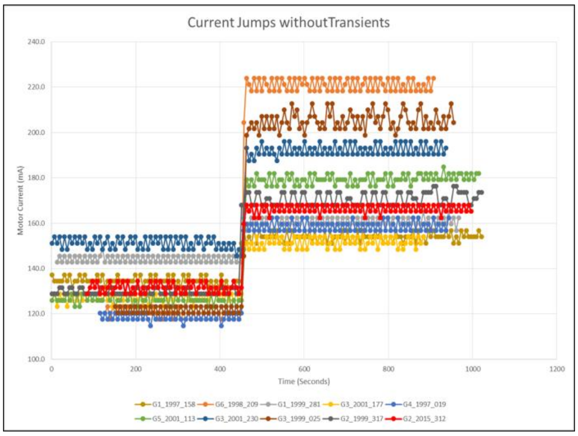

Figure 6. Current Jumps Without Transients

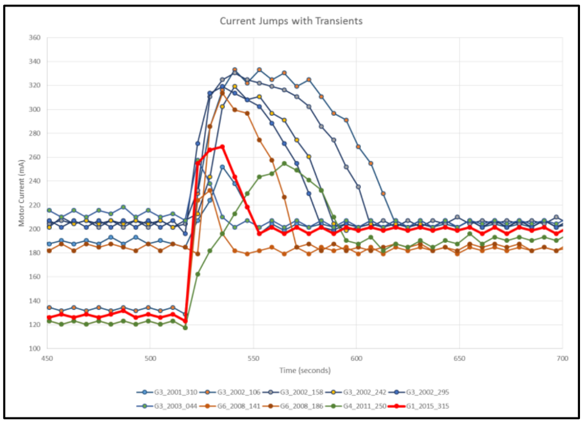

Figure 7. Current Jumps With Transients

Why didn’t we see more reductions in K_t and K_b during the testing like has been seen on orbit? It must be that the test method to force rotor repoling is more severe than what occurs during a rotor restriction event.

The theory does explain with the counterintuitive argument that torque capability increases and remains when a rotor restriction event occurs. In that argument, we never assumed a lower applied voltage. For the test method, we needed to lower the applied voltage to force the repoling to occur. So, it is possible that repoling occurring from a rotor restriction event would be less severe. The poles might barely slide in the rotor material for each event with increasing torque capability along with nearly simultaneous return of nominal drag torque. The motor shaft always remains synchronous, but just lags slightly after each rotor restriction event.

A NEW UNDERSTANDING OF BEHAVIOR

The HST team embraced the new theory since it does explain gyro behavior for which there was never a complete explanation. It is now understood that reduction of rotor magnetization is the root cause for increased HST gyro current as a result of short term rotor restriction. With the new understanding that bearing current is nominal even though current is elevated, the team became open to performing a restart to restore current to nominal. The team considered recommending implementation of a running restart. A typical restart would require bringing the gyro to a complete stop and restarting. A gyro that has exhibited rotor restriction leads to concern about letting the gyro lose bearing levitation, which could generate more debris. A running restart would be performed within a few seconds, so the bearings would never lose levitation.

An analysis was performed to determine how much life could be increased if the gyros with the higher currents would be restarted. The reason current affects life is the fact that gyro failures have been attributed to flex lead failures. The flex leads corrode as a result of interaction with the fluid that is in the gryo to provide buoyancy, allowing 1-g operation. Higher current heats the corroded areas and accelerates the corrosion process. The team concluded that the analysis did not offer a significant enough increase in gyro life to risk implementation of a running restart.

WHEN GRYO FAILURE IS IMMINENT

With the realization that there are cases when the rotor restriction increases drag torque for an extended period, and the belief that there have been failures of past gyros from excessive drag torque, the team proposed performing an autonomous running restart. When such conditions occur, a running restart will provide the needed torque to get through the rotor restriction event. The restart may even bring the current back to nominal. Software was implemented and tested at the VEST facility. The proposal was approved by NASA headquarters and the software has been implemented on HST.

CLOSING REMARKS

It has been my pleasure to have had the opportunity to work on the Hubble Space Telescope (HST), work with the HST team, and to contribute to such an incredible mission by bringing new understanding to long misunderstood gyro behavior. A 30 year mystery was finally solved. This new understanding enhances the HST team’s ability to make decisions that affect the life of the HST mission, which is one of NASA’s most highly celebrated achievements.