Effect of Space Vehicle Structure Vibration on Control Moment Gyroscope Dynamics

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Control Moment Gyroscopes (CMGs) are used for non-propulsive attitude control of satellites and space stations, including the International Space Station (ISS). A CMG is a mechanical device that has a spinning wheel and one or two gimbals used to change the position of the spin axis. When the spin axis is moving, the CMG angular momentum is changing, thus providing a torque for space vehicle attitude control.

CMG performance is critical for operation of a vehicle since CMG failures or degraded performance limit vehicle attitude control capabilities. CMGs could be essential for future long-duration space missions due to the fact that they help to save propellant. CMGs were successfully tested on the ground for many years, and have been successfully used on satellites. However, after a little more than a year of operation on the ISS, the first CMG had failed. The CMG failure resulted in the limitation of the attitude control capabilities, increased propellant consumption, and additional operational issues. About 4 years later, periods of higher-than-nominal CMG vibrations triggered a second CMG problem on the ISS. As a result, another CMG was shut down and returned to Earth. The question was raised: why is the CMG service life on the ISS significantly shorter than the predicted service life of 15 years? Since the dynamic environment of the ISS differs greatly from the nominal environment of satellites, it was important to analyze how operations specific to the ISS (dockings and undockings, solar array motion, crew exercise, robotic operations, etc.) affect CMG performance. The goal of this work was to analyze the CMG dynamics in the ISS environment, to suggest explanations to the observed CMG telemetry, and to find ways to increase the CMG service life onboard the ISS. In this work, the equations describing the coupling of CMG dynamics with the vehicle structure vibrations were derived. The equations were obtained for the unbalanced gimbals to match the CMG configuration on ISS. The analysis shows that at a certain frequency of ISS structure oscillations, CMG vibrations are significantly increased. This result reveals the resonance in the system due to coupling of external vibrations with the CMG motion in case of unbalanced gimbals. It was found that the effect of the vehicle structure vibration depends on the magnitude of gimbal imbalance, the direction of vehicle structure vibration, and the gimbal friction. Computer modeling results show that nominal CMG dynamics coupled with external vibration of the vehicle structure can cause off-nominal CMG vibration spikes similar to the spikes, observed on the ISS.

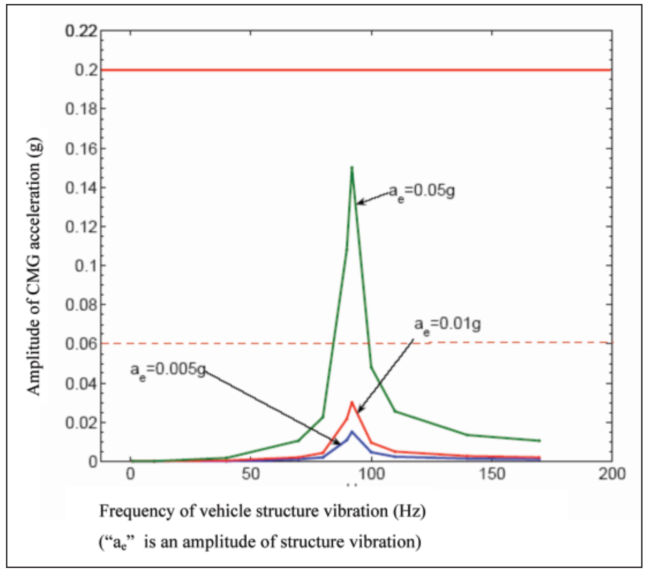

Fig. 1. *Amplitude of Control Moment Gyroscope acceleration (g) vs. frequency of vehicle structure vibration (Hz).*

Figure 1 shows the computation results: the dependence of CMG accelerations on the frequency and amplitude of external vibration. Calculations show that the nominal value of the CMG acceleration amplitude is in the range of 0.005g to 0.02g. This value is of the order of the CMG vibration measurements on the ISS. For the typically observed vehicle structure vibrations, the magnitude of computed spikes at resonance is in the nominal range (below the dotted line in figure 1). However, computations with decreased gimbal friction or increased magnitude of external vibration resulted in off-nominal resonance spikes. Based on the equations and computation results, the resonance effect is more noticeable if:

1. The magnitude of structure vibrations is higher than usual (crew exercises, robotic operations, thruster firings, etc.).
2. The gimbal friction is lower than usual. (This may occur when gimbal rates are high since gimbal friction decreases with the increase of gimbal rate.)

Both of these conclusions match the onboard observations on the ISS. First, most of the spikes seen onboard were correlated with increased dynamic activities. In addition, the second conclusion suggests the possible explanation for the onboard telemetry observations: it explains why the CMG vibration spikes were, in most cases, correlated with high gimbal rates. Figure 2 shows gimbal rates and an off-nominal vibration spike. This case was recorded during a Russian segment extravehicular activity. A command to position gimbals, which caused the gimbal rates to increase, triggered this event. In 2008, the problem with CMG vibration spikes was supposedly fixed by limiting the CMG gimbal rates, after which no spikes were observed onboard.

The results of this work show that the vehicle structure vibrations coupled with CMG motion can increase CMG accelerations (even to the off-nominal levels), thus increasing loads and possibly decreasing the CMG service life. The effect of a single CMG vibration spike at resonance may not be enough to cause a CMG failure. However, since the external vibrations are constantly applied to CMGs, they may have a noticeable accumulated effect on the CMG service life similar to the effect of small wheel unbalance loads. There are several ways to reduce the CMG vibrations due to vehicle structure oscillations:

1. Balancing CMG gimbals can decrease the CMG vibrations since it eliminates the coupling terms in the equations of motion.
2. A proper selection of gimbal friction (not too low) can adjust the CMG accelerations to suitable levels.

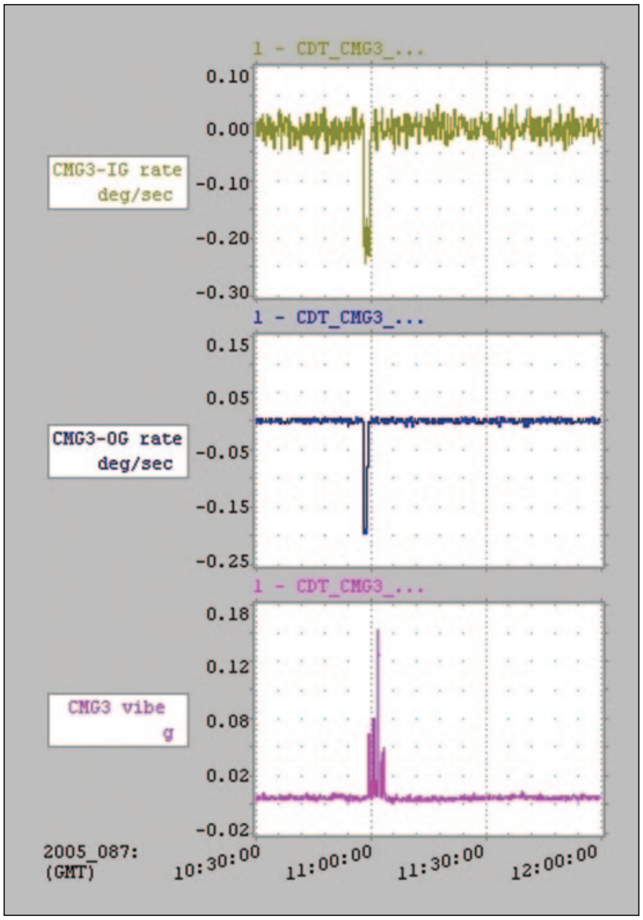

Fig. 2. *Control Moment Gyroscope gimbal rates and vibrations as functions of time.*

The suggested modifications could increase the CMG service life beyond the current expectations and might allow the use of higher gimbal rates (as was initially designed), thus improving vehicle attitude control capability.