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On-orbit jitter control in momentum actuators using a three-flywheel system

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ABSTRACT

Vibrations on-board a spacecraft have degrading effects on the performance of certain payloads like astronomical telescopes, Earth observation systems, optical communication equipment, etc. The major source of these vibrations include momentum actuators used for attitude control, thrusters, solar array drives and other rotary mechanical equipment. The effect of these vibrations is spacecraft jitter which causes for example, smearing of images in a telescope. Spacecraft jitter due to rotor imbalance in momentum actuators is considered. Publications to date have researched isolation and suppression of vibration thus caused. This paper investigates the dynamics of jitter due to rotor imbalance and proposes a modification to the momentum actuators that provides a long term jitter management solution. The modification involves replacing a flywheel/rotor in the momentum actuator by a three-flywheel system. This method overcomes the need for prior precision balancing of individual flywheels and is capable of achieving a balanced system on orbit. It also provides limited redundancy against flywheel failure and may help accelerate testing and calibration. The dynamics of the three-flywheel system are developed and elaborate simulations are performed to verify the validity of the method. The performances of the proposed three-flywheel system and an equivalent single-flywheel system are compared. The effect of single/multiple flywheel failure in the three-flywheel system is investigated. An indicative design of the three-flywheel system and other implementation aspects are discussed to evidence its practicality. The potential increase in the mass, and power consumption of the three-flywheel system is discussed using a power and mass analysis based on the indicative design.

1. Introduction

An extremely quiet/disturbance-free spacecraft platform is desired by payloads with precision pointing requirements such as astronomical telescopes, Earth observation and remote sensing systems, optical communication and other directional communication systems. On-board vibrations affect the pointing stability of the spacecraft resulting in attitude oscillations called jitter. While vibrations also cause translational effects, in this paper, we consider only the rotational or attitude effects. Obtaining a low-vibration environment is often a challenge for spacecraft designers due to the presence of various disturbance sources on the spacecraft. A major and common source of vibration is rotor imbalance in momentum actuators such as reaction wheels and control moment gyroscopes (CMG). Other rotary sources include solar array drives, cryo-cooler pumps, and antenna gimbal drives. Certain other sources such as thruster firings and thermal snap of solar arrays cause short term transient vibrations.

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Several methods involving passive and/or active isolators have been devised and implemented to attenuate vibrations and reduce its impact on the performance of the payloads [1–8]. These methods function by either isolating the source of vibration from the rest of the spacecraft or by isolating the payload alone which is sensitive to vibrations. In some cases, both the payload and the sources of vibration are isolated. The benefits and limitations of various isolators are briefly discussed. Passive isolators are usually some form of viscoelastic material (e.g., rubber), or specially designed viscous dampers with variable stiffness and damping. These isolators are placed between the vibration source and the payload. The isolator functions as a mechanical low pass filter absorbing the vibration energy at certain frequencies and thus decreases the magnitude of vibration seen by the payload. They provide reduced transmissibility only beyond the break frequency and roll off as a second order system at 40 dB/decade. Although a low break frequency may provide isolation at lower frequencies, it reduces the stiffness of the supports. This makes the payload vulnerable to large displacements during launch and collision with other spacecraft components. It also introduces undesirable dynamics (e.g., rattle) during attitude control. Passive isolators have been used on many missions [1–3] including the Hubble Space Telescope. Active isolators include electromechanical actuators such as voice coils, magnetic actuators, and piezo-electric stacks. Multiple such actuators are sometimes used in a hexapod configuration (e.g., Stewart platform) [4,5] to provide multi degree-of-freedom isolation. The control of these actuators is based on feedback from accelerometers/force sensors mounted at the payload interface. These isolators provide great isolation at low frequencies but are limited by the bandwidth of the actuators/control systems at higher frequencies. Active isolators require continuous power to isolate and even support the payload. Thus, active isolators require some sort of a launch lock for restraint during launch. The performance of the active actuators depends on vibration feedback sensors and control algorithms. The various components of the active isolators add significant mass to the spacecraft. Hybrid actuators [5–7] that include a combination of active and passive isolators have been implemented to provide a wider bandwidth of isolation and a steeper roll off. They may also be used to perform limited but fine pointing of the payload. Hybrid actuators with adaptive damping based on shape memory alloys have also been developed [8]. However, hybrid systems experience challenges encountered in both active and passive systems. In addition to attenuation mechanisms just discussed, there also exist mechanisms for jitter compensation such as fast steering mirrors that compensate for jitter by dynamically altering the path of the optical beam in optical communication and imaging satellites [9]. Another compensation method is the use of post-processing techniques to restore jitter affected images [10]. This method, specific to imaging payloads, is not sufficient in itself and is typically used to augment the performance obtained by physical jitter reduction methods such as isolators.

The jitter mitigation methods described above are means to reduce the *effect* of jitter on the payload, and do not reduce the jitter produced by the source. This paper introduces a method that reduces the jitter caused by imbalance in momentum actuators. However, the method presented here is not intended to completely replace jitter attenuation strategies, but reduce the magnitude of jitter produced by the actuator so that the combined use of the method presented here and the attenuators leads to improved performance. Momentum actuators consist of spinning rotors at variable (e.g., reaction wheels) or at constant (e.g., CMGs) angular speeds. The presence of static and dynamic imbalances in rotors is the root cause of jitter. Traditionally, the rotors are precisely balanced to reduce the magnitude of imbalance. The precision balancing process is time consuming and expensive; yet (it will be shown later in the paper), the residual imbalance can result in significant jitter. Further, the imbalance in rotors increase during their lifetime due to several effects (e.g., thermal distortion of the rotors and supporting structure, hoop strain, etc.) resulting in a gradual deterioration from their beginning-of-life (BOL) imbalance values. This effect is often seen in composite flywheels which suffer from imbalance growth due to inter-laminar flaws [11]. The jitter mitigation/control method described in this paper replaces the single flywheel[2] (rotor) in momentum actuators by a set of three flywheels to achieve static and dynamic balance levels that are otherwise difficult to achieve using traditional balancing methods. The method provides a certain level of adaptability to changes in flywheel imbalance, and hence, over the lifetime of the actuator, delivers a smaller deviation from the BOL jitter.

The remainder of the paper is organized as follows. The dynamics of a spacecraft with an unbalanced flywheel are developed in Section 2. Jitter reduction using a three-flywheel approach is described in Section 3 along with a dynamic model for a spacecraft with a three-flywheel system. Simulations and results that compare the performance of single- and three-flywheel systems are presented in Section 4. An indicative design of a three-flywheel system, power and mass trades, and implementation are discussed in Section 5. Summary and conclusions are given in Section 6.

2. Flywheel imbalance and spacecraft jitter

Consider the schematic of a spacecraft shown in Fig. 1. The spacecraft consists of a rigid spacecraft structure and a flywheel attached to it. Since we are interested only in the source of vibration and not its transmission through the spacecraft structure, a rigid spacecraft is considered. A single unbalanced flywheel is considered for clarity, and to provide better insight into the effects of an unbalanced flywheel. Furthermore, inclusion of multiple flywheels in the analysis does not provide any additional information on the dynamics of jitter. The flywheel is assumed to contain some imbalance, and is rigidly secured to the spacecraft using bearings such that it can rotate about an

[2] Rotors will be referred to as flywheels for the remainder of the paper as they aptly describe the physical form of rotors in momentum actuators.