Lubrication for Moving Mechanical Systems used in Spacecraft  
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Keywords: Space Tribology, Momentum wheels, Centrifugal lubricators, Lubrication.

Abstract: Spacecraft, irrespective of their mission’s purpose, contain a number of moving mechanical assemblies such as control moment gyros, momentum/reaction wheels, gyroscopes, scanners, solar array drives, etc. Most problems encountered with these moving systems are related to tribology and, specifically, lubrication. Lubrication problems result from the loss of lubricant from the working zone by evaporation, surface migration, etc. Therefore, to ensure long-term uninterrupted performance of these systems, an efficient lubricant replenishment system is essential. This article describes various lubricating methods and lubrication systems used for the successful operation of some of these systems for the entire mission periods.

Introduction

Spacecraft incorporates a wide variety of machine elements which must operate with total reliability in the space environment. There are a surprisingly large number of systems with moving surfaces on modern spacecraft. Each subsystem of a spacecraft is a combination of both electronic and mechanical components. These are designed to work effectively and efficiently for the entire mission period. Today, the attention is focused on the development of subsystems for spacecrafts with longer mission duration of more than 20 years [1]. This long life requirement brings a lot of challenges with it, especially in the area of moving mechanical systems (MMS). These systems contain sliding or rolling contacts that are required to operate with least frictional power loss, due to the limited power availability on board the spacecraft. Each of these systems is designed to perform some definite task, for example, the gyroscopes are used as an inertial sensor to detect the attitude error of the spacecraft, the momentum/reaction wheels of various angular momentum are used as actuators for the control and stabilization of spacecrafts, which is essential for the pointing accuracies of the antennas and other optical equipment like very high resolution radiometers etc. Solar array drive mechanism (SADM) is another MMS used to rotate the solar arrays to be normal with respect to the sun, and transmit electrical power. Solar array drives rotate at very low speeds (typically rev/day for geostationary satellites) [2].

The attitude control system (ACS) is composed of three elements; the attitude error sensors (gyroscopes), which sense the attitude error, the controller is a computer placed onboard the spacecraft which estimates the control action required based on the error and the actuators such as thrusters, magnetic torquers and momentum/reaction wheels which correct the errors and maintain the required accuracy in orientation. Most spacecrafts use momentum wheels (MW) or reaction wheels (RW) in the attitude control system as actuators to correct the attitude error and maintain the spacecraft attitude. The lubrication of these high speed MMS are presented in this paper.

Momentum wheels (Fig.1) are simple disks (rotors) that are spun by an electric motor. When the motor applies a torque to speed up or slow down the rotor, it produces a reacting torque on the body of the satellite. Momentum wheels provide three-axis stabilization of the satellite with two axes in the orbit plane being held in their position by the gyroscopic effect of the momentum wheel and the third axis, is controlled by the torque produced by accelerating or decelerating the wheel. Since, control and maintenance of spacecraft attitude is a continuous process, various elements of the attitude control system have to work continuously till the end of the mission. In these high speed systems, failures are mostly related to tribology. A number of mission failures are reported due to the tribological malfunction of attitude control systems. Skylab, Insat-1D are typical examples [4,5] and
the most recent is the bearing failure in the control moment gyro (CMG) of the international space station [6]. Therefore, the development of high speed attitude control systems for the future requires advancement of tribology technology. These systems use high precision angular contact ball bearings of various sizes and run continuously at speeds of several thousand rpm (typically, 4000 to 10 000 rpm). Tribological failures of momentum/reaction wheels are related to lubricant breakdown, loss of lubricant due to evaporation, surface migration and retainer instability. Retainer instability is the most dangerous mode of failure in MW/RW bearings. Uneven cage wear, lubricant degradation and insufficient lubrication are the prime causes for it [7]. Therefore, with the selection of proper lubricant and proven retainer design, lubrication remains the principle life limiting problem on momentum wheels.

**Figure. 1 Momentum wheel assembly [3]**

**Lubrication of Attitude Control System**

**Momentum wheel Lubrication:** Since the attitude control is a continuous process, the life of a spacecraft largely depends upon the life and performance of momentum wheels. The trouble free rotation of the wheel is essential and that can be achieved only through the smooth performance of the bearing unit assembly (Fig.2). Thus, the bearing unit becomes the most critical sub-assembly of a momentum wheel, because it is the only component which has relative motion and undergoes wear and tear. Momentum wheels are lubricated by liquid lubricants specially developed for space environments. Various types of lubricants used are appearing in ref.[8]. Increased speeds, higher temperatures, improved accuracy and reliability requirements result in the need for closer attention to lubrication selection. Research shows that friction torque of the momentum wheels during the initial stage of running will be the maximum (10 mN-m) and therefore it will be in the upper boundary of EHD regime. When the wheel is rotating, lubricant starts depleting from the adjacent region of contact, the film thickness decreases and as a result, the friction torque also decreases. If no makeup oil is supplied, the decrease in lubricant film thickness continues and direct metal to metal contact occurs, that lead to failure of the wheel. This is eliminated by incorporating a supplementary lubrication system to the bearing unit. According to the nature of operation, the lubrication systems used in momentum wheels can be broadly classified as active lubrication systems and passive lubrication systems. The active lubrication systems, also known as positive lubrication systems [9,10], supplies a controlled amount of lubricant to the bearings when it is actuated by external commands. The positive commandable lubricators, remote in-situ systems, etc. are examples of active systems. The passive systems, also known as continuous systems, supplies lubricant continuously to the bearings and is driven by centrifugal force or by surface migration force. The centrifugal lubricators [11] and the oozing flow lubricator [12] come under this classification. The centrifugal lubricators and the command lubrication system (CLS) [13] developed by the author
are presented here.

**Centrifugal Lubricator:** The centrifugal lubricator consists of an outer cup and an inner sleeve made of aluminum, machined with a high degree of precision. When the outer cup and inner sleeves are assembled, the space between the two become the reservoir space for the lubricant. The capacity of the reservoir is approximately 5 cc. To make the reservoir leakproof, both ends of the assembly are sealed using a space proven adhesive, electron beam welding or other metal joining methods. On one of the faces of the outer cup, a small hole is provided to fill the lubricating oil. After oil filling, this hole is plugged and sealed with adhesives. Mounting holes are provided on the periphery of the outer cup to assemble the lubricator to the rotating outer spacer. A small hole (called the main orifice) of 150 μm diameter is drilled on the periphery of the outer cup through which the lubricant flows out. The estimated maximum pressure at the orifice when the lubricator is full and rotating at 5,000 rpm is about 13 kPa. Under this pressure, the entire oil in the reservoir will be drained within a few minutes through the 150 μm orifice. To avoid this and to control the oil flow rate to the required level (<10 μg/h), a flow restrictor is incorporated at the main orifice. Here, the flow rate is restricted by using additional micro orifice, called the control orifice, created on a copper foil of 50 μm thickness using a pulsed laser system. The control orifice plate is mounted over the 150 μm orifice as shown in Fig 3(a). The centrifugal pressure causes the oil to flow through the control orifice. The oil particles coming out of the orifice are flowing into the bearings placed on either side of the lubricator. Fig. 3(b) shows the lubricator assembly. In this design, a dry poros sleeve (sintered nylon) is used as a secondary reservoir, which absorbs the oil coming out of the lubricator during the initial period and prevent flooding of lubricant in the bearing and keep the viscous drag to a minimum. Once the sleeve is saturated with oil, it starts supply to the bearings. The diameter of the control orifice is calculated depending on the required flow rate by using the following equation [11].

\[
q = K \frac{\pi \rho^2 \omega^2 r^4}{8 \eta} \left[ \frac{R_2^2 - R_1^2}{R_3 - R_2} \right]
\]

where \(K\) is the flow coefficient (\(K = 0.326\); Sathyan, et al. [11]), \(\rho\) is the density of the lubricant (kg/m\(^3\)), \(\eta\) is the dynamic viscosity of the lubricant (kg/m-s), \(\omega\) is the angular velocity (rad/s), \(r\) is the
radius of the orifice (m), \( R_1 \) is the instantaneous radius of the oil inner layer in the reservoir (m), \( R_2 \) is the radius at which oil enters the orifice (m), and \( R_3 \) is the radius at which oil leaves the orifice (m). In this case, \( R_2 \) and \( R_3 \) are constants and the difference between the two gives the flow length; \( q \) is the mass flow rate (kg/s). In this work, proven space lubricant ISOFLEX PDP 65, a synthetic diester oil (Kluber Lubrication, Munchen, KG), was used. The predicted performance of the lubricator having an orifice diameter 2.2 \( \mu \)m using Eq.1 and the experimental data of the same are compared in Fig. 4.

**Command Lubrication System (CLS):** The command lubrication system [3,13] is an active lubrication system developed for the supplementary lubrication of high speed mechanisms requiring remote lubrication. The CLS consists of a compression type metallic bellows of swept volume approximately 1.5 cc, which acts as the oil reservoir. The bellows is actuated by a geared micro stepping motor through a high precision frictionless ball screw as shown in Fig. 5. Oil is stored in the reservoir under pressure equal to the internal pressure of the momentum wheel, which is typically between 20 and 500 mbar. The ball screw converts the rotary motion of the motor shaft into linear motion and thus compress the bellow. On the delivery end of the bellows, a nozzle is attached which connects the capillary tubes (0.5mm diameter), which deliver the oil to the bearings. The delivery end of the tube is ground and squared and is coated with an anti migration film. This coating will help in the formation of oil droplet by preventing spread of oil around the nozzle tip.

![Developmental model of CLS](Fig.5)  ![Oil delivered vs operating time](Fig.6)

The experimental data on the developmental model of CLS for various duration of motor operation is shown in Fig.6. It is estimated that CLS can supply lubricant for morethan 15 years, if two actuations per year of each 5s is planned.

**Reaction Wheel Lubrication:** A reaction wheel (RW) is similar in construction as momentum wheels and they are particularly useful when the spacecraft must be rotated by very small amounts and therefore they are often used in spacecraft carrying cameras or telescopes such as remote sensing satellites. Generally, reactions wheels are of low angular momentum capacity (typically 0.1 to 5 Nms) and operating speed of ±3000 rpm. Since the operating speed is low and varying, the lubricant...
depletion rate is low unlike the momentum wheels. Therefore, in RW bearings, vapor phase lubrication using poros oil reservoirs is generally employed. Positive lubrication systems and specially designed centrifugal lubricators are also used.

**Porous Reservoir:** In this system the lubricant is supplied partially in vapor form and partially in liquid form. It consists of a porous material sleeve impregnated with the lubricating oil and serve as the oil reservoir. Sintered nylon or polyimide are generally used as the reservoir. These materials have porosity ranges from 25 to 30% of volume. The porous reservoir is mounted on a thin aluminum sleeve. On the inner surface of the aluminum sleeve a foil heater is mounted as shown in Fig. 7. This assembly is rigidly mounted on the stationary inner spacer of the bearing unit. A 10 W heater is sufficient for raising the temperature up to 120 °C. A thermister is also provided on the aluminum sleeve to measure the temperature attained.

The normal operating temperature of the wheel is 40°C. During normal operation, the oil in the reservoir surface evaporates at a very low rate because of the low vapor pressure of the space lubricants (10^{-4} to 10^{-8} mbar) and fills the free space around it. When the bearing friction increases due to lubricant starvation, the bearing temperature rises. The heater is switched on and the reservoir is heated up. The temperature of the oil inside the reservoir increases and it flows out of the reservoir pores due to differential thermal expansion. The oil thus coming out of the pores form a thick layer at the surface of the reservoir. The higher temperature accelerate the rate of evaporation and the density of oil vapor in the free space increase. The oil vapor comes in contact with the bearing cage and outer spacer surfaces condenses and forms oil film, since these surfaces are at a lower temperature than the vapor. The oil film on the surface of the outer spacer moves towards the bearings because of the taper of the surface and centrifugal force.

**Gyroscope Lubrication**

Inertial navigation is a self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation and velocity. Inertial measurement units typically contain three orthogonal gyroscopes and accelerometers, measuring angular velocity and linear acceleration respectively. There are different types of gyroscopes such as mechanical, optical, MEMS gyros, etc. The main disadvantage of mechanical gyroscopes is that they contain moving parts that cause friction, which in turn causes the output to drift over time. To minimize friction, high-precision bearings and special lubricants are used. In most spacecrafts, mechanical gyroscopes are successfully used. A dynamic tuned gyroscope (known as DTG), is one of the options nowadays that can provide the required performance for spacecraft applications. The
various components of the DTG are shown in Fig. 8. The rotating shaft with the rotor assembly is supported by precision ball bearings, suitable for stable operation up to 15,000 rpm under an axial pre-load. It is capable of withstanding the launch vibration and operates satisfactory during the required mission life of more than 15 years.

The bearings used are high precision angular contact ball bearings of ABEC-7P having ball tolerances conform to AFBMA grade 3. R3 or R4 size (3/16 inch or 4/16 inch bore diameter) bearings are generally selected. These bearings use cotton based phenolic or polyimide retainers and vacuum impregnated with liquid lubricants, generally Krytox 143AC, a fluorinated oil, which has superior load carrying capability and lubricity. This oil is also very stable under wide range of temperature. Generally, oil soaked porous sleeve is introduced as supplementary lubrication system in some designs. In such cases oil film migrates to the bearing and compensates the loss from the bearings. Thus ensures desired mission life.

**Conclusion**

In this paper, the tribological aspects of various moving mechanical systems are presented. There are classified into high speed mechanisms and low speed mechanisms. Generally high speed mechanisms are lubricated by space proven liquid lubricants. The lubrication systems presented here such as the centrifugal lubricators, poros reservoirs and the command lubrication system are capable of supplying lubricant for high speed MS that require very long mission life of greater than 20 years.

**References**


