Development of a Positive Lubrication System for Space Application

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The success of a spacecraft mission depends to a great extent on the performance of the moving mechanical systems. The most common mode of failure in these systems is tribological. Tribological failures occur mainly due to non availability of lubricant at the working zone of the bearings as a result of degradation, evaporation and creep. The life of these moving mechanical systems could be extended, if lubricant is replenished by some means. This paper describes the development of a positive lubrication system named as command lubrication system (CLS). This is an active lubrication system which when actuated by external commands delivers lubricant to the bearings. It is actuated only when there is a demand for lubricant indicated by increase in frictional torque or bearing temperature. The outstanding feature of this system is that the lubricant is stored under ambient pressure and hence less chance of leakage. The CLS can solve the lubrication problem of spacecraft systems which require very long mission life of more than 20 years. It is also suitable to tribosystems in terrestrial devices.

Keywords: positive lubrication, spacecraft, momentum wheels, space tribology

1. Introduction

Spacecrafts use a number of moving mechanical systems which could be broadly classified into high-speed systems such as control moment gyros (CMG), momentum wheel, gyroscopes etc and low speed systems such as solar array drives, scanners etc. Many of these systems use precision ball bearings and rely on liquid lubricants to provide uninterrupted long-term service. Unlike in the past, currently the mission lives of such systems are much longer (>10 years) and efforts are being made for the development of moving mechanical systems to cope with such requirements.

The attitude control system of a spacecraft uses the high speed systems mentioned above. They are used as sensors to determine the attitude error and as actuators for correcting this error. A gyroscope in a spacecraft acts as a sensor while momentum / reaction wheels functions as actuators. Attitude control¹⁻³⁾ can be defined as the process of achieving and maintaining a desired orientation of the spacecraft in space. Control of the attitude of a satellite is important to increase its usefulness and effectiveness to establish reliable

communications links. If a satellite is stabilized in an orbit, its directional antennas can be properly pointed toward the earth to enable communications with the earth station.

The most dominant mode of failure in attitude control systems is tribological. Although tribological components constitute only a small fraction of the spacecraft's cost, their failure can often cripple or debilitate expensive spacecraft. The Galileo spacecraft is a classic example of a single point tribological failure affecting the entire mission⁴⁾. More on-orbit failures are reported in ref^{5,6)}.

Tribological failure of high speed systems such as control moment gyros (CMG), momentum wheel, gyroscopes etc occurs mainly due to two reasons; lubricant starvation and retainer instability. The later problem can be completely eliminated by using retainerless bearings. Today, momentum/reaction wheels with retainerless bearings are commercially available^{7,8)}. The former problem occurs when the lubricant degrades or evaporates and therefore loses its ability to lubricate the contact zone. The starvation problem can be solved by replenishing the lost oil by suitable means. Supplementary lubrication systems are incorporated in to high speed systems which ensures required amount of

lubricant at the tribological contacts.

2. Spacecraft lubrication systems

According to the nature of operation, the lubrication systems used in high speed attitude control systems can be broadly classified as passive lubrication systems and active lubrication systems.

2.1. Passive lubrication 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^{9,10}, the oozing flow lubricators¹¹⁻¹⁴, wick feed systems¹⁵, porous lubricant reservoirs¹⁰ etc come under this classification.

2.2. Active lubrication systems

The active lubrication systems also known as positive lubrication systems, supplies a controlled amount of lubricant to the bearings when it is actuated by external commands. The command to actuate the lubricator is executed when a demand for lubricant arise. The demand is indicated either by an increase in power consumption as a result of increased bearing frictional torque or by increase in bearing temperature resultant of increased bearing friction torque. Different versions of positive lubrication systems are available with different actuators such as solenoid valves, stepper motors etc.

The Hughes Aircraft Company developed a commandable oiler¹⁶ in which a solenoid operated piston moves inside a reservoir, one end of which acts as a cylinder. A quantity of oil equal to the cylinder volume is discharged during every operation. The oil coming out of the cylinder is directed to the bearings through 1.5 mm stainless steel tubing. The capacity of the reservoir is 6 grams and the quantity delivered per stroke is 45 mg. This system had been used in the Intelsat IV satellites.

The positive lubrication system (PLUS) developed by Smith and Hooper¹⁷ is of solenoid operated type. In this system, the oil is stored in a metallic bellow and is pressurized by a compression spring. The high pressure (500 kPa) oil is delivered to the bearings by actuating the solenoid valve connected to the reservoir. The amount of oil delivered is 0.2 to 5 mg for 125 milliseconds opening of the valve. The amount of oil delivered depends on the reservoir pressure, oil temperature and plumbing flow resistance.

The positive-pressure feed system Proposed by James¹⁸ consisted of a spring loaded metallic bellow in which oil is stored under pressure. A release valve when operated, the oil flows out to the line through the metering bellows and the metering valve. The lubricant feed line which terminates near the bearing delivers oil to the bearing surface. The amount of oil delivered is controlled by the metering bellows.

The Marchetti et al^{19,20} developed an in-situ on

demand lubricator, which consists of a porous material cartridge to which an electric heater is attached. The cartridge is impregnated with oil and is attached to the stationary race of the bearing. When the cartridge is heated, due to the higher thermal expansion of the oil compared to the porous material, oil flows out of the cartridge. The oil coming out of the cartridge is migrated to the bearing surfaces due to the low surface tension of oil compared to the bearing metal. The system has been evaluated using a spiral orbit tribometer and proved its feasibility to use in long-lived spacecrafts²¹.

The positive lubrication systems mentioned above are high pressure systems in which the lubricant is stored under pressure except the in-situ lubricator. These systems are more prone to leak which results in failure of the system. This paper describes the development of a positive lubrication system in which the oil is stored under ambient pressure, which can be used for long-term lubrication of high speed systems like momentum/reaction wheels etc.

3. The command lubrication system

The command lubrication system is an active lubrication system developed for supplementary lubrication of high speed mechanisms requiring remote lubrication. In this system, unlike the systems mentioned above, the lubricant is stored at ambient pressure and thus the chances of leak are the minimum. The design features of the system are presented in the following sections.

3.1. Design of CLS

The CLS consists of a metallic bellows, a micro stepping motor, a frictionless ball screw, injection nozzle and capillary tubes. The stainless steel bellows act as the oil reservoir in which the oil is stored under ambient pressure. This pressure is usually the internal pressure of the momentum/reaction wheel or CMG, if it is placed inside the system and is usually varies between 15 torr and 350 torr. The bellows is of compression type having a swept volume of approximately 1.5 cm³, i.e. the difference between the normal state and fully compressed state. The micro stepping motor, which is the actuator, is a geared motor having a torque capacity of 130 mN·m and is driven through the drive electronics. The motor shaft is connected to the reservoir bellows through the ball screw. The high precision frictionless ball screw is of miniature type having 3 mm (M3 size) screw. It is properly lubricated with space proven lubricant and protected from contaminants. One end of the screw is rigidly connected to the motor shaft. The housing/nut of the ball screw is attached to the bellows through the link. The ball screw converts the rotary motion of the motor shaft into liner motion and thus actuates the bellow. On the delivery end of the bellows, a nozzle is attached which connects the capillary tubes with the bellows as shown in Fig. 1.

Fig. 1 Developmental model of CLS¹⁰⁾

The stainless steel capillary tubes are of 0.5 mm in diameter and are suitably shaped to reach up to the bearings as shown in Fig. 2. The delivery end of the tube which acts as the delivery nozzle is ground and squared and is coated with anti migration film as shown in the Fig. 3. The coating will help in the formation of oil droplet by preventing spreading of oil around the nozzle tip.

The reservoir is fully charged with lubricant before it is being assembled with the drive motor. Oil filling is done by dipping the bellows assembly in oil kept under vacuum. The vacuum level is maintained at 10^{-2} torr until all the air molecules are removed. During oil filling, temperature is maintained at 50 °C. After filling, the outlet port is immediately closed with a dummy cover to prevent contamination. The total mass of the system is about 60 mg including lubricant and the mounting bracket.

Fig. 2 CLS delivering oil to bearing unit outer spacer

3.2. Functioning of CLS

Most high speed bearings used in spacecraft are assembled with an initial charge of lubricant. Typically, in a momentum wheel bearing with phenolic retainer, the initial oil is about 60 to 80 mg. This initial charge of

Fig. 3 Oil droplet at the delivery tip

oil is sufficient for normal operation up to three years and then it will start showing symptoms of abnormality which indicate the demand for lubricant. In spacecraft, the demand for lubricant is indicated either by an increase in bearing temperature as a result of increased bearing friction torque or increased motor current to maintain the rotational speed. In such situation, the drive motor of the CLS is actuated for a predetermined period of time to deliver oil to the bearings. When the motor shaft rotates, the ball screw attached to it also rotates. The housing/nut of the ball screw which is rigidly mounted on the bellows moves linearly and presses the bellows. As a result, the pressure of oil in the reservoir bellows increases and it flows out through the capillary tubes. At the delivery tip of the tube, oil forms a drop and when the size of the drop is sufficiently large, it touches the rotating outer spacer of the bearing unit. From the outer spacer, the oil flows axially to the bearing due to centrifugal force as shown in Fig. 3. It is to be noted that the tubes are routed through the stationary part of the bearing unit so it is stationary. The set-off distance i.e. the distance between the nozzle tip and the rotating element of the bearing is determined from the size of the oil droplet. It was experimentally determined that the weight of a drop of oil (Kluber PDP-65 oil) is approximately 8 mg and the size is about

2.5 mm. therefore, the set-off distance in this case is 2 mm. The nozzle tip can be suitably located near the bearing depending on the design of the bearing unit to ensure oil discharge to bearings.

4. Results and discussions

The CLS need to be calibrated before it is being integrated to the system. This is done to determine the actuation time required to deliver each drop of oil. The actuation time depends on the rotational speed of the motor shaft and the pitch of the screw. The calibration data of the developmental model CLS is shown in Fig. 4. The test is done under a vacuum of 350 torr at 25 °C and the motor input is kept constant. The motor is run for duration of 5 seconds each and the oil discharge at the delivery tip is collected and weighed. The discharge was approximately 15 mg (2 drops) per cycle. The data obtained for 50 cycles are presented in Fig. 4. A trend line fitted through the data points shows a reduction in the discharge and it is due to the non linearity in the swept volume of the bellows. It can be seen from the figure that the total discharge in 50 cycles is about 750 mg, which is only half of the swept volume, i.e. oil available for lubrication.

It is well understood that lubricant losses in liquid lubricated space systems are mainly due to evaporation and surface migration. The evaporation loss can be estimated from the chemical structure of the lubricant. The surface migration occurs due to two reasons: surface roughness and thermal migration due to Marangoni effect^{20,22}. Also, Kingsbury²³ has shown that only 0.2 micrograms per hour lubricant flow rate is needed for steady state operation. Using this data, assuming a maximum loss of 10 mg/year, only two drops (15 mg) oil is needed to compensate for the losses. It means that if we supply one drop of oil every six months or a maximum of three drops per year, the failure due to lubricant starvation can be completely eliminated. From the calibration data of the CLS, even if two operations of 5 seconds each are planned every year, this system would provide lubrication up to 25 years.

Fig. 4 Measured oil discharge from CLS

The amount oil discharge from the CLS can be varied by varying the duration of operation time. Fig. 5 shows the measured oil discharge for different actuation periods. It is seen that the flow is about 10 mg when the motor is run for 4 seconds and 40 mg when is run for 10 seconds. This shows that the amount of oil discharge can be controlled by adjusting the actuation period. The data presented is obtained when the reservoir is fully charged and there will be reduction in the discharge at a later stage. The oil discharge can be properly controlled by selecting suitable actuator motor, fine pitch ball screws and suitable bellows.

Fig. 5 Oil discharge vs. operating time

4.1. Experiments with bearing unit

The performance of the CLS is demonstrated on a momentum wheel bearing unit. The bearing unit is assembled with saturated bearings having phenolic retainers. The bearing used is high precision angular contact ball bearing (104 size) of ABEC 9P class. The lubrication system is mounted external to the bearing unit and the nozzle tip is directed to the bearing retainer surface. The friction torque of the bearing unit at 5000 rpm is recorded continuously for two days. After attaining the steady state condition, the CLS is activated for five seconds. It was observed that a few minutes after actuation of the CLS motor, the bearing friction torque increased gradually from 2.5 mN·m to 5 mN·m as shown in Fig. 6. This torque increase is due to the increased viscous drag and confirms the presence of additional oil in the bearing working surfaces. It can be seen from the Fig. 6 that the torque is doubled just by adding one drop (8 mg) of oil. This is due to the sensitivity of the retainer to lubricant quantity. The retainer design used for this experiment is highly sensitive to lubricant quantity and is developed to operate under elastohydrodynamic (EHD) lubrication condition. However, if the bearings are starved, it will be running with higher friction torque and addition of oil would cause reduction of friction torque and smooth operation of bearings. The lubricant used in this experiment is a proven space lubricant with high viscosity index (Synthetic diester oil, VI = 235). Therefore, change in viscosity in the operating temperature range of 20 - 60 °C will not have much effect on the performance of the CLS. Moreover, the

average working temperature of a momentum wheel in a geostationary satellite is about 40 °C and so the CLS can be operated at a selected temperature if necessary.

Fig. 6 Bearing unit friction torque before and after actuating the CLS

5. Conclusions

Tribological failures in lubricated spacecraft mechanical systems are often caused by lack of lubricant due to degradation, evaporation and surface migration. Hence, the command lubrication system (CLS) is suggested to maintain sufficient amounts of lubricant and to overcome the drawbacks observed at existing automated lubrication systems. In this system the lubricant is stored under ambient pressure and thus the chances of leak are the minimum. The working of the system is successfully demonstrated on a momentum wheel bearing unit. From the calibration data of the CLS, it is estimated that even if two operations of 5 seconds each are planned every year, this system would provide lubrication up to 25 years. This results show that the CLS can effectively lubricate high speed space mechanism requiring very long mission life.

6. References

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