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Controlled-Leakage Sealing of Bearings for Fluid Lubrication in a Space Vacuum Environment

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This paper analyzes an example of sealing hydrodynamic bearings to the extreme requirements established by the functional mission of space vehicles in synchronous orbit for extended periods of time. The present concept of a synchronous orbit is a constant altitude of between 20,000 and 25,000 miles. The economy of many missions in synchronous orbit will require functional effectiveness for at least 7 years.

The problems imposed by severe environmental conditions for the extended period of time are discussed so that relevant design criteria for hydrodynamic bearing lubrication systems can be established.

I. Introduction

The applicability of synchronous orbiting mechanisms to space technology is manifested in the communications satellite. The *Applications Technology Satellite* (ATS) and COMSAT designs represent the state-of-the-art concepts for reception and transmission, forming an important facet of a global communications network. Both designs depend on bearings for stability and orientation. Some designs utilize bearings in power and signal transfer. In all designs, the reliability of bearing function is critical to the success of the mission. A bearing failure is catastrophic.

Valuable information covering the probable failure modes of antifriction bearings and bearing surfaces in the space vacuum environment is available from such publications as NASA technical reports; proceedings of the annual Aerospace Mechanisms Symposiums; proceedings of meetings conducted by the American Society of Lubrication Engineers and the Aerospace Council; and company research projects funded by government agencies. Such information is obtained, for the most part, from the results of simulated tests in terrestrial laboratories, and, to a lesser degree, from information transmitted by orbiting spacecraft.

II. Constraints

The lubrication of spacecraft systems operating in a synchronous orbit is complicated by (1) ultra-high vacuum, (2) volatilization, (3) condensation of volatiles, (4) absence of reactive gases, (5) poor thermal conductivity, (6) weightlessness, (7) temperature extremes, and (8) penetrating radiation. When knowledge of constraints is applied to bearing design, the resulting lubrication system should be the product of the proper selection of materials, suitable engineering design, and the careful application of nondestructive testing and check-out procedures.

A. Ultra-high Vacuum

The most important problem in the space environment influencing materials for lubricated systems is ultra-high vacuum. The ambient pressure of the synchronous orbit is about 10^{-13} torr. The detrimental effects on the lubrication system attributed to this low ambient pressure are volatilization, condensation of the volatiles, absence of reactive gases, and poor thermal conductivity.

1. Volatilization. The equilibrium value is a thermodynamic function of the molecular species involved and is established when the rate of molecules returning to a surface equals the rate of leaving. In an absolute vacuum, the mean free path is large enough so that those departing molecules can be permanently lost and equilibrium cannot be attained. Therefore, if a solid or fluid lubricant has a high vapor pressure, it may evaporate appreciably during long-time space orbits, with a contingent loss of lubricative function.

2. Condensation of volatiles. The detrimental effect of volatiles condensing on a cold surface is contamination. Optical and thermal control surfaces are particularly vulnerable and cannot perform satisfactorily with gross changes in diffraction, absorption, and emissivity. Electrical contacts, slip rings, and brushes are detrimentally affected by changes in conductivity due to contaminating films.

3. Absence of reactive gases. Absorbed or chemisorbed gas films, such as oxides, are normally present on even the cleanest metal surfaces in terrestrial atmosphere. Such films prevent bare metal-to-metal contact and the formation of strong welded junctions. However, when these films are removed by frictional phenomena, they are lost to space vacuum, and gross seizure and welding can occur.

4. Poor thermal conductivity. Poor thermal conductivity results from the absence of gases between adjacent or contacting surfaces down to the prominent asperity level. In the terrestrial atmosphere, the spaces between contacting asperities are filled with air which conducts thermal energy from one substrate surface to another, thereby producing a low gradient. However, in vacuum, the absence of thermal conducting gases restricts the flow of heat to the real areas of contact (asperities), resulting in a high gradient. The poor thermal conductivity, coupled with the absence of convection cooling, establishes higher heat-resistance requirements for lubrication systems.

B. Weightlessness

The only beneficial effect of weightlessness is that, once in orbit, bearings need not support a structural load. The bearing load is reduced to the level required by the initial load associated with acceleration and deceleration, the effect of unbalanced dynamic forces, and the centrifugal force of the bearing against raceways and retaining mechanisms. Reduced bearing load means less wear and friction. However, the detrimental effects have a greater influence on bearing design. The latter effects are:

(1) The obvious malfunction of gravity-fed systems such as fluid reservoirs and hydraulic system accumulators.

(2) In combination with ultra-high vacuum, the absence of convection currents for cooling. Therefore, frictional surfaces will operate at higher temperatures than those induced by the same loading conditions in a terrestrial environment.

C. Temperature Extremes

The effect of temperature extremes on spacecraft lubrication is more pronounced on those parts outside of the vehicle skin. The cause is direct radiation from the sun and, to a lesser extent, solar reflection from the earth. Components such as solar array bearings can experience temperatures as low as $-280°F$ when positioned away from the influence of solar radiation. Temperatures within the vehicle are protected from extreme conditions by controlling the absorptivity and emissivity of the outer spacecraft skins so that the only problem is the increased temperature rise on frictional surfaces caused by the lack of convection heat transfer.

D. Penetrating Radiation

The net effect of penetrating radiation on lubrication is the energy supplied for chemical reactions within the molecular structure of the lubricants and the temperature rise due to the absorption of energy, which can detrimentally affect required chemical and physical lubricant properties. Space environment radiation is not considered a major problem in lubrication. Radiation-resistant lubricants have been developed, newer lubrication system design provides effective shielding through housings and retaining mechanisms, and the oxygen required to accelerate radiation degradation in some lubricant materials is absent in space vacuum environments.

III. Lubrication Systems

There are many bearing surfaces and mechanisms functionally peculiar or common to the communications satellite. These include mechanisms such as motors, gear chains and trains, gyros, or stabilization wheels; mechanical devices such as pull pins, threaded fasteners, closures, and valves; equipment for recording and transmission, relays, and timing devices; electrical contact surfaces such as brushes and slip rings; and critical bearings for positioning antennas and solar arrays or for spinning and despinning the satellite.

The purpose of a lubrication system is two-fold: (1) to maintain a low torque level consistent with part function and available allotted power, and (2) to maintain the required conductivity for contacting electrical surfaces. Increasing the torque of any of the aforementioned mechanisms can render the available power supply inadequate, and a failure mode is established. Increasing torque is the product of friction, wear, and adhesion. Decreased electrical conductivity can render electrical power and signal transfer inoperable.

We must design a lubrication system for mission life We can discount the problem of environmental radiation where the bearings are housed and shielded unless there is a nuclear power source for the spacecraft. The problem of meteoroids is part of total spacecraft design and not peculiar to the lubrication system. Therefore, we must design for protection against the adverse conditions imposed by the low ambient pressures, weightlessness, and temperature extremes.

The primary consideration is the lubricant itself. The two most widely used generic types are fluid and solid. The fluids (oils and greases) are useful for hydrodynamic systems, and the solids are more applicable where boundary conditions are encountered.

A. Solid Lubricants

We will not dwell on the solid lubricants, although they are more compatible with the space vacuum environment than the fluids. However, they have a tendency toward sacrificial wear, whereby they reduce the wear rate between rubbing surfaces by wearing themselves, until they are removed or the debris formed becomes a contaminant. If a thicker film is employed for longer wear, the wear can become greater than design-allowable dimensional tolerances, or the greater amount of debris can compound the contamination problem. An excellent example is in electrical contacts such as slip rings and brushes, where debris from contacting brushes can create a "short" by depositing a conductive path between adjacent slip rings. Another problem is that the greater the speed of rubbing surfaces, the faster the wear. The failure mode with solid lubricants is usually catastrophic. However, there are applications where only solid lubricants can be used, and a judicious selection should be made.

B. Fluid Lubricants

For the purpose of this session we will discuss the design of hydrodynamic lubrication systems for bearings and flexures in space vacuum environments.

The greatest problem with fluid lubricants is volatility. Vacuum increases the evaporation rate of the material, and any increase in temperature from friction with the lack of convection cooling accelerates volatilization. Therefore, an oil or grease with low volatility and thermal stability should be selected. We have found that lubricating fluids based on chlorophenylmethyl polysiloxane and fluorosilicones impart excellent lubrication to instrument-type bearings in vacuum for rather long periods of time. A test using a fluorosilicone is still in progress after more than 5½ years, in a chamber pressurized at 1×10^{-8} torr. The tests performed on fluid lubricants at 10^{-8} or 10^{-9} torr are valid even though the synchronous orbit ambient pressure is 10^{-13} torr. Effectively designed shielding and sealing of bearings will increase the pressure surrounding the bearing to from 10^{-3} to 10^{-8} torr. Some of the highly refined paraffinic and petroleum oils and greases show promise, but the changes in viscosity are more pronounced than those of the silicones with changes in temperature.

C. Bearing Materials

Another important factor in vacuum bearing technology is the selection of the bearing material. Two metals often used are 52100 chrome steel and 440C corrosion-resistant steel — both materials heat treated to a Rockwell hardness of C58-63; vacuum melt fabrication stock is preferred to assure freedom from gross imperfections during alloying. We prefer the 440C for the total mission because of its resistance to the prelaunch atmospheric environment.

IV. Controlled-Leakage Sealing

When the type of bearing and the lubricant have been selected, the design of the lubricating system for mission life follows. Design parameters should include calculations assuring an adequate supply of lubricating fluid. Since volatilized fluids are gases in vacuum, the calculations should be derived from the flow behavior of gases at the different pressure levels.

Complete or hermetic sealing of the lubrication system is most effective in vacuum. However, there is a possibility that the optimum seal could be broken by disrupting forces during the 7-year minimum requirement. Therefore, other sealing methods that can function with some exposure to ultra-high vacuum should be investigated. An excellent, flight-proven candidate is controlled-leakage sealing.

The design for controlled-leakage sealing is based on a minimum loss of lubricant by evaporation. M. Knudsen (Ref. 1) states that since on a molecular scale even smooth surfaces appear rough, the direction in which a molecule rebounds after collision with the surface is statistically independent of the angle of incidence. Therefore, the molecular flow resistance of small orifices can be made relatively high.

A. Theoretical Discussion

We relate the controlled-leakage mechanism to the molecular flow of gases rather than to viscous flow because the reduced pressure of space vacuum causes the molecular mean free path to exceed the cross-sectional area of the gas path, and tangential shear between gas layers cannot be effected. An equation developed by M. Knudsen and colleagues modifying the classic kinetic gas theory is useful in designing a fluid lubrication system for functional bearing life by calculating the escape rate of oil from a bearing assembly. The equation is

$$Q = \frac{4}{3}(2\pi)^{1/2}\left[\frac{(R_2^2 - R_1^2)(R_2 - R_1)}{L}\right]\frac{1}{(\rho_1)^{1/2}}(p_1 - p_2) \tag{1}$$

where

Q = volume flow rate of oil vapor

R_1, R_2 = inside and outside radii of annulus

L = length of annulus

ρ_1 = density of oil vapor at standard conditions

p_1 = pressure in the housing

p_2 = ambient pressure

According to M. B. Weinreb (Ref. 2), this equation was employed in designing a radiometer spindle assembly for the *Tiros II* meteorological satellite (Fig. 1). The lubricant used was a MIL-L-6085A diester oil with a vapor pressure of 10^{-4} torr. When the ambient pressure reaches 10^{-2} torr, molecular gas flow occurs around the shaft through the small clearance of 0.0005 in.

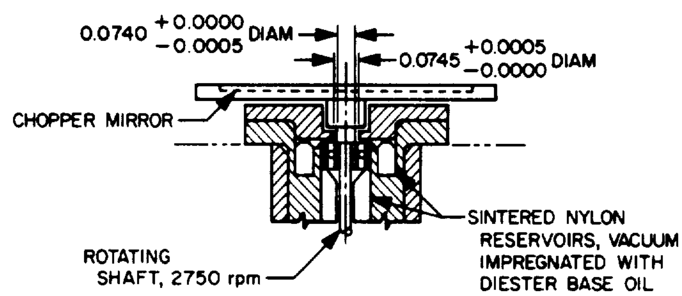

Fig. 1. Radiometer spindle assembly

S. P. Lester (Ref. 3) describes the effect of modifying the kinetic gas theory for a simple aperture (Eq. 2):

$$w = 0.0583\, P\left(\frac{M}{T}\right)^{1/2} A\,\frac{\text{grams}}{\text{second}} \tag{2}$$

where

w = weight loss in grams/second through simple aperture

P = vapor pressure of the gas in torr

M = molecular weight of the gas

T = temperature of gas in degrees Kelvin

A = area of the aperture in cm^2

Equation (2) should be further modified by a fraction factor of loss f. Since f is based on gap width a and channel length l in the order of mean free path, it is possible to establish a numerical value of f for escape path configurations other than the simple aperture. The Monte Carlo Technique (Ref. 4) can be used for this calculation if the (l/a) ratio of the path length to width is 16 or greater in the equation $f = \pi(a/l)$. The term f can then be introduced into Eq. (2) as follows:

$$w = \left[0.0583\, P \left(\frac{M}{T} \right)^{1/2} A \right] f \,\frac{\text{grams}}{\text{second}} \qquad (3)$$

Several examples of escape paths measurable for f are shown in Fig. 2. These and other possible configurations contribute to the effective design of labyrinth seals. Controlled-leakage sealing is augmented by using fluid lubricants with low vapor pressures. It is sometimes difficult to correlate a high average molecular weight product with a uniform low vapor pressure, since many fluid lubricants contain a wide range of molecular weights. The low molecular weights probably volatilize first so that the loss factor will be somewhat erratic until the system is stabilized. This should be considered when calculating sealing requirements.

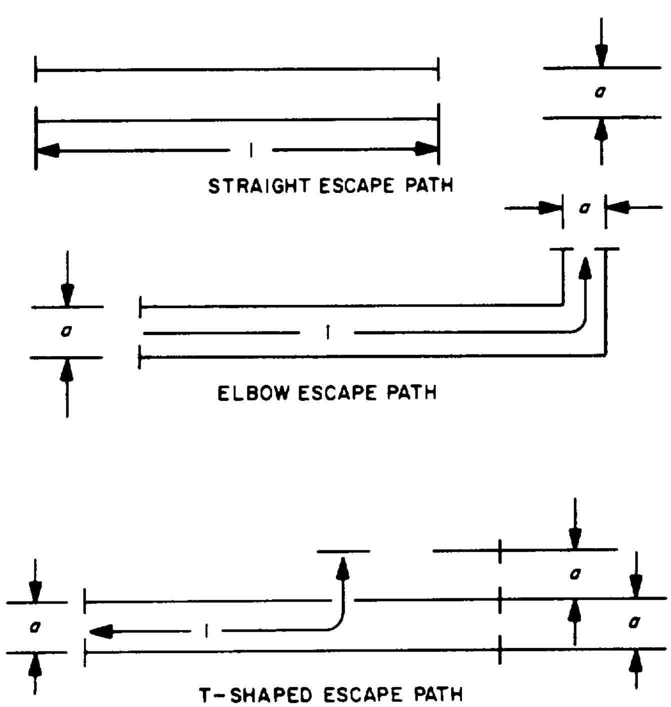

Fig. 2. Measurable escape paths

B. Results of Tests on Selected Oils

S. P. Lester (Ref. 3) tabulated the vapor pressure and viscosity of oils that were selected for low-vapor properties and that have been evaluated by the Lockheed Missiles & Space Company as lubricants for instrument-size ball bearings (Ref. 5). These are listed by generic chemical type in Table 1. The results of the tests are tabulated in Table 2.

Table 1. Vapor pressure and viscosity of selected oils

Oil (chemical type)	Vapor pressure, torr	Viscosity, cS
Chlorophenyl-methyl polysiloxane	0.1 at 125°F	52 at 100°F
Petroleum base oil	1×10^{-9} at 70°F 1×10^{-3} at 572°F	3535 at 104°F
Paraffinic base petroleum oil with additive	5×10^{-4} at 70°F	440 at 70°F 155 at 100°F 15 at 210°F
Dioctyl sebacate	3×10^{-5} at 70°F 1×10^{-3} at 176°F	23.5 at 70°F 9.37 at 130°F 3.85 at 210°F

Except for the dioctyl sebacate, all the lubricants were operable in vacuum for more than 1 year with impregnated phenolic retainers and without labyrinth seals. A fluorosilicone oil (not listed in the table), with a viscosity of 250 cS, is operating in a pressure of 1×10^{-8} torr after more than 5½ years. A well-designed labyrinth seal should improve the performance of the tested oils.

Table 2. Test results for selected oils (Ref. 5)

Oil (chemical type)	Maximum test pressure, torr	Results (as of Sept. 1967)
Chlorophenyl-methyl polysiloxane	4×10^{-9}	Motor stalled at 23, 460 h. Cause of failure being determined.
Petroleum base oil	1×10^{-8}	Test discontinued at 20,019 h. Bearings were satisfactory with oil still present. No change in torque from start to finish.
Paraffinic base petroleum oil with additive	1×10^{-8}	Still running after 18,457 h in an ambient temperature of 250°F.
Dioctyl sebacate	1×10^{-3}	Failed at 3584 h.

V. Specific Recommendations

To optimize the design of a fluid lubrication system for bearings in the space vacuum environment for extended periods of time, the following recommendations are made:

(1) The bearings should be fabricated from vacuum-melt 440C corrosion-resistant steel, hardened to Rockwell C 58-63.

(2) Retainers should be porous phenolic laminate, vacuum-impregnated with a low-vapor-pressure fluid lubricant selected from the first three types listed in Tables 1 and 2.

(3) Controlled-leakage seals should be designed with an adequate supply of low-vapor-pressure fluid lubricant (for mission life) vacuum-impregnated into sintered nylon reservoirs (18–25% porous).

(4) The judicious deployment of barrier films will decrease creepage of the lubricant from the bearing surface and the minimized surface area exposed to low pressures will reduce the loss factor.

VI. Conclusions

The vacuum space environment does afford some advantages to the hydrodynamic lubrication systems using fluids. Weightlessness reduces the high bearing loads and the boundary condition resulting from the loss of the fluid film. With controlled-leakage sealing, the reservoirs need not be in direct physical contact with the bearing; as a result, the torque requirement is decreased.

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