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EHL Transition Temperature Measurements on a Geostationary Operational Environmental Satellite (GOES) Filter Wheel Bearing

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ABSTRACT

The elastohydrodynamic lubrication (EHL) transition temperature was measured for a Geostationary Operational Environmental Satellite (GOES) sounder filter wheel bearing in a vacuum tribometer. Conditions included both an 89 N (20 lb.) hard and soft load, 600 RPM, temperatures between 23°C (73°F) and 85°C (185°F), and a vacuum of approximately 1.3×10^{-5} Pa. Elastohydrodynamic to mixed lubrication started to occur at approximately 70°C (158°F).

INTRODUCTION

The Geostationary Operational Environmental Satellite (GOES) program provides constant and reliable weather data to the United States. The key element in the program are satellites that operate in geosynchronous orbit and monitor the United States, Atlantic, Pacific, and Central and South America. One of the main instruments on the satellite is the Sounder unit, which is used to measure vertical atmospheric temperature and moisture profiles, surface and cloud top temperature, and ozone distribution [1].

The GOES Sounder utilizes a filter wheel (FW) consisting of 19 spectral bandpass filters mounted on a 29.2 cm (11.5") aluminum disk. The disk is rotated at a constant 600 RPM by a synchronous hysteresis motor. Infrared radiation passes through the filters and strikes detectors. By sensing the amount of energy passing through each filter, the spectral make-up of earth's infrared radiation is determined. Proper operation requires that the wheel's wobble and jitter be minimized.

The assembly utilizes a duplex bearing pair (MPB 1219). These bearings have 440C diamond polished, passivated races, TiC coated 440C balls, and polyimide cages. The HIRS sounder for Tiros has a similar bearing system. The cage is impregnated with 130 mg of a perfluoropolyether (Krytox 143AB). In addition, 20 mg of free oil is added to each bearing. Required orbital life is 5 years and design life is 7 years. Operating conditions were predicted to be 8°C (46°F) to 38°C (100°F) with a preload of 89 N (20 lb.). Under these conditions, the bearings should operate in the EHL regime. The FW successfully passed a six-year qualification test at these temperatures.

After GOES 8 launch, telemetry indicated that the FW motor housing was operating at temperatures to 53°C (127°F) each day and at one point had reached 59°C (138°F). Concern was raised about shortened FW life due to possible lubricant loss and/or transition from EHL into mixed lubrication.

The purpose of this work was to explore the transition from EHL to boundary lubrication as a function of temperature. Therefore, a series of tests were performed on a replica bearing in a vacuum tribometer capable of measuring torque and the EHL transition temperature. Conditions included an 89 N (20 lb.) hard or soft load, 600 RPM, Krytox 143AB lubricant, temperatures between 23°C (73°F) and 85°C (185°F), and a vacuum of approximately 1.3×10^{-5} Pa.

EHL CALCULATIONS

EHL is the regime that describes a bearing where the balls and races are completely separated by a lubricant film. EHL film thickness calculations [2], assuming a fully flooded inlet, were completed using the appropriate FW bearing parameters including an 89 N (20 lb.) load, a rotational speed of 600 RPM, and lubricant properties such as pressure viscosity coefficients, kinematic viscosity, and density. Minimum film thickness (μm) at the inner race-ball contact as a function of temperature (°C) appears in Figure 1. The transition from EHL to mixed lubrication would first appear at the inner race, as the film thickness at the inner race-ball contact is less than that at the outer race-ball contact. The pressure-viscosity coefficient and the absolute viscosity of the oil are the driving force behind the temperature-thickness relationship.

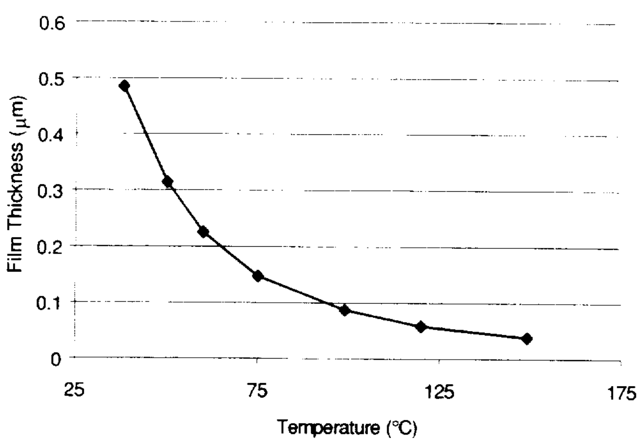

Figure 1 - Film thickness as a function of temperature for Krytox 143AB and a MPB 1219 angular contact bearing assuming a fully flooded contact

LAMBDA RATIO

Obviously, asperity contact between the ball and race is a function of both film thickness and surface roughness. All else being equal, smoother surfaces can operate with thinner film and still remain in the EHL regime. A common parameter used to estimate the degree of surface contact is the lambda (Λ) ratio. The Λ-ratio is calculated by dividing the minimum film thickness by the composite surface roughness (σ_c), which is the square root of the sum of the squares of the ball and race surface roughnesses (R_{RMS}). In general, Λ-ratios greater than three indicate complete surface separation. A transition from full EHL to mixed lubrication (partial EHL film and some asperity contact) occurs in the Λ range between 1 and 3. At Λ-values less than approximately one, boundary lubrication ensues with continual asperity contact and little contribution from fluid films. Λ-values were calculated for the MPB 1219 bearing and Krytox 143AB and are shown in Figure 2. Surface roughness (R_{RMS}) for both the ball and race were assumed to be 0.025 μm (1 microinch). This surface roughness is for commercial quality bearings and is the worst-case scenario; flight quality bearings are expected to have a lower surface roughness. Based on these values, the Λ-value drops below 3 near 95°C (203°F).

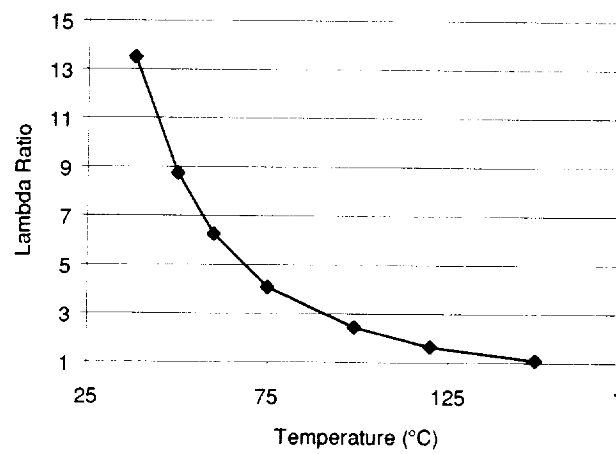

Figure 2 – Lambda ratio for MPB 1219 bearing and Krytox 143AB as a function of temperature assuming a race and ball surface roughness of 0.025 μm (1 microinch)

EXPERIMENTAL

APPARATUS

The GOES bearing test facility (Figure 3) [3] was used to evaluate a FW bearing prepared by ITT to flight specifications. Bearings were from a lot that was rejected for minor defects, which did not affect the short-term tests. Parameters measured include torque, temperature, cross race resistance, load, and vacuum level. Cross race resistance is determined by placing a known resistance in parallel with the bearing. A DC current source is applied across these resistances to allow a maximum of 1 mv to be developed across the fixed resistor for infinite contact resistance. Non-infinite resistance lowers the potential developed across the parallel pair to less than 1 mv. The potential is measured and the resistance is obtained from the circuit equation. A single bearing (SN 7-1115A) was placed in the bearing assembly and subjected to a normal run-in procedure, except that vacuum was used instead of ambient air. After run-in, the bearing was subjected to a variety of tests, including the effect of temperature on film formation and speed on contact resistance.

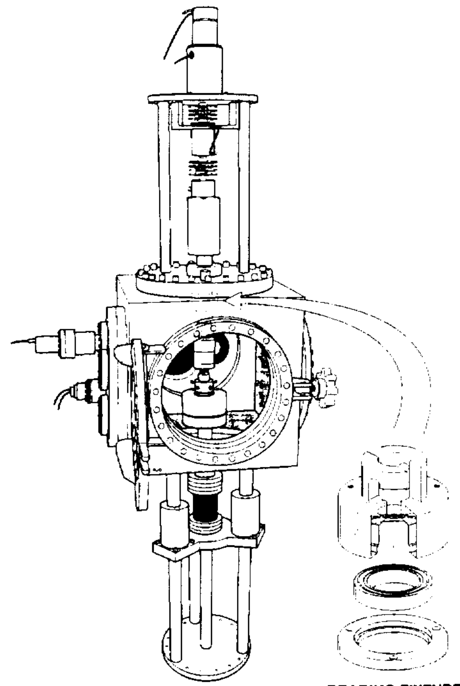

Figure 3 – GOES bearing test rig and bearing fixture

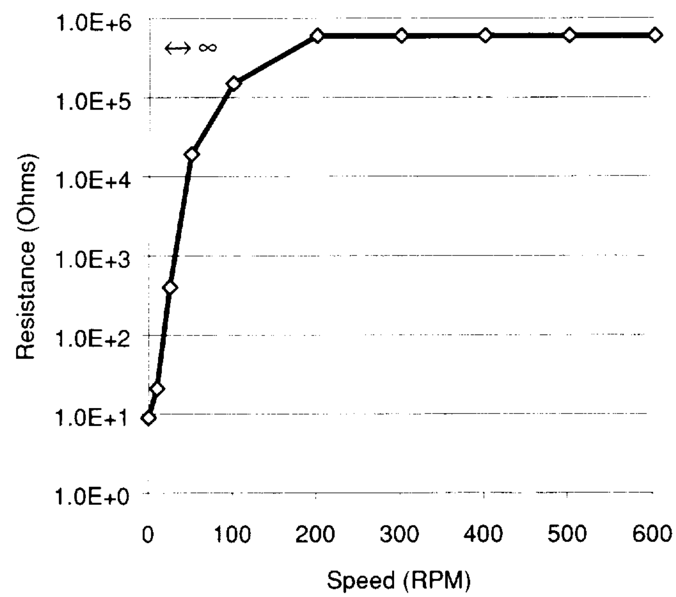

Figure 4 – Resistance as a function of speed using 89 N hard load, vacuum ~1.3×10^{-5} Pa, 23°C

EFFECT OF SPEED

At the end of run-in, a torque trace was performed (0.5 rpm and 27 N (6 lb.) load). This was for comparison with the low speed dynamometer trace made at the FW manufacturer. Sinusoidal traces were obtained both CCW and CW. This is in contrast to the flat traces from the FW manufacturer. It is suspected that this may be due to an alignment problem in the bearing test rig. At any rate, the average torque for the NASA data was approximately 3.2×10^{-3} Nm (0.45 in-oz.) compared to the ITT result of 3.1×10^{-3} Nm (0.43 in-oz.).

Contact resistance as a function of speed using an 89 N (20 lb.) hard load appears in Figure 4. A hard loaded system meant that the bearing was held rigidly, with a load applied through a screw mechanism. A soft load allowed the bearing a degree of freedom and was implemented with a dead weight. The transition between EHL and mixed lubrication occurred between 100 and 200 rpm at room temperature (23°C).

EFFECT OF TEMPERATURE

The effect of temperature on torque and contact resistance was observed at a constant speed of 600 RPM. A thermocouple was spot welded to the bottom of the inner race and an infrared heat lamp was directed on the bearing assembly through the window. The temperature-time trace is shown in Figure 5.

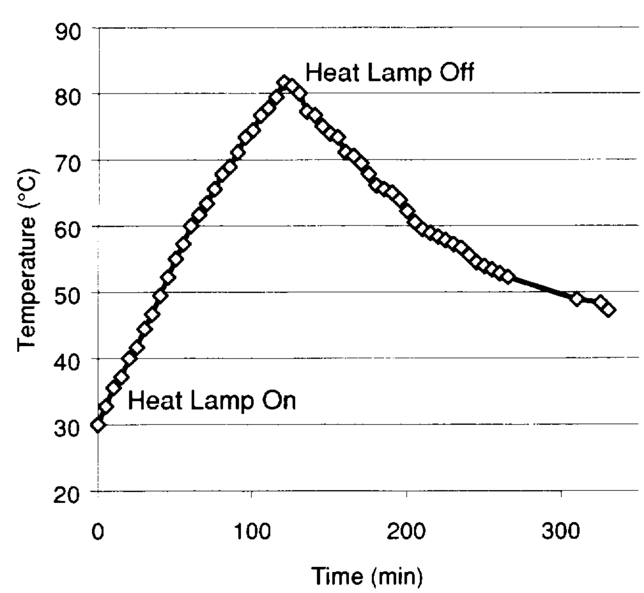

Figure 5 – Heating rate of GOES test facility using heat lamp and 89 N hard load

As can be seen, a heating rate of approximately 0.5°C/min (0.8°F/min) was attained. Torque and resistance as a function of temperature appear in Figures 6a and 6b, respectively. This was the first time this facility was operated above room temperature using a hard load. The hard load is effected by a precision screw mechanism below the test rig [3], which simulates the condition in the filter wheel. The elevated temperatures caused the bearing to unload, reaching 30 N (6.8 lb.) at 82°C (180°F). The transition from EHL to mixed lubrication occurred about 70°C (158°F).

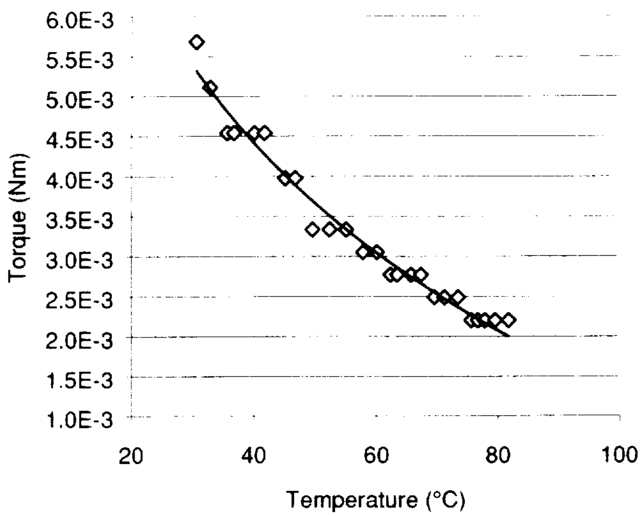

Figure 6(a) – Torque as a function of temperature using an 89 N hard load

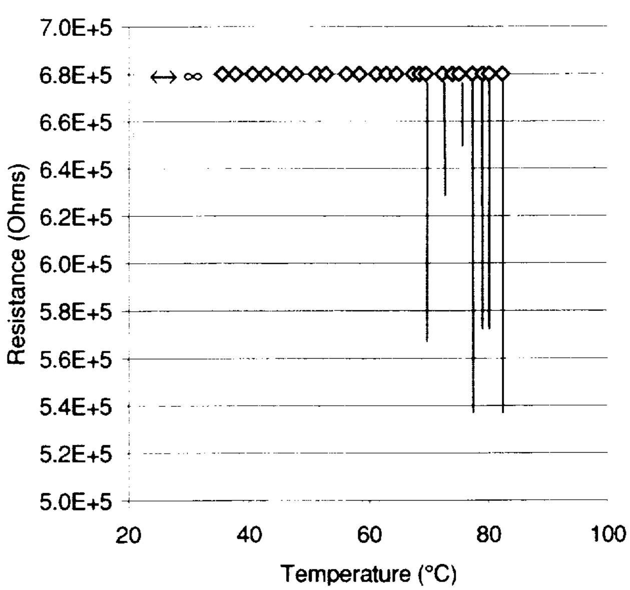

Figure 6(b) – Resistance as a function of temperature for 89 N hard load

A second test was performed on the same bearing using a soft 89 N (20 lb.) load. A soft load is applied by disconnecting the screw mechanism and replacing it with deadweight. This type of loading is not affected by temperature. In this test, an aluminum shroud was placed around the bottom of the test fixture to mask the torque and load sensors from the infrared lamp. The heating rate 0.35°C/min (0.45°F/min) (Figure 7) was neither as efficient nor as linear. Start up torque was lower, 4.6×10^{-3} Nm (0.65 in-oz), but the final value at 85°C (185°F) was 2.6×10^{-3} Nm (0.37 in-oz), which was similar. There was a drop of contact resistance (Figure 8) at 54°C (130°F), but the rapid decrease occurred at approximately 70°C (158°F).

RESULTS

INSPECTION

Inspection of the bearing components at low magnification (10x) showed no unusual features, evidence of surface distress, or other damage. There was no obvious ball banding or tracking. There was a thin, non-uniform layer of oil on the ball surface. The infrared signature of this layer was identical to virgin Krytox 143AB.

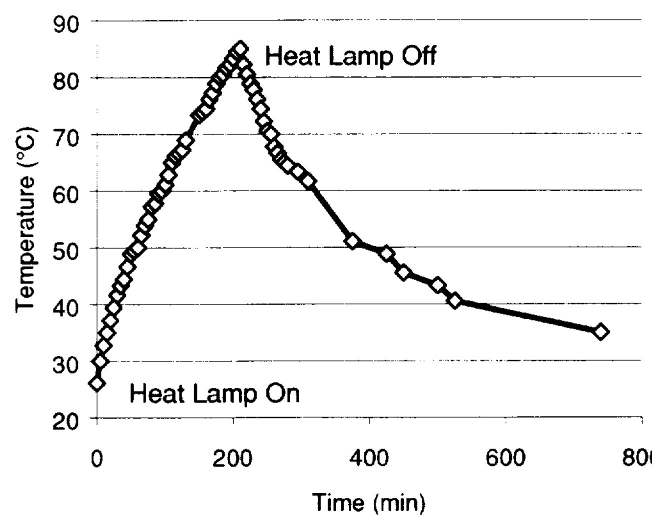

Figure 7 - Heating rate of GOES test facility using heat lamp and 89 N dead weight

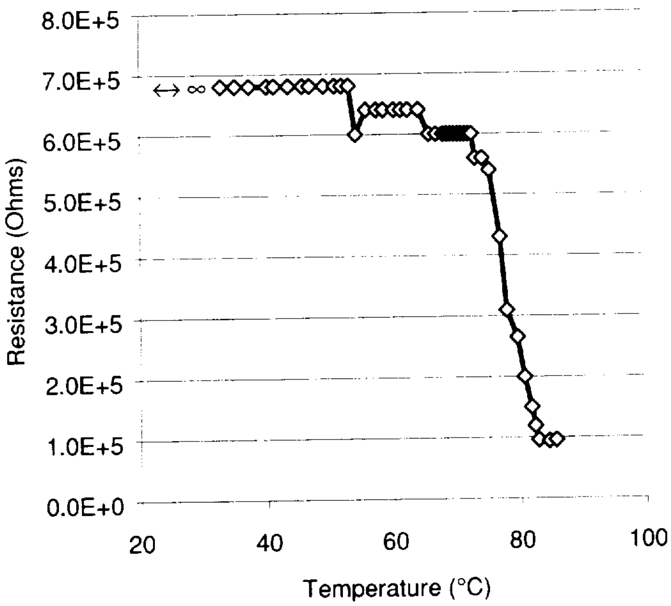

Figure 8 – Resistance as a function of temperature for MPB 1219 bearing using an 89 N dead weight load, CCW Rotation

CONCLUSION

1. Operation of FW bearings (MPB 1219) lubricated with Krytox 143AB, preloaded to 89 N (20 lb.), and operating at 600 RPM and at temperatures less than 70°C (158°F) is not detrimental, since EHL conditions still exist, as indicated by the infinite electrical resistance across the bearing.
2. Transition from EHL to mixed lubrication appears to occur above 70°C (158°F) and will limit bearing lifetime (possibly to months) at 600 RPM.
3. Experimental measurements of the temperature for transition from EHL to mixed, agrees well with theory.

RECOMMENDATIONS

1. An actual GOES-FW assembly should be instrumented and tested in vacuum for motor housing temperatures to 70°C (158°F). Bearing temperatures should be monitored and lubricant loss rates should be determined as a function of temperature.
2. GOES-8 and GOES-J sounder bearings should never be operated above 70°C (158°F).

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1. "GOES I-M DataBook", Loral Space Systems, Ref. #S-415-19, August, 1996.
2. Hamrock, B.J., Dowson, D., Ball Bearing Lubrication. The Elastohydrodynamics of Elliptical Contacts, John Wiley & Sons, Inc., 1981.
3. Jones, W.R., Jr. et al., "The Preliminary Evaluation of Liquid Lubricants for Space Applications by Vacuum Tribometery", 28th Aerospace Mech. Symp., May 18-20, 1994.

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