Grease Lubrication of the High-Speed Ball Bearing for Small Turbomachines

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The feasibility of the operation of a mainshaft ball bearing with grease lubrication at high speed has been demonstrated by rig tests. Angular contact ball bearings of 8 mm bore were used under the 137 N axial load. In order to achieve a good reliability of the grease lubrication at very high speed, the bearings have been subjected to a variety of hostile tests, including the snap accelerations from 0 to 100000 rpm within 10 seconds, extended operation at high axial loading, operation at high speed, and operation exposed to hot air at turbine inlet. From extensive experiments, it was found that the bearings could be operated up to the speed of 0.87 million DN with grease lubrication, and a low-cost grease lubrication system was developed for an expendable small turbomachine.

Key Words: Grease Lubrication, High-Speed, Angular Contact Ball Bearing, Acceleration, Small Turbomachine

1. Introduction

Limited-duty or limited-life small turbomchines are becoming increasingly important in special applications ranging from tactical missile systems to unmanned aircrafts where small turbomachines are needed. Those small turbomachines require a special cooling device for the cooling of the sophisticated electronic devices. Since the unmanned aircraft lose its control when the cooling of the electronic devices fails, the increased emphasis is placed on this type of machine. Interest has also increased in the development of technologies that can simplify such machines and reduce machine weight and cost. Thus, in the development of a limited-life small turbomachine, the lubrication system and its components can be of primary concern when taking these factors into consideration.

Several potential lubrication systems have considered such as a total-loss type oil mist lubrication, a recirculating oil mist lubrication, a grease lubrication system, and a solid lubrication system. The oil systems would provide bearing with adequate lubrication and cooling, however, light weight requirements, sealing requirements during storage, and higher cost eliminated them from further consideration. The solid lubrication systems (both externally supplied and self-contained) were considered too costly to develop for the short design life requirement like several hours. The grease lubrication system offered the greatest potential for payoff with good reliability if this system can overcome the speed due limit to increase of temperature and loss of grease. The speed limitation of grease lubricated bearings is mainly due to the limited capacity of dissipating heat, but it is also affected by the type of bearing and cage. Standard quality (ABEC-1 or 3) ball and cylindrical roller bearings with stamped steel cages are generally limited to 0. 2 to 0. 3 million DN (DN is a speed parameter which is the bore in millimeters multiplied by the speed in rpm). More precision bearings (ABEC-5 or 7) with machined metallic or phenolic cages may be operated as high as 0. 4 to 0. 6 million DN (Parker, 1980). However, the grease lubrication system exclude extra components such as oil pump, filter, and cooler compared to the oil lubrication sys-

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tem. Thus, the lightest weight requirement is satisfied with the grease lubrication system. Furthermore, the incorporation of a grease lubrication system for limited-life small turbomachine has many advantages including enhanced stop-start problem, enhanced squeeze film lubrication due to a grease acts almost as an elastic solid, and enhanced sealing problems in addition to the low cost.

Researches on the grease lubrication had been reported from a long time ago due to the wide use in the industrial applications. They include the mechanism of the grease lubrication (Scarlett, 1967-68) and the measurement of the film thickness (Dyson and Wilson, 1969-70). Furthermore, the development of special greases make it possible for the bearings to operate at high speeds and temperatures.

In this study, the feasibility of the operation of a mainshaft ball bearing was investigated up to the speed of 0. 87 million DN with grease lubrication in order to develop the low-cost grease lubrication system for an expendable small turbomachine. This paper also describes the development history based mainly on rig testing, as well as the system design overcome in designing the grease lubrication system for an expendable small turbomachine.

2. High Speed Bearing Test Apparatus

A high-speed bearing test apparatus was specially devised, and it consists of a rotor bearing assembly, a control and measurement system, and a compressed-air supply system (Fig. 1). It is

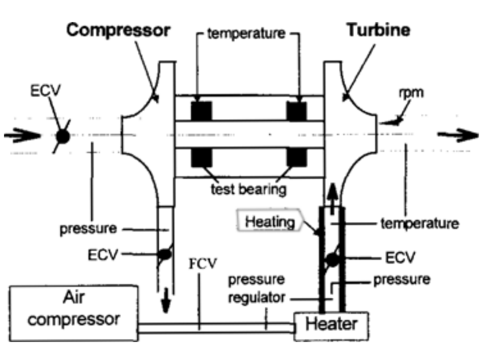

Fig. 1 High speed bearing test apparatus.

noted that the test bearings themselves support the rotor without supporting of slave bearings. The rotor weight was 1.96 N. The rotor including a compressor and a turbine was balanced corresponding to the class of G6.3 with a 0.1 g-mm, which is generally applied to the aerospace gas turbines and high-speed spindles. The test bearings are driven by an air turbine, where heated or unheated compressed air is supplied to the air turbine. The operating speed of bearings can be controlled directly up to above 100000 rpm by varying flowrate, temperature, pressure of air at both inlets of the turbine and the compressor. The air flow is controlled by two electronic control valves (ECV), a flow control valve (FCV) and a pressure regulator. Since the axial load is generated due mainly to the pressure difference between the turbine inlet and compressor side, it is controlled by changing the pressure at the turbine inlet and the compressor outlet. The temperatures of the bearings and the air are monitored at both inlet and outlet of the turbine. Those measured data are saved during testing, and users can simultaneously control operating speeds.

3. Lubricant

A synthesized hydrocarbon-base grease satisfying MIL-G-81322D was used as the lubricating grease, and it is effective over the range from -62 °C to 204°C. This grease has been used in such components as aircraft control systems, sealed

Table 1 Major properties of grease MIL-G-81322D).

Endurance life, 204 bearing, h 10000 rpm @ 177°C	5000
Dropping point @ 204°C	262 1.3
Oil separation, wt loss, % 30 h @ 177°C	5
Evaporation, wt loss, % 22 h @ 177°C	10
Low temperature torque, N-m Starting/Running -54°C	0.6272/0.0735

bearing motors, and helicopter rotor bearings, etc. The major properties of grease are shown in Table 1. In this study, the grease was not replenished to the bearings after grease applied initially.

4. Analysis of Air Flow and Axial Loading

In order to find the axial load on the test bearing, the air flow analysis was performed on the hydraulic network using the design data of the testing machine such as the cycle analysis results, the aerodynamic design data of the compressor and the turbine, the geometrical shape of the engine, etc. The hydraulic network is composed of flow channels and cavities, where the flow channels are flow area accompanied by a pressure drop, and the cavities are flow areas without a pressure change. Since the detailed analysis of the air flow and the calculation are beyond the scope of this paper, they will not be described here in detail. At a typical operating condition shown in Table 2, the calculated axial load on the bearing is the 137 N which is applied to the direction from the compressor to the turbine.

Table 2 Axial load on the bearing at 100000 rpm.

		Pressure	Temp.	Velocity
Operating condition	Compressor inlet	0.1 MPa	28°C	0 m/s
	Compressor outlet	0.15 MPa	89°C	-
	Turbine inlet	0.41 MPa	39°C	-
	Turbine outlet	0.1 MPa	28°C	50 m/s
Calculated axial load. (N)	on Compressor blade			-196
	on Compressor rear cavities			-137
	on Turbine blade			372
	on Turbine rear cavities			-186
	Total axial load			-137

5. Results and Discussion

The general bearing characteristics with grease lubrication were observed with the 40°C supply air at turbine inlet, and then the bearing characteristics with hot air were investigated to apply the grease lubricated bearing system for expendable small turbomachines. The performance of the bearings was investigated by measuring the bearing temperature at the outer ring, the air inlet and outlet temperatures of the turbine, the air pressure at the turbine inlet. The bearing speed was measured at the end face of the rotor with an optical fiber photoelectric switch sensor at turbine outlet. The pre-load on the bearings was 100 N.

5.1 High speed bearing characteristics with grease lubrication

The operating characteristics of the bearing with grease lubrication has been investigated without heating the driving air of 40°C and 0.31 MPa pressure, such as the start-stop capability, the limit operating time without the replenishment of the grease, the pressure equilibrium at the bearing, and the possible maximum speed.

The effect of speed on the bearing temperature with 40°C supply air at turbine inlet is shown in Fig. 2. The bearing temperature increases as the speed increases from 0 rpm to 100000 rpm with a 5000 rpm increment, and both bearing temperatures at the compressor and at the turbine sides increases with the similar rate until 40000 rpm. However, the increasing rate for beyond 40000 rpm differs from that for below 40000 rpm, and the difference in the increase rate becomes higher as the speed increases further. It is noted that the bearing temperature at turbine side is initially higher than that at compressor side until 40000 rpm, but the former is lower than the latter beyond 40000 rpm. This is due to the decrease in the expanded air temperature at the turbine outlet as shown in Fig. 2. Since the expanded air temperature at the turbine outlet decreases after 40000

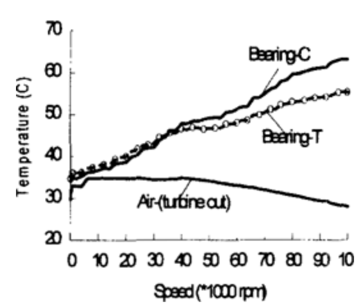

Fig. 2 The effect of speed on the bearing temperature with 40°C driving air at turbine inlet.

rpm, the temperature of the surrounding parts of the turbine decreases, and this woned influence on the decrease in the bearing temperature at the turbine side.

During the 14-hour oiperation without grease replenishment, the turbo-system was stopped at every 2 hours and restarted. The test results are shown in Figs. 3-5 and those figures are typical ones along with the operating time to show the behavior of the bearing temperature for the total operating time. Fig. 3 shows the bearing temperature before 10 hour operation, and Fig. 4 shows it between 10 and 12 hours. Finally, Fig. 5 shows the temperature after 12 hours. Since the test was done at the same conditions for the whole operation, the variation of the bearing temperature shown in Fig. 3 to Fig. 5 shows that the change in the operating characteristics occurs along with the operating time, such as grease starvation, thermal degradation of grease, and breakdown of the lubricant film, etc. .

The bearing temperature was stable until 10 hour running. A typical result is shown in Fig. 3 for a 30 minute period, and the average bearing temperatures were 55°C at the turbine side and 61 °C at the compressor side. It seemed to take several minutes to reach a steady state temperature at constant speed, and this is shown in Fig. 3, but this is not shown in Fig. 4 and 5 due to the sufficient pre-running at testing conditions before measuring the bearing temperatures. After 10 hour running, however, the bearing temperatures were varied as shown in Fig. 4, and it seemed that the bearings were running at unstable conditions compared to those in Fig. 3. The bearings seemed to approach to the failure point, but the bearing temperature returned to the steady state after some variation (Fig. 4). After 10 hour running, the bearing temperatures showed unexpected increases (Fig. 5), and the overall behavior of those was less stable compared to the temperatures before 10 hours.

In order to find the maximum feasible bearing speed of the current system, the bearings were tested at 106300 rpm and at 109000 rpm. Initially the bearing temperatures increased slowly, and

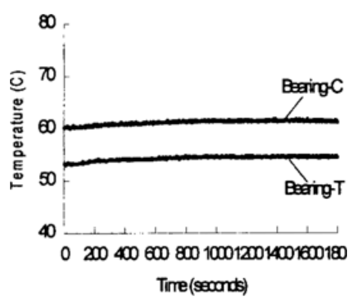

Fig. 3 The bearing temperatures at 100000 rpm before 10 hours operation.

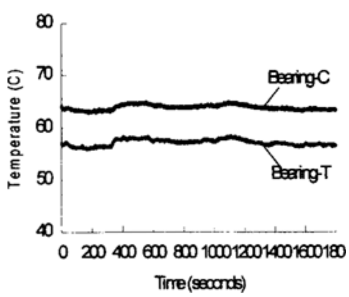

Fig. 4 The bearing temperatures at 100000 rpm after 10 hours operation.

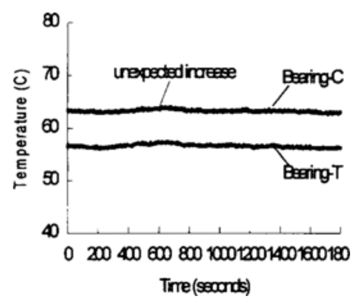

Fig. 5 The variation of the bearing temperatures after 12 hours operation at 100000 rpm.

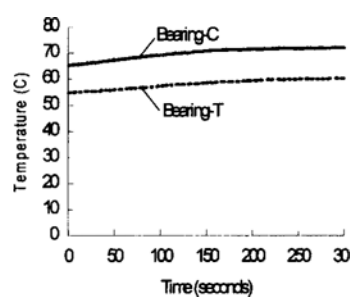

Fig. 6 The bearing temperatures at 106300 rpm for 5 minutes.

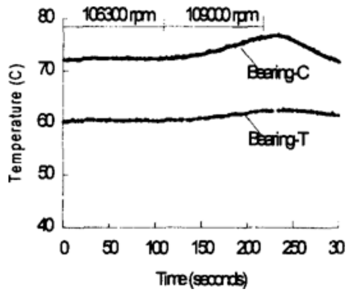

Fig. 7 The bearing temperatures at 106300 rpm and at 109000 rpm.

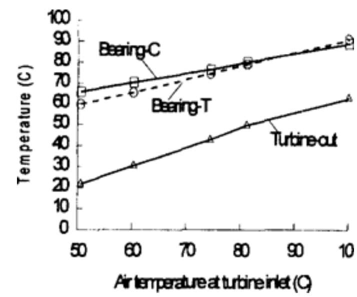

Fig. 8 The effect of hot air at the turbine inlet on the bearing Temperature.

then they approached steady temperatures of 72°C and 60°C, respectively, at compressor and turbine side during 5 minute test at 106300 rpm (Fig. 6). From this result, it is found that the bearing can be operable with the grease lubrication up to 106300 rpm for longer than 5 minutes. As shown in Fig. 7, the bearing temperatures are constant at 106300 rpm, but they increases with a relatively higher rate at 109000 rpm. Thus, the testing was stopped after 50 second run at 109000 rpm due to both the unstable temperatures and the higher rate of the temperature increases (Fig. 7).

The test bearings were inspected visually after 14 hour running, and they were in good condition. However, a small amount of grease was shown between the compressor case and the body. It seemed that the grease escaped from the bearing due to the pressure difference between the front face and the rear face of the bearing. In order to find the reason of the grease leakage, the test without an air filter which causes the greatest pressure difference in the system was carried out, but the result was the same as before. Finally, it was found that the escaping of the grease was due to the sealing problem between the compressor casing and the body of the system. Therefore, it was judged that the pressure equilibrium is important at high-speed bearing with grease lubrication. Thus, it is presumed that the bearing can operate successfully for 14 hours with very small amount of grease at high speed if the internal pressure equilibrium is obtained at the bearing. This assisted further study of the development of the grease lubrication system for the limited-life small turbomachines.

5.2 Bearing characteristics with hot air

Since the expendable small turbomachines are usually operated with hot air supplied from engine bleed air, the bearing characteristics were investigated with hot air ranging from 50°C and 100°C. Problems may occur with hot air driving, because the bearing performance can be affected significantly by heat conduction and convection from the hot air to the bearing when the air temperature at turbine inlet changes.

The air temperature at turbine inlet was varied during the total of 25 minute testing at the constant speed of 100000 rpm, and the measurement was carried out for 5 minutes at each air temperature. As shown in Fig. 8, the bearing temperatures increased linearly with increasing the supply air temperature, and the temperature of turbine-side bearing increased from 60°C to 90°C when the supply air temperature increased from 50°C to 100°C. Since both bearing temperatures were stable during each test point, it was verified that the bearings with grease lubrication can be operable up to the 100°C supply air at the turbine inlet. The air temperature at the turbine outlet was also shown in the figure to describe the result expected at small turbomachines. From this result, it is found that the bearing temperature is strongly affected by the supply air temperature at the turbine inlet, and it is also supposed that a limit temperature exists on the supply air temperature with regard to the safe operating of the bearing.

In addition to the effect of hot air at turbine inlet on the bearing temperature, the operating of the bearing was observed with the constant tem-

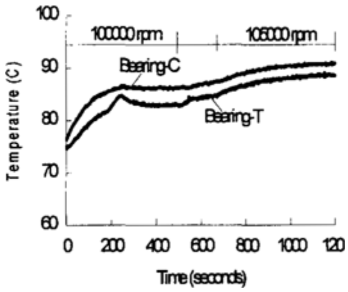

Fig. 9 The bearing temperatures with the 100°C constant supply air at the driving turbine.

perature of 100°C supply air at turbine inlet for 2 hours. The speed was controlled to between 100000 rpm and 105000 rpm during the test, and a typical measurement is shown in Fig. 9 for the beginning period of 20 minutes. It is seen that the bearing temperatures approach to a steady state after an initial increase and they were maintained at steady temperatures of 91°C at the compressor -side bearing and 89°C at the turbine-side bearing during further continuous running. After visual inspection of the test bearings, it was found that the bearings were well lubricated during the test because the grease remained around the bearing.

From the various tests described above, it was shown that the development of the grease lubricated system for high speed bearing is feasible for a limited use without the replenishment of grease. However, the application of the grease lubrication to high speed bearings should be examined carefully before applying it, because the performance of the bearing depends strongly on the design of the system. Furthermore, the applied load on the bearing should also be examined especially for high speeds, because the grease lubricated bearings do not have the cooling capability themselves in general. It is found that the pressure equilibrium at the open type bearing is important in the design of a grease lubrication system for an expendable small turbomachine. If the pressure equilibrium is not maintained at the bearing, it may cause early failure due to the depletion of the grease at high speed.

6. Conclusions

The feasibility of the grease lubrication applied to the high speed angular contact ball bearing was demonstrated based mainly on the temperature of the bearing. The bearings were capable to run safely up to the speed of 0.87 million DN without the replenishment of grease for 10 hours. Through the extensive tests, it is confirmed that the low -cost grease lubricated system can be developed for small expendable turbomachines. The results are summarized as follows :

1. The maximum speed limit was 106300 rpm for the current turbo-system with 40°C supply air to the driving turbine.
2. A limit temperature exists at the supply air at turbine inlet regarding the safe operation of the bearing.
3. Grease lubricated bearing system without shield and seal requires internal pressure equilibrium around the bearing especially at high speeds especially.

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