Empirical correlation of heat generation in hybrid ball bearings, depending on the operational conditions in the aero-engine rotor supports

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Abstract. Modern gas turbine bearings operate at high rotational speeds. Their speed index reaches \(d_an = 3 \ldots 3.5 \times 10^6 \text{ mm} \cdot \text{rpm}\), where \(d_a\) = bearing mean diameter, and \(n\) = rotational speed. At high speeds, significant heat is generated in conventional steel bearings, and substantial cooling oil consumption may be required. A promising solution to this problem is using hybrid bearings with steel rings and ceramic rolling elements. Due to ceramic’s relatively small coefficient of thermal expansion, hybrid bearings retain radial clearance in a wide temperature range. Hybrid ball bearings, with an inner diameter of 130mm and 150mm, were tested in the bearings test rigs at the Central Institute of Aviation Motors (CIAM). From these tests, an empirical method for determining the thermal state of the bearings was developed. The calculated values correspond well with the experimental data presented in the extant literature.

1. Introduction

Angular contact bearings with split inner rings and three possible contact points are used to support high-speed turbofan engines. Under the action of a radial load, such a bearing has three contact points, and, under an axial load, it has two contact points—one with the outer ring and one with the inner ring (Figure 1). This design allows the bearings to take significant axial loads in both directions, while remaining relatively lightweight and capable of operating at high speeds.

However, at high speeds, a great amount of heat builds up in the bearing. Its thermal state affects its radial clearance and how the rings fit on the shaft and in the housing. If the bearing becomes too hot, radial clearance may be lost, and the bearing will operate in thermal expansion mode. On the contrary, strong heating of the outer ring, with a cold inner ring, can greatly increase the bearing’s radial clearance, which adversely affects the distribution of the radial load over the rolling elements. Excessive heating of the inner ring can lead to loss of tightness and fretting corrosion between the ring and the shaft. Therefore, it is an important practical task to determine a bearing’s expected thermal state since the reliability and performance of an aircraft engine depend, to a large extent, on correct consideration of the bearings’ operating conditions. However, previously developed methods for determining heat generation in aircraft bearings [1–9] are of limited use because they are applicable only to steel bearings operating at a speed index below \(2.5 \times 10^6 \text{ mm} \cdot \text{rpm}\).

For high-speed applications, hybrid bearings with steel rings and ceramic rolling elements are attractive. The density of oxide-free ceramics (usually silicon nitride) is 2.5 times lower than that of steel, so the centrifugal forces passing from the ceramic rolling elements to the outer ring raceway will be lower than they are with steel rolling elements. In addition, the size of the ceramic rolling elements

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increases slightly as operating temperature increases due to the low value of the coefficient of thermal expansion. This allows radial bearing clearance to be maintained over a wide temperature range.

Thermal state calculations for hybrid bearings with ceramic rolling elements are presented by Shoda et al. [10], Forster et al. [11], and the Svenska Kullagerfabriken (Swedish Bearing Factory, SKF) catalog [8]. However, the uses of these methods are limited. The empirical method [11] can only be used for bearings with an inner diameter of 133 mm; the SKF method is applicable to rolling bearings operating at low speeds; and the approach presented by Shoda et al. [10] requires a reasonable choice for the friction coefficient value. The friction coefficient value depends on a number of factors (i.e., lubricant type, raceway roughness, oil film thickness, and oil temperature at contact), and it can only be obtained from experimental studies.

This research is a continuation of a previous study concerning the thermal state of high-speed bearings. It presents the results of the development of dependencies for hybrid bearings with ceramic rolling elements, based on the CIAM bearing stand tests. It also communicates the results of developing a method to calculate the thermal state of steel bearings at high speeds [12].

2. Hybrid bearings testing
A precise description of the heat generation and heat transfer processes in bearings cooled by an abundant supply of oil is hampered by the lack of an accurate mathematical model. The solution to this problem is to use empirical methods developed from bearing test results. However, it should be noted that the regularities obtained in this way do not give a complete picture of the processes occurring in the bearing and cannot be used outside the area of experiment planning.

In this research, planning the experimental studies for angular contact bearings consisted of choosing the number of experiments necessary to and sufficient for obtaining empirical dependencies, through which it is possible to determine the bearing’s thermal state under different operating conditions. Analyzing previous theoretical and experimental studies of ball bearings revealed that heat generation depends on rotational speed, axial load, bearing size, oil consumption, and oil kinematic viscosity. These parameters were varied during the present experiments.

To develop empirical relationships, hybrid bearings with inner diameters, \(d\), of 130mm and 150mm were tested. The bearing rings were made of EI347Sh heat-resistant steel, and the rolling elements were made of silicon nitride. The tests were carried out on a bearing stand (Figure 2). The oil consumption values during the tests were \(V = 4\text{l/min}, 5\text{l/min}, 7\text{l/min},\) and \(10\text{l/min}\). The rotational speed, \(n\), was varied from 5,000rpm to 21,200rpm. The axial load, \(F_a\), was also varied from 10kN to 53kN. The required oil viscosity, \(v\), was provided by changing the oil inlet temperature, \(T_{\text{oil,in}}\), from 70°C to 140°C.
3. Developing an empirical method for determining the thermal state of a hybrid bearing with ceramic rolling elements

A search for the regression coefficients of heat generation \( Q \) and the temperatures of the outer (TOR) and inner (TIR) rings was carried out for the following dependencies:

\[
Q = 10^{a_0} \cdot d^{a_1} \cdot n^{a_2} \cdot F_a^{a_3} \cdot V^{a_4} \cdot v^{a_5}
\]

\[\text{TOR} = T_{\text{oil,in}} + 10^{b_0} \cdot d^{b_1} \cdot n^{b_2} \cdot F_a^{b_3} \cdot V^{b_4} \cdot v^{b_5}\]

\[\text{TIR} = T_{\text{oil,in}} + 10^{c_0} \cdot d^{c_1} \cdot n^{c_2} \cdot F_a^{c_3} \cdot V^{c_4} \cdot v^{c_5}\]

where \( a_i, b_i, \) and \( c_i = \) the regression coefficients.

Equations 1–3 are nonlinear. However, they may be brought into a linear form using the logarithm function. Having done this, the values of \( Q, \) TOR, and TIR were represented as linear dependences on independent parameters \( d, n, F_a, V, \) and \( v:\)

from equation 1:

\[
\log_{10}(Q) = \log_{10}(10^{a_0} \cdot d^{a_1} \cdot n^{a_2} \cdot F_a^{a_3} \cdot V^{a_4} \cdot v^{a_5})
\]

\[= a_0 + a_1 \cdot \log_{10} d + a_2 \cdot \log_{10} n + a_3 \cdot \log_{10} F_a + a_4 \cdot \log_{10} V + a_5 \cdot \log_{10} v\]

(5)

from equation 2:

\[
\log_{10}(\text{TOR} - T_{\text{oil,in}}) = \log_{10}(10^{b_0} \cdot d^{b_1} \cdot n^{b_2} \cdot F_a^{b_3} \cdot V^{b_4} \cdot v^{b_5}),
\]

\[= b_0 + b_1 \cdot \log_{10} d + b_2 \cdot \log_{10} n + b_3 \cdot \log_{10} F_a + b_4 \cdot \log_{10} V + b_5 \cdot \log_{10} v,
\]

(6)

from equation 3:

\[
\log_{10}(\text{TIR} - T_{\text{oil,in}}) = \log_{10}(10^{c_0} \cdot d^{c_1} \cdot n^{c_2} \cdot F_a^{c_3} \cdot V^{c_4} \cdot v^{c_5}),
\]

\[= c_0 + c_1 \cdot \log_{10} d + c_2 \cdot \log_{10} n + c_3 \cdot \log_{10} F_a + c_4 \cdot \log_{10} V + c_5 \cdot \log_{10} v.
\]

(7)

During the tests, the TOR and TIR values were measured, as well as the temperature of the oil at the inlet and outlet \( (T_{\text{oil, out}}) \) from the bearing. The amount of heat generation in the bearing, \( Q, \) was defined as the heat removed from the bearing by the oil, excluding heat dissipated to the mating parts and the environment. As shown by Gloeckner et al. [13], such an assumption is acceptable and does not give a significant error:

\[
Q = \frac{C_p \rho V}{60} (T_{\text{oil,out}} - T_{\text{oil,in}}) \cdot 10^{-3},
\]

(10)

where \( C_p = \) oil heat capacity, \( J/(\text{kg} \cdot ^\circ\text{C}), \) and \( \rho = \) oil density.
4. Experimental results

Figure 3 shows the experimental results. Figure 3a) presents the experimental values of heat generation ($Q$) in the bearing, depending on speed index ($d_{mn}$). The recorded $Q$ values ranged from 0.5 kW to 28 kW. Figures 3b) and 3c) show the experimental TOR and TIR values. The TOR varied from 75°C to 238°C, depending on the operating mode, and the TIR varied from 75°C to 200°C.

Experimental data values ($Q$, TOR, and TIR) were processed to obtain the linear regression coefficients $a_i$, $b_i$ and $c_i$—in equations 5–7. After determining the regression coefficients, the $Q$, TOR, and TIR values were calculated via equations 1–3. Figure 4 compares the experimental and calculated values of $Q$, TOR, and TIR. The x-axis shows the experimental values, and the y-axis shows the calculated values. This comparison indicates that the regression coefficients were chosen correctly, and the calculated values correspond to the experimental data.

To check the correctness of the selected regression coefficients for hybrid bearings, $Q$, TOR and TIR were calculated for experimental data in previous literature. A comparison with experimental data presented by Shoda et al. (Japan) [6] is shown in Figure 5, and a comparison with experimental data from Forster et al. (USA) [11] is presented in Figure 6.
The comparison presented in Figures 5 and 6 show that the calculated values of $Q$, TOR, and TIR are consistent with the experimental results.

5. Conclusions

Hybrid bearings with inner diameters of 130mm and 150mm have been tested. Based on the results of experimental data processing, empirical formulas have been developed to determine heat generation ($Q$) and the temperatures of the outer (TOR) and inner (TIR) rings in the hybrid bearings operating at high speeds. The calculated values correspond well with the experimental data presented in the extant literature.

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