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Damage evolution and contact surfaces analysis of high-loaded oscillating hybrid bearings

Ilaria Ghezzi[a,b,*], Eymard W. Houara Komba[a], Davide Tonazzi[b], Nathalie Bouscharain[a], Gwenole Le Jeune[c], Jean-Baptiste Coudert[c], Francesco Massi[a]

[a] University of Lyon, INSA-Lyon, LaMCoS, UMR5259, F-69621 Villeurbanne, France
[b] University of Rome 'La Sapienza', Department of Mechanical and Aerospace Engineering, via Eudossiana 18, 00184 Rome, Italy
[c] SKF Aerospace, 29 chemin de Thabor CS90114, 26904, Cedex 9, Valence, France

ABSTRACT

High-loaded oscillating bearings are used in industrial applications such as actuators, wind turbines, aircraft, robots, and assembly line equipment. These bearings are subjected to extremely high local contact pressures with relatively low oscillation speeds. This work deals with the role of the materials chosen for the rolling elements of such bearings, with a particular focus on silicon nitride (ceramic) balls in hybrid bearings. The degradation processes for high-loaded oscillating hybrid bearings are analyzed step-by-step, highlighting in particular the nucleation and evolution of damage on the most loaded balls and on the inner ring raceway. A comparison with the wear processes in steel-on-steel bearings is also provided.

1. Introduction

Rolling bearings are commonly used as machine elements, interposed between machine parts in mutual rotation. They are employed to permit the rotary motion of shafts both in simple commercial devices and in complex engineering mechanisms such as wind turbines, aircraft, gyroscopes and power transmissions [1,2]. The boundary conditions investigated in this work are high load and oscillating motion, typical conditions in aeronautical, naval and aerospace applications [3]. Their application is required whenever position control and alternating motion must be performed under loading conditions. Due to transient kinematics and system inertia, oscillating bearings usually operate at a low relative speed, on the order of mm/s [4,5]. For this reason, this type of bearing is generally lubricated with grease [6–8].

However, the reduced size of the contact pairs, together with the applied high loads, gives rise to high contact pressures, of the order of several GPa, on a small contact zone [5,9]. The combination of high load and oscillatory motion can be considered as specific and extreme working conditions. Some works in the literature [10–14] propose different models to describe damage evolution and scenarios in a general approach.

Considering that such working conditions can lead to the degradation of steel rolling elements through plastic fatigue damage [2,5,8,9,15,16], this work investigates the possibility of using hybrid bearings for such applications. High quality silicon nitride ceramics have excellent high temperature strength, low density, and exceptional wear resistance due to their low friction [17–19]. The combination of these properties makes silicon nitride an attractive material for the rolling elements of bearings. Despite the fact that these bearings have been used in many applications, few works in the literature [20–24] have addressed the study of hybrid bearing damage under high-load conditions and oscillatory motion. Nonetheless, for both economic and safety reasons, there is a real industrial interest in understanding how hybrid bearings operate in such contexts and under such extreme conditions.

The goal of this work is to reproduce and experimentally investigate the damage scenario of an oscillating greased hybrid bearing under a high radial load. First, following the procedures already validated in previous works [5], tests are performed to reproduce the bearing life under the imposed loading and motion conditions. The tests are interrupted at different phases of the bearing's lifetime and surface analyses are presented to highlight the contact surface evolution of the bearing components through to the bearing's end-of-life. Finally, a comparison with a steel-steel bearing is presented.

2. Reproduction of the degradation scenario

2.1. Materials and methods

The bearings used for the experimental tests are deep-groove ball

* Corresponding author.
E-mail address: ilaria.ghezzi@insa-lyon.fr (I. Ghezzi).

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Table 1
Material properties of ceramic Si3N4 (rolling element) and steel 100Cr6 (bearing rings).

Mechanical properties	Ceramic Si3N4	Steel 100Cr6
Density [g/cm^3]	3.2	7.9
Hardness	1600 HV10	700 HV10
Modulus of elasticity [kN/mm^2]	310	210
Thermal expansion [10^{-6}/K]	3	12
Electrical resistivity [Ωm]	10^{12} (Insulator)	0.4 * 10^{-6} (Conductor)

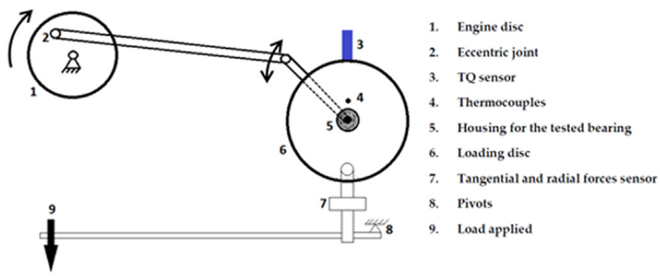

Fig. 1. Diagram of "R2" test bench [5].

bearings with a pitch diameter of 18 mm and a ball diameter of 4.5 mm. The rings are made of 100Cr6 steel and the balls are Si3N4 ceramic (Table 1).

The bearing is greased with commercial synthetic lithium-complex grease, filled 100%.

The experimental tests are performed on a dedicated test bench named "R2" (diagram in Fig. 1).

The test bench makes it possible to apply an oscillating motion to the tested bearing, while also applying an imposed load using dead weights and a lever. Resistant torque and applied load are monitored the endurance tests. The displacement between the inner and outer rings is measured using a proximity sensor, model TQ-401 (Vibro-Meter® Meggitt SA, Fribourg, Switzerland), referred to below as the "TQ sensor". The forces are measured using a bi-axial force transducer (model FX2-2, SIXAXES SA, Argenteuil, France). The acquisition system is a modular recorder (model OR36, OROS Instruments, Grenoble, France). Details regarding the test bench can be found in [5]. For the current investigation, the radial load is maintained at a constant value of 11000 N and applied on the bearing's outer ring. The oscillation amplitude is set to ± 20° and it is applied on the inner ring, while the outer ring is fixed. In order to avoid overheating of the contact, the oscillation frequency is set to ≈ 5 Hz, which corresponds to five complete cycles per second. In order to simplify the interpretation of the surface observations, the imposed oscillation for all of the tests is set to avoid overlapping of the rolling traces. The oscillation amplitude is subsequently chosen to fall within the dither angle and the critical angle [5]. Table 2 summarizes the test parameters.

The signals measured by the sensors are recorded in real time for the entire duration of the endurance test. The relative displacement

Table 2
Materials and applied conditions for tested hybrid bearings.

Bearing Type	Hybrid
Ball Material	Ceramic: Si3N4
Inner/Outer Ring Material	High-carbon steel: 100Cr6
Lubricant	Aeroshell Grease 33
Level of Lubrication	A-side: 100% B-side: grease excess (more than 100%)
Radial Static Load Applied $\|\overrightarrow{F_r}\|$	11000 N
Motion Type	Oscillatory motion
Amplitude of the oscillatory motion	40°
Oscillation Frequency	5 Hz

between the inner and the outer rings (RD), measured by the proximity sensor, and the resistant torque (RT), measured by the force sensor, are the signals analyzed below to obtain the bearing life analysis.

2.2. *Greased hybrid bearing damage evolution*

In this section the evolution of the recorded signals throughout the lifetime of the bearing has been analyzed. Fig. 2 shows the resistant torque and the evolution of the relative displacement between the inner and the outer rings. The red curves on the graphs represent, respectively, the mean value of the relative displacement (RD) and the peak-to-peak amplitude of the oscillation of the resistant torque (RT).

An increase in the value of the RD means that the outer and inner rings are approaching each other along the load direction. The bearing's RT is a periodic signal with a main frequency equal to that of the imposed oscillating motion, 5 Hz. The periodic signal of the RT presents a rectangular shape (Fig. 2-A), while the imposed oscillatory motion has a sinusoidal shape. This is due to the fact that the value of the RT, which changes its sign with the inversion of the rolling direction, remains almost constant relative to the variation of the rolling velocity. The relative displacement between the outer and the inner rings of the bearing along the vertical direction is a also a periodic signal, with the main period equal to that of the imposed oscillating motion (Fig. 2-B). Both the oscillation amplitude of the RT and the mean value of the RD undergo several variations during the bearing's lifetime, so that different phases can be identified (Fig. 3), representing the phases of evolution of the bearing's life [10,13,14,25].

After a first transitory evolution, lasting for approximately the first 1000 cycles, the RD signal begins to gradually increase until reaching 20,000 cycles (Phase I in Fig. 3). After this running-in phase, both the RD and the RT amplitudes remain constant during the steady state phase, from 20,000 cycles to approximately 60,000 cycles (Phase II). This first phase of steady state is interrupted when the amplitude of the RT starts to increase slowly with several fluctuations (Phase III in Fig. 3), ending with the start of the second steady state (Phase IV) at about 110,000 cycles.

The progressive increase of the RT amplitude is followed by a progressive increase of the RD signal (Phase III), i.e. a progressive degradation of the surfaces, which causes the outer and inner rings to draw progressively closer to each other.

After this progressive evolution of the bearing damage, at about 135,000 cycles we find that the distance between the inner and the outer rings is decreasing significantly and the signals start to increase strongly (Phase V), marking the beginning of the bearing's end-of-life. An increase in the RT signal means an increase in the rolling resistance, i.e. a clear sign of damage at the contact interfaces.

A representative set of experimental tests were carried out with the same operating conditions. Although the number of lifetime cycles for each bearing were relatively different from one another, the RT and RD signals always had the same trends, with a second steady state of varying length. Consequently, the results shown in Figs. 2 and 3 can be considered representative of the degradation evolution of an oscillating hybrid bearing subjected to the imposed boundary conditions. In agreement with the literature [5,10], it is possible to trace a reference model that represents the trend of the signals (Fig. 4), identifying the five different phases.

The different phases will be discussed and explained in Section 3, along with the observations of the contact surfaces during the different phases [5].

2.2.1. *Comparison between greased and ungreased bearings*

In order to investigate the role of grease on bearing lifetime, tests were carried out without the addition of lubricant, but with the same oscillatory motion amplitude and load conditions as in the greased case. Like the greased bearings, the ungreased hybrid bearings showed a well-defined and repeatable evolution of the recorded signals.