USE OF CERAMIC AND HYBRID ROLLING BEARINGS IN MODERN TECHNOLOGY AND THEIR COMPARATIVE TESTS

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Abstract: *The analysis of the support units of high-speed rotors with rolling bearings made of steel or ceramic materials is carried out in terms of the possibility of their use for modern and advanced turbines of diesel engines. Hybrid bearings have become widespread in medical equipment, vacuum pumps for various applications, spacecraft, food industry, chemical industry, entertainment and sports, miniature gas turbine engines for aircraft models, electric vehicles, CNC machine tool spindles, the military industry, etc. Possible advantages and shortcomings of ceramic or hybrid (steel and ceramic) rolling bearings and the ambiguity of data on their characteristics given in the literature. The design of an experimental setup for conducting comparative tests of steel and ceramic bearings and a methodology for their implementation have been developed. The setup allows testing of angular contact rolling bearings in the presence of radial and axial loads, external cooling or heating. In the process of testing, control and measurements are carried out: temperature of the outer ring of the bearing; oil temperature at the inlet and outlet of the bearings; air temperature at the inlet and outlet of the unit; rotational resistance moment for a pair of bearings; oil flow through the bearings.*

Key words: *silicon nitride, turbines, engines, tank, compressor, supercharger*

1. INTRODUCTION

The recent trend in engine building to increase power due to the use of engine turbo-charging leads to a decrease in the dimensions of parts and an increase in speeds at which rotor parts have to work including bearings. The reliability of an engine de-pends to a large extent on the reliability of the bearings, so the reliability of the bearing plays an important role in the performance of the turbine and the entire engine. In the turbine engines of the last decade, the bearings have to operate at their maximum speeds. At such high levels of the speed parameter, it is necessary to resort to various kinds of design solutions (Heshmat, et. all, 2018) to ensure a high level of durability and stability of the rolling bearings. In the practice of designing such stressed bearings in mechanical engineering, they went in two ways: the improvement of conventional rolling bearings and the replacement of rolling bearings with plain bearings with gas, liquid and less often magnetic working environment.

The use of plain bearings (Nazin, Determining…, 2021) in turbine rotors (Nazin, Revealing…, 2021), diesel engine turbines has become widespread. However, their use has a number of negative effects:

1) high frequency of stops and starts of the engine, which reduces the reliability of the support as a whole due to the instability of bearings in transition periods;
2) the relative complexity of the nodes of the sliding supports and the system for supplying the working environment;
3) greater sensitivity of the support to changes in the supply of the working environment, which leads to the complication of the supply system;
4) each plain bearing is unique in its characteristics and therefore requires an individual approach to tuning and maintenance;
5) the production of plain bearings requires special high-precision production facilities (Gnytko, et. all, 2022, 2023), while the creation of rolling bearings is carried out at existing specialized mass enterprises.

In connection with the foregoing rolling bearings and seals (Kolomoets, et. all, 2012) still prevail in structures, for example, aircraft engines, etc. Rolling bearings are also used as supports for the tank supercharger and compressor. Rolling bearings are widely used in medical instrumentation (He, et. all, 2021). There are a large number of works on the development of the use of rolling bearings in the design of spindle assemblies of CNC machines in terms of vibration (Miao, et. all, 2021), thermal analysis (Krstić, et. all, 2018), wear characteristics (Pham, et. all, 2022), other.

As a result of an increase in the speed parameter and loads on bearings, a number of works have been carried out to improve their characteristics:

- specialized bearing materials have been developed and improved (Quaranta, et. all, 2022);
- accuracy of manufacturing of the parts (accuracy and cleanliness of surfaces) was increased;
- various nanostructures: a single-crystalline metal oxide nanostructures (Guo, et. all, 2019), 1D metal oxide nanostructures (Baranov, et. all, 2021), copper oxide nanowires (Baranov, et. all, 2019), (Breus, Anodic..., et. all, 2022) are considered as perspective means to reduce friction in contact with other parts;
- surface treatment: TiN coatings (Baranov, et. all, 2013), carbon nanostructure (Breus, et. all, 2021), (Breus, Catalytic..., et. all, 2022), coating grows (Baranov, et. all, 2012) methods have been developed and can be applied to increase their wear resistance;
- special forms of rolling tracks have been developed to increase the bearing capacity of bearings and reduce friction losses during rolling;
- methods have been developed to reduce the mass of rolling elements;
- means and methods of cooling and lubricating (Piet, et. all, 2022) bearings are being improved, which includes the use of new materials for lubrication (Sun, et. all, 2022);
- accuracy of calculations of bearing characteristics by taking into account a larger number of factors that affect them was increased (Wu, et. all, 2022).

The use of ceramic materials for rolling bearings has become one of the possible ways to improve the performance of bearings.

The widest spread are the so-called hybrid bearings, in which the rings are made of conventional bearing steels, and the rolling elements are made of ceramics. The use of bearings with ceramic rings is limited by the complexity of finishing ceramic rings and the complexity of mounting the bearing on the shaft, as well as the rather low impact strength of ceramics. Ceramic materials have the following features compared to steel:

• low density (~60% less);
• high modulus of elasticity (more by ~50%);
• chemical inertness in more aggressive environments;
• coefficient of dry friction in ceramic-steel pair is less than in steel-steel pair;
• lower coefficient of thermal expansion and high heat capacity and heat resistance;
• ceramics - dielectric;
• low impact strength.

These features provide a number of advantages of ceramics over steel when used as materials for rolling elements of bearings:

• reduction of centrifugal forces;
• reduction of power losses due to friction;
• increase in the service life of the lubricant and rolling elements in aggressive environments;
• reduction of preload in the bearing (up to 33%);
• complete electrical isolation of the inner ring from the outer one;
• reduction of radial clearance in the bearing;
• reduction of operating temperatures of the bearing;
• reduction of vibration and noise of the bearing;
• the possibility of long-term operation in the absence of lubrication.

The first experience with bearings with silicon nitride balls has been known since 1975. However, works in this area, judging by the content and the attached discussion, do not provide unambiguous answers to a number of important questions. These works confirm the possibility of reducing the preload up to 30%, however, they differ in the results of studies regarding friction losses. It is indicated that the fatigue life of hybrid bearings does not show any special advantages over conventional steel bearings when operating up to dn = 3•106. However, further work led by Ervin V. Zaretsky on bearing life prediction led to the fact that the idea of revising the theory of life calculation based on the Lundberg-Palmgren equation was proposed, and the opinion that all-metal bearings under the same operating conditions have a longer service life than hybrid bearings, but there is no experimental confirmation of this opinion.

Experimentation with ceramic rolling elements for aerospace bearings began decades ago when NASA's space shuttle engines used them in the early 1990s.

In 2005 Timken was awarded two contracts under VAATE's gas turbine engine optimization program to develop hybrid bearings for an aircraft gas turbine engine.
Recently Timken engineers have worked closely with defense aircraft manufacturers to develop hybrid roller bearings for several applications, including aircraft gas turbine engine development. Timken intends to begin full-scale production to support aerospace customers by 2023.
Electric vehicle component manufacturers, including SKF, are tackling the issue of future-proofing hybrid bearings by improving their performance, efficiency and reliability.
Hybrid bearings provide efficient operation under conditions of improper lubrication and contamination, but the reasons for this and their effect on performance are still not fully investigated. According to the results of SKF's research only the steel component is subject to moderate wear in a hybrid bearing, while the ceramic part is practically unaffected. Under conditions of contamination, moderate wear, plastic deformation and maintenance of surface smoothness at the edges of dents in hybrid bearings contribute to the reduction of local stresses. It is shown that the increase in the service life of hybrid bearings with dents occurs due to high resistance to surface destruction and damage associated with extreme lubrication conditions and the lubricating film integrity failure.
From the above, we can conclude that hybrid bearings are widely used in various industries.

2. METHODS

Of all ceramics, silicon nitride (Si3N4) is the most widespread (Li, et. all, 2022). Properties of silicon nitride in comparison with bearing steel are given in Table 1.

Table 1: Properties of bearing materials

Material	Modulus of elasticity ($\times 10^6$ PSI)	Density (Lbs/in^3)	Poisson's ratio	Coefficient of linear thermal expansion (µin/inch/°F)	Hardness (HRC)	Limit operating temperature (ºF)
Steel AISI 440C (M&I)*	30	0,28	0,28	5,7	60 – 63	300
Steel AISI 440C (S&T)*	30	0,28	0,28	5,7	56 – 60	600
Ceramic	46	0,1156	0,26	1,7	78	2000
Steel AISI M50	30	0,288	0,29	6,6	61 – 64	650
Steel SAE 52100 (M&I)	30	0,28	0,29	6,7	62 – 65	350
Steel SAE52100 (S&T)	30	0,28	0,29	6,7	58,5 – 65	390

*Barden designations: M&I - Miniature & Instrument - miniature bearings and bearings for measuring instruments (d=4…35 mm); S&T - Spindle & Turbine - bearings for machine tool spindles and turbomachines (d=22…290 mm).

The properties of balls made from various ceramic materials are given in Table 2.

Table 2: Properties of balls made from various ceramic materials

Material	Rockwell hardness at 294 K	Limiting temperature of bearing use*, K	Density, g/cm3	Modulus of elasticity at 294 K, 109 N/m2	Poisson's ratio	Thermal conductivity, W/(m·K)		Thermal expansion coefficient at 273…1073 K, 10^{-6} m/K	Weibull module**
						at 294 K	at 1073 K		
Crystalline glass ceramics	53	> 644	2.5	87	0.25	1.6	2.0 at 873 K	0.4	3.3
Alumina	85	~ 1367	3.9	350	0.25	7.2	1.7	8.5	2.7
Silicon carbide	90	< 1367	3.2	410	0.25	35	12	5	2.1
Titanium carbide with nickel-based binder	67	< 867	6.3	390	0.23	14	6.8	10.7	1.4
Silicon nitride	78	1367	3.11… 3.24	310	0.26	7.3	4.7	2.9	1.7

* From the condition of maintaining hardness and experimental data
** From experiments to determine the fatigue of rolling elements

The lack of specific recommendations on the use of hybrid bearings and the calculation of support units with them in the available domestic and foreign literature prompted us, together with the experimental design company, to prepare comparative tests of traditional aircraft bearings and their counterparts with ceramic rolling elements. The interest of experimental design company is due to the fact that the enterprise has a need to increase the resource of the auxiliary power installation. One of the areas of work to increase the resource was to consider the possibility of replacing a serial bearing with its hybrid counterpart. This led to the choice of bearing sizes for testing. The main parameters and operating conditions of the auxiliary power unit bearing are shown in Figure 1.

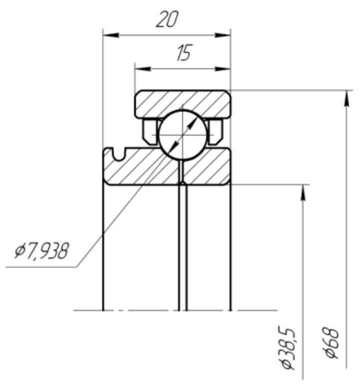

Figure 1: Parameters and operating conditions of the bearing. Working conditions: working speed 40000 - 55000 rpm; load on one bearing: radial - 38 kgf, axial - 200 kgf; operating temperature of the bearing 250 ºC

To test the bearing, a test complex was developed, the basic design of the block of tested bearings of which is shown in Figure 2.

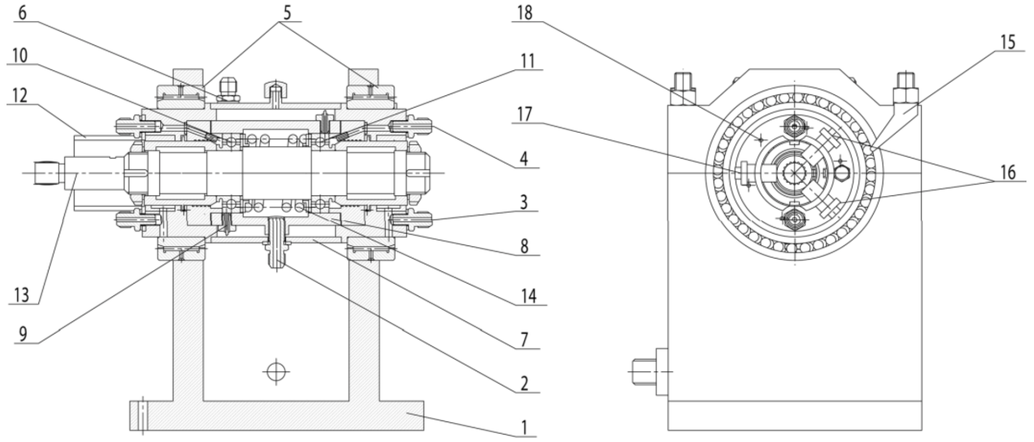

Figure 2: Block of tested bearings:1 - bearing block housing; 2 - oil outlet; 3 - air supply to create a radial force; 4 - oil supply; 5 - thrust bearings; 6 – fitting for air supply for bearing heating; 7 - heating casing; 8 - bearing housing; 9 - thermocouple; 10, 11 - tested bearings; 12 – body of sensors; 13 - shaft; 14 - spring; 15 - retainer; 16 – rotor oscillation sensors; 17 – speed measurement sensor

The axial load on the bearings is created using a compression spring 14, which allows us to lock the load inside the system and evenly distribute it between the bearings, the load remains unchanged within acceptable limits and does not depend on external energy sources. The loading limits are limited only by the design of the spring. However, in this case, the ability to purposefully change the load during testing is lost. If necessary, such a loading system with minimal changes in the design can be replaced by a system with external loading using a pneumatic or hydraulic cylinder. Load control is carried out according to the degree of compression of the spring. The radial load is created using a kind of pneumostatic bearing. Load

control is carried out by air pressure in the system. The maximum created load on one bearing is 588,6 N (60 kg), with an air pressure in the system of 0,49 MPa (5,85 kgf/cm2).
Lubrication is carried out with the help of a jet of oil supplied through jets separately to each bearing (supply is carried out into the gap between the separator and the inner ring of the bearing). Oil outlet from bearings - common through fitting.
Lubrication system - closed, circulating, separate for the tested bearings and multi-plier bearings. The oil temperature is controlled by thermocouples at the inlet to the bearings and at the outlet of the bearing block housing. There is no forced oil heating. The oil is cleaned with a 10 μm filter. The bearings were lubricated with Turbonicoil 210A or IPM-10 synthetic hydrocarbon grease.
The bearing housing 8 is blown by air entering through the fitting 6. The supplied air allows additional cooling or heating of the bearings. It is possible to control the heat flow from the bearings through the bearing block housing by the temperature difference between the incoming and outgoing air. Temperature control is carried out by thermocouples. The air blowing system of the bearing housing is independent of the radial load system.
The temperature of the outer rings of the bearings is controlled by thermocouples 11.
The speed control of the shaft of the installation is carried out using an inductive sensor 17. Two additional inductive sensors 16 allow you to record the vibrations of the shaft.
The block of tested bearings is installed in the housing 1 roller bearings 5, which allows you to directly measure the moment of resistance in a pair of bearings under study. Clamps 15 prevent axial movement of the outer rings of the bearings.
The drive of the block of tested bearings is carried out from the electric motor 1 through the multiplier 2 (Figure 3). Achievable speed - up to 40,000 rpm.

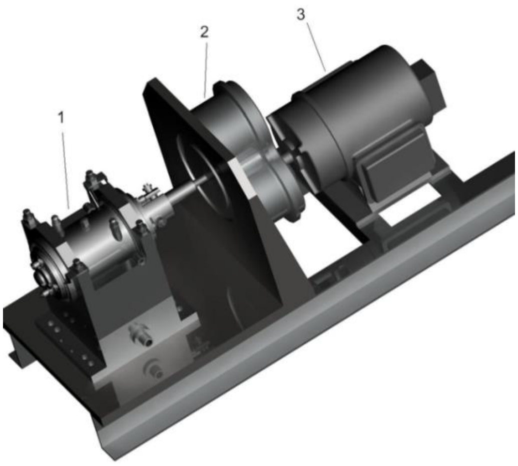

Figure 3: Bearing test facility: 1 - block of tested bearings; 2 - multiplier; 3 - electric motor

3. RESULTS

Thus, the developed setup allows testing of angular contact rolling bearings in the presence of radial and axial loads, external cooling or heating.
In the process of testing, control and measurements are carried out (Dotsenko, et. all, 2023):

- temperature of the outer ring of the bearing;
- oil temperature at the inlet and outlet of the bearings;
- air temperature at the inlet and outlet of the unit;
- rotational resistance moment for a pair of bearings;
- oil flow through the bearings.

Carrying out comparative tests of hybrid bearings and conventional serial aircraft bearings with metal balls provides for the solution of the following tasks:

- determination of heat dissipation in bearings under the same operating conditions (load, lubrication, ambient temperature) by determining the temperature of the outer rings of bearings;
- determination of the degree of wear of bearings under the same operating conditions for a period equal to the designated service life for a serial aircraft bearing;

• determination of friction losses by determining the moment of resistance, heat removal to the oil and through the housing to the blowing air when testing a pair of hybrid bearings and a pair of conventional bearings;

• determination of optimal lubrication conditions that ensure minimum friction losses and optimal cooling of hybrid bearings;

• creation of recommendations on the expediency of using hybrid bearings;

• creation of recommendations for the use of hybrid bearings, namely: methods for determining the optimal lubricant consumption, the optimal radial clearance of the bearing (based on thermal conditions and taking into account the special physical and mechanical properties of the bearing materials).

4. CONCLUSIONS

In the paper, the analysis of the support units of high-speed rotors with plain and rolling bearings made of steel and ceramic materials was carried out in terms of the possibility of their use for modern and advanced turbines of diesel engines. Possible advantages and disadvantages of ceramic or hybrid (steel and ceramic) rolling bearings and the ambiguity of the literature data on their characteristics are noted. Design of an experimental setup for conducting comparative tests of steel and ceramic bearings and a methodology for their implementation have been developed. The developed setup will be used to study the performance characteristics of bearings with ceramic rolling elements for diesel engine turbines.

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