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Implementation of High Strength Composite Ceramic Materials for Producing Tribotechnical Parts of Gas Turbine Engines as Constructional Nano-Structured Materials

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Abstract:

Failure of bearing support in jet engines and their diagnostics. Results of experimental research of the bearings are presented.

1. Introduction

Currently the durability of the bearings in serial jet engines has come to its “ceiling”. It does not allow designers use existing bearing supports of rotors in advanced engines.

Design solutions for the future engines require the supports with increased loading and minimum lubricant consumption in comparison with existing ones.

There are two ways to settle the problem – to upgrade quality of the rolling bearings or to use the other type of bearing.

The activities on rolling bearings improvement have different trends and ever since have found no actual results in considerable increase of their workability.

Hybrid rolling bearings made of ceramic materials are considered. The carried out experiments show the pressure stress increase on contacting surfaces i.e. with material hardness increase the contact patch square shrinks and the loading on the bearing parts stays the same. The other negative moment is connected with the ceramic coating life reduction and their shelling from the metal contact path during long operation. Softer substrate under coating and hard surface ceramic layer experience considerable bending alternating-sign stresses which change its maximum values for each surface element. As a result the life of bearing increases by some percent, and its cost increases in order.

Completely manufactured ceramic bearings are expensive because of high specs requirements to the geometry which in turn significantly increases technological complexity. Such bearings are apt at duplicating the drawbacks of the conventional rolling bearings like slippage.

The magnetic bearings does not incorporate the majority of shortcomings typical to rolling bearings as the magnetic suspension completely exclude mechanical contact between bearing parts, and the air environment has a negligible drag caused by viscosity of the turbulent air streams. But with high vibrations in gas turbine engine there are no guarantees that the part contact will not occur, that consequently leads to extensive wearing.

Gas bearings are made operational due to pressure difference of the supplied gas to the surfaces, but because of high inertness of the control system also does not exclude mechanical contact between parts for the high vibration engine modes.

As an alternative to the rolling bearings, sliding bearings may be implemented. Sliding bearings appeared prior to rolling bearings but were rarely used because of higher sliding friction coefficient versus rolling and higher losses of mechanical power consequently increasing with bearing speed which in turn cause considerable wearing increase and lose in life cycle.

2. Ceramic materials of new generation – the basis for development of tribo-technical parts

For the time being new Russian ceramic materials appeared which allow to gain considerable decrease of the friction coefficient and acquire losses close to that of the rolling ones. Thus, sliding bearings provide better results in terms of the efficiency of the bearing supports and gas turbine engine as a general mechanism in a wide range of rotation speed.

Comparing parameters which characterize material properties traditionally used for sliding bearings (iron, babbit, capron, teflon and etc.) and new generation ceramic, it is worth while mentioning that the latter has higher hardness and coefficient of thermal conductivity,, lesser weight, coefficient of thermal expansion close to steel value and what is most important – lower friction coefficient. (Table 1).

Table 1

#	Parameter	Composites on silicon carbide basis	Composites on titanium carbon nitride basis	Composites on titanium boride basis
1	Linear expansion factor	2,4 – 3,6 x 10^{-6}	12 x 10^{-6}	15 x 10^{-6}
2	Friction coefficient	0,01 – 0,3	0,07 – 0,2	0,05 – 0,19
3	Density g/cm^3	2,9 – 3,1	5,5 – 6,0	5 – 5,5
4	Elasticity modulus, ГПа	350 - 400	490	480
5	Hardness (HRa)	88 - 94	90 - 92	89 - 92
6	Bending strength, МПа	300	1500	1000
7	Thermal conductivity factor, W/m K^0.	140 - 200	20 - 40	65 - 75
8	Operation temperature range	- 50 - +1050	- 50 - +1250	- 50 - +1100

Varying the original ingredients content and consequently the properties of the produced ceramic materials it is possible not only to have ceramic sliding bearings in gas turbine operational environment but also improve characteristics versus metal and hybrid rolling bearings.

Specifically ceramic bearings has wider thermal operational range (limited by the properties of the lubricating materials), vibration stability, chemical resistance to different aggressive environment, noiseless in operation, workability in shortage of lubricant or its absence. The process of bearing failure comes gradually and therefore can be forecasted at the beginning of its fracture propagation.

3. The designed types of sliding bearings

To estimate the implementation of the new generation ceramic bearings in the gas turbine engine rotor support Lyulka Design Bureau designed and tested some configuration designs of different ceramic materials used as a friction couple.

Before starting the design work on bearing configuration the rigidity and buffer properties were analyzed.

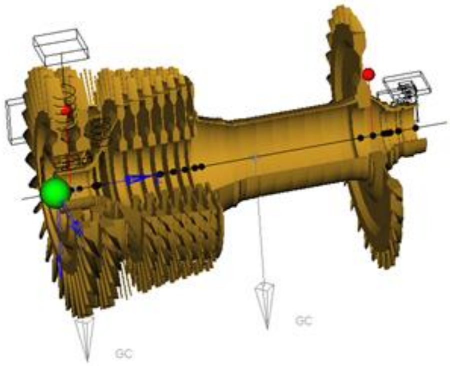

Fig. 3.1. Designed model

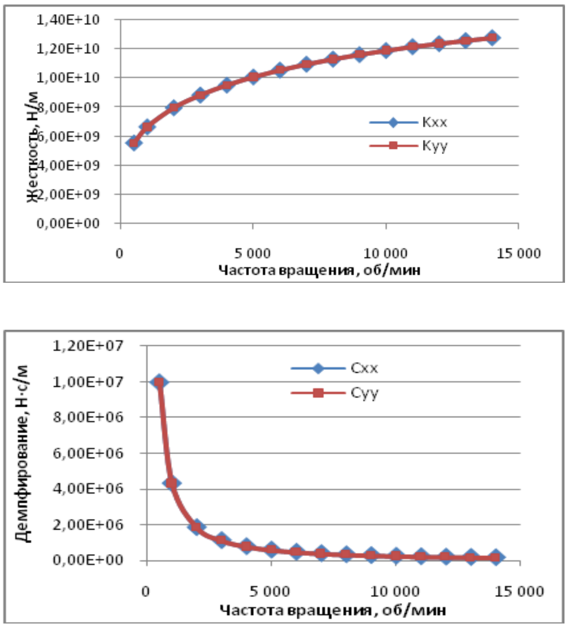

Fig. 3.2. The obtained results

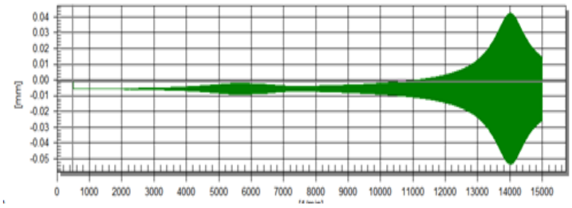

Fig. 3.3. Vibration shift in high pressure turbine support with the rolling bearings

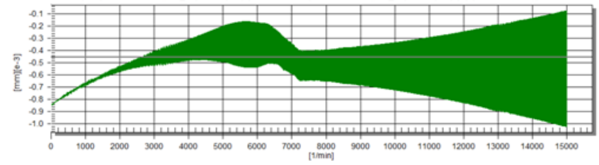

Fig. 3.4. Vibration shift in high pressure turbine support with sliding bearings.
(Working clearance 0.02 mm)

Thus, the workability of the designed bearing within the operational rotor speed was confirmed.

One of the designs, “smooth” hydrodynamic sliding bearing, has some options. The studies were done with the speed ~ 40 m/sec, corresponding to operation of the actual roller bearing support in the aviation gas turbine engine. The pictures of the outer and inner rings are presented on Fig. 3.5 and 3.6.

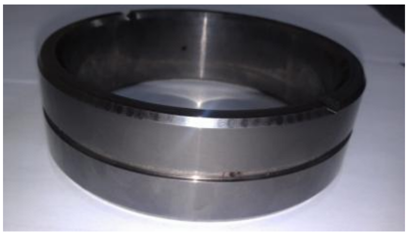

Fig. 3.5. Inner bearing ring

Fig. 3.6. Outer bearing ring

Segmental sliding bearing

The studies of the segmental sliding bearing were done with ~ 120 m/sec speed.

In its configuration the bearing differs from the traditional segmental sliding bearing:

1) The boring of the bearing brass coincides with the rotor shaft radius – as a result, the liquid friction starts with the shaft rotation because the full pressure diagram is realized in hydro wedge. The operation scheme and pressure distribution at start-up for different bearing types are shown on Fig. 3,7.

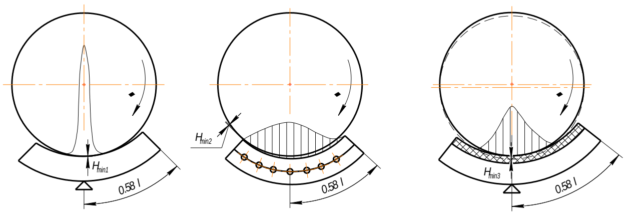

Fig. 3.7. Pressure distribution at start-up:
- with axial segmental boring (traditional);
- with segmental boring by shaft radius;
- elastic-hydrodynamic bearing

2) elastic-hydraulic operation clearance take-up.

The forced loading of all bearing brasses which is realized through the forced clearance take-up by the elastic-hydraulic segment ram effect is the remedy to exclude the possibility of the "shoe flutter" which is inevitable for boring by the shaft radius.

Due to configuration peculiarities the designed ceramic segmental sliding bearing possesses the features and possibilities which conventional hydrodynamic sliding bearings are deprived of, including operation on the oil hunger mode. In the designed bearing in case of shortage of oil supply in the operational clearance between bearing brass and the shaft, the characteristic pressure distribution is realized with vacuum in the front of the bearing brass where the oil-distributing groove is located. Such distribution is definitely realized because it is the condition of ensuring stable balance of the bearing brass within hydrodynamic forces. Such bearing can operate up to certain circumferential values even without forced oil supply into the oil groove due to unique mechanical properties of the new ceramic materials.

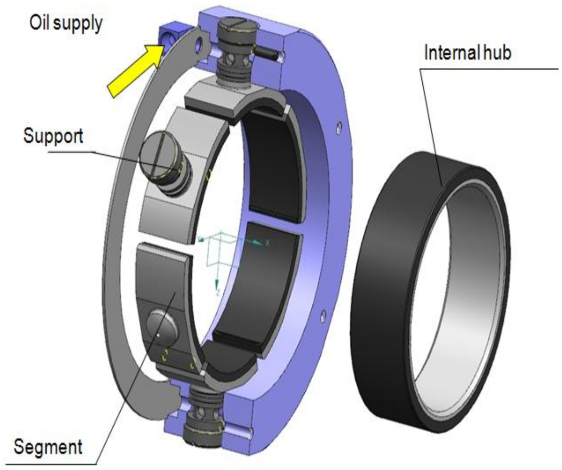

Fig. 3.8. The scheme of the developed segmental sliding bearing

Thus, the sliding bearings versus roliing bearing has high stability to dynamic and vibration loading, configuration simplicity, low noise, optimized diagnostic procedures of their technical conditions; with all that said make them competitive in the gas turbine engines.

But the sliding bearings have shortcomings which should be considered when taking decision on their implementation, it is a trade-off:

- Strict requirements to the non-alignment of the bearing parts axes;
- Shortage of analyses of their behavior regarding auto vibrations on some engine and bearing operation modes;
- Relatively bigger axial dimensions.

4. The order of experiments

The main studies were carried out on the CIAM test rig. To obtain and analyze sliding bearing properties additional temperature sensors were installed on the inner surface of the inner hub and at the inlet and exit of the experimental rig to measure oil temperature.Test rig vibration conditions were monitored during experiment.

General view of the experimental test rig is shown on fig.4.1

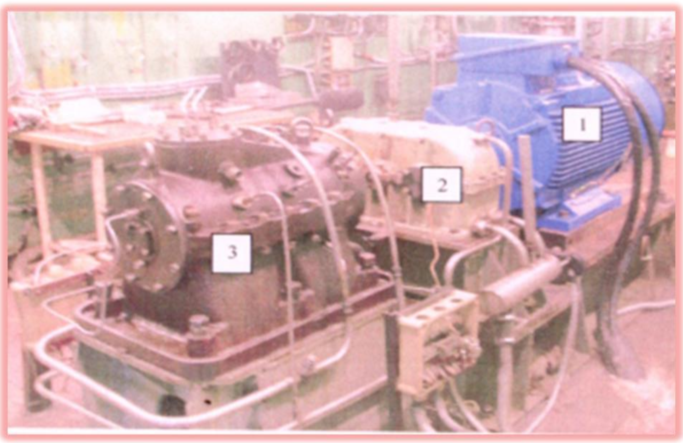

Fig. 4.1. General view of the experimental test rig

This test rig allows carrying out all bearing testing types with two shafts rotating clockwise and counterclockwise with the speed up to 15000 rpm. The radial loading to the tested bearing casing is up to 500 kgf. The test rig is equipped with the circulating oil system with the controlled flow up to 10 l/sec and is capable to maintain designed temperature in the system from 20^0C to160^0C and pressure from 0 to 10 kgf/cm^2.

The test schedule included a step-by-step change of outer loadings within 0 - 12000 rpm range. The range of the tested bearings workability was analyzed.

The studies of the bearings at start-up without forced oil supply were carried out by Lyulka Design Bureau at its test facilities.

The test rig allows changing speed gradually within the range 0 - 3000 rpm with the attached radial loading from 0 to 250 kgf. The drop oil feeding into the operational zone of the bearing was used. The test rig is equipped with the electronic control system with the sensor control board.

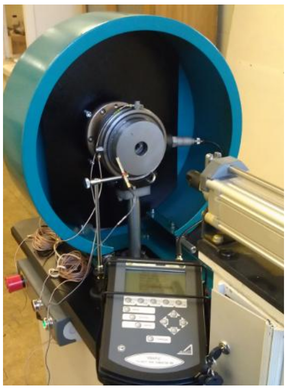

Fig. 4.2. General view of the test rig with installed bearing

The opportunity of visual estimate of the bearing technical conditions together with the vibration diagnostic instrumentation and part thermo metering in real time scale, permits efficiently enhance the test program.

5. Diagnostic accompaniment of experimental sliding bearings tests

Constant monitoring of the tested bearing was carried out. To estimate the outer factors impact altering according to the test program (radial loading, oil supply to the bearing, changes in vibration loading, misbalance of the rig rotors and etc.), the complex approach to the diagnosed parts of the tested bearing was implemented. It was based on the oil flow through the bearing spectrum analysis, thermal analysis of the bearing part and its lubricant, vibration analysis of the experimental bearing test rig.

The evaluation of the temperature changes of the bearing parts (Fig.5.1) and heat degree of the oil through the bearing parts, the approximate value of the friction coefficient in the friction couple in the sliding bearing and thermal losses in operation were calculated.

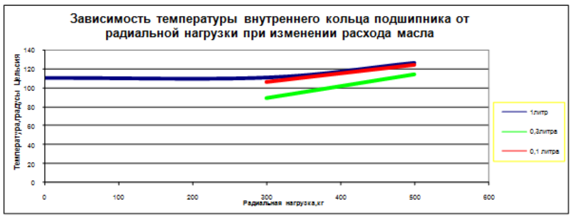

Fig. 5.1. Temperature fluctuations in the flat ceramic sliding bearing versus applied radialloading at the constant speed 5900 rpm

However, this information gives the limited estimation of the bearing conditions and has some inertia in altering parameters which is caused by the specific character of the temperature gauges operation and time required for heating and cooling the massive bearing test rig hardware.

The spectrum analysis of the oil ingredients helps to detect the initial wearing stages of the contacting parts and their changing tendency to forecast the part operation conditions. But the inability of the “Prism”, “Spectroil” and Spectroscan” instrumentation to tell the ceramic ingredients in oil, makes this approach informally poor.

The method of the part technical condition estimation by its vibrations is the most acceptable for the bearing diagnostics in real time scale

On the first step of the bearing technical condition evaluation by the 2D and 3D detailed amplitude-frequency characteristic, the most critical modes of its operation are chosen and estimated.

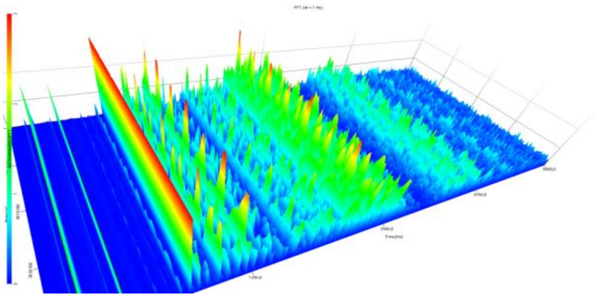

Fig. 5.2. 3D vibration spectrum of the bearing

Further, the detailed analysis of the vibration conditions by means of additional types of investigations was made for the selected areas.

To evaluate the technical conditions of the rotor system on bearing test rig the spectral and orbital vibration analysis were chosen to define possible experimental part technical conditions and their deviations which impact its workability in real time scale. These methods can easily determine the emergent rotor oscillations, warp and fracture of the rotor axes, straight and reversal precession, rotor and stator mechanical contact, rotor and other test rig parts resonance within operation modes.

One of the examples of the vibration spectrum with the quick Fourier transformation is shown on Fig.5.3.

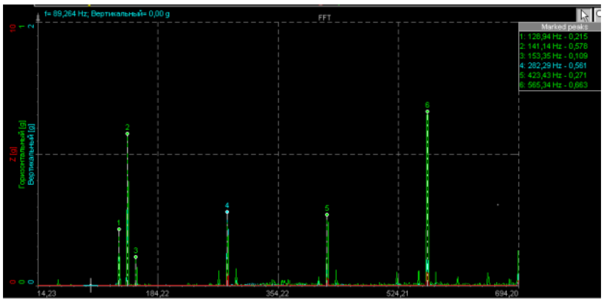

Fig. 5.3. Rotor vibration spectrum with one of the first experimental bearing

The orbital analysis for the qualitative evaluation of the separate rotor spots trajectory was implemented.

It is easy to visualize the rotor shift character by constructing the graph of the fictitious shaft center.

By altering the test conditions program the shaft orbit character helps to understand the character of the vibration condition changes of the experimental part.

As an example, two orbits of the rotor shift for different modes are shown on Fig. 5.4.

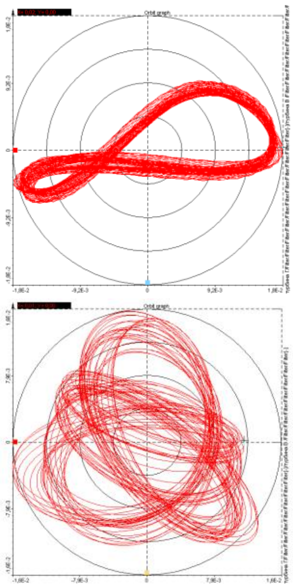

Fig. 5.4. Example of the rotor shaft orbit

The complex implementation of the orbital and spectral vibration analysis expands the data base of the received information and permits to diagnose the tested parts technical conditions more accurately.

The above number of the condition criteria of condition analysis gives the opportunity to make analysis directly while investigating the characteristics of the operational processes and evaluate their deviations from the designed testing program conditions. It allows during the experiment, modify the changes of the outer loading for obtaining more careful and accurate test results in due time.

In cases when it is impossible to change the test rig characteristics while operating, the implementation of the vibration-diagnostic accompaniment gives the opportunity to alter the received test results with the off-design outer effect impact in place.

While analyzing the vibration conditions of the experimental part, diagnostic features of some different events characterizing changes or deviations in the tested bearing in operation can coincide.

To identify the concrete demonstration of the bearing technical condition it is necessary to make a number of vibration analysis and provided there is a coincidence in results, the probability of the correct detection of the diagnostic event will significantly increase. In the other case the individual features will be revealed, non characteristic to this event that will help to detect it as a false one.

Thus, for instance, the analysis of the "raw" vibration signal brings additional information and has a high level of info comprehension. Already developed and initiating defects of the contacting bearing surfaces may be detected.

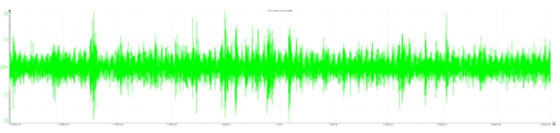

Fig. 5.5. Amplitude vs Time characteristic of the "raw" vibration signal

One of the simplest methods of estimating vibration conditions is the trend analysis of the Peak-factor, excess and mean-square values. Comparing test data with the received earlier values and their gradient changes the forecast of the part workability is drawn.

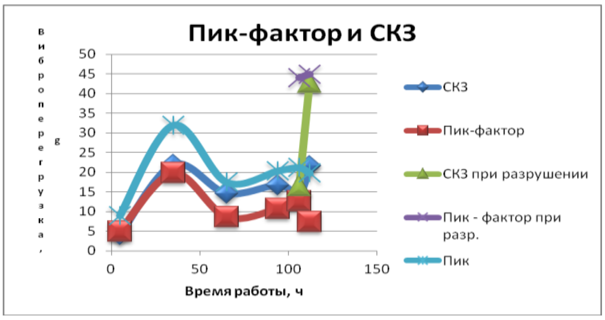

Fig. 5.6. Peak-factor and mean-square value of the tested bearing

On the basis of the complex estimate of the received diagnostic information and characteristic parameters in place, analysis story and etc, the experts in vibration diagnostics make a conclusion about technical conditions of the tested bearing, draw a forecast for its workability and make a decision on altering the test program.

The accurate evaluation of the tested bearing conditions in operation permits to choose the optimum modes, applicable loading and have more careful testing.

Detecting a flaw of the experimental ceramic sliding bearing made after the completion of the test program and consequent test rig disassembly, confirmed the conclusions received as a result of diagnostics by means of vibration analysis right during the testing.

Therefore, diagnostic implementation for the experimental bearing parts in real time scale decreased the number of test rig modifications for visual and instrumentation estimate of the contacting elements that shortened general test duration and its cost.

6. The results of the experiments

The best workability of the sliding bearing was demonstrated while using a friction couple of new generation ceramics (composite on silicon carbide basis with composite on titanium carbinitride basis).

The configuration of the hydrodynamic "smooth" bearing made of new generation ceramic materials proved the workability within gas turbine rotor support operation at decreased oil consumption up to 0.1 l/min and radial loading – up to 500 кgf. In comparison with the oil consumption in contemporary gas turbine engine with the rolling bearing oil consumption diminished by 10 times.

A new segmental ceramic sliding bearing which confirmed prior received ceramic material properties and higher circumferential speeds achieved in a friction couple, is the further step in developing advanced bearings.

The parameters of the designed configuration not only yield to the existing similar roller bearings tested at the same conditions and on the same CIAM stand, but also surpass them.

The means of vibration diagnostics confirmed the workability of the ceramic sliding bearings of a new generation.

The total time of testing, the number of stops and test rig modifications for visual and instrumentation part analysis were shortened, thereby, cutting the general test costs.

After the completion of tests while detecting defects the accuracy of the working bearing parts condition evaluation made by vibration diagnostics was confirmed, that in turn confirmed the accuracy of the chosen approaches to the algorithm definition.

The results obtained for high speed ceramic bearings proved the conclusion of their convenience within rotor support in gas turbine engines and paved the way for their further improvement.

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