

Particles Wear-Out Behavior of Reciprocating Engine Crankshaft During the Initial Running-in Operation

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ABSTRACT

Reciprocating engines are popular in automobile and small airplane applications, and their reliability relies on the operating life of the crankshaft journal bearings.

Traditionally, reciprocating engines have been designed based on an assumed journal wear rate, which is calculated on the basis of the maximum load, maximum velocity, average project area and maximum oil temperature over the entire sliding surface of a journal bearing. A prediction of journal wear rate suggests that engine parts have some allowances to carry loads. From the perspective of energy conservation, it is desirable to minimize, if not eliminate, such gap. However there have been few attempts to examine the real loads on engine journals. Therefore it may be worthwhile to examine engine parts for excessive margins incorporated in the conventional design of reciprocating engines.

This research is intended to propose a method for measuring the load and the pressure distribution on the journal bearing surface with the intention of modernizing the engine design on the basis of tribological data rather than assumption. From this study, the reliability of engine bearings will increase if the wear particles generated during the initial running-in operation.

1. Introduction

As reciprocating engines have been used for almost a century, automobile engine manufacturers have accumulated a lot of experience and know-how related to engine design. For this reason, reciprocating engines have been designed on the basis of past experience and such established practices have been accepted without question.

The wear of the metal journal bearings in a reciprocating engine is one of the most important and critical issues which determine the reliability and product life of engines. Therefore it is important to study both the pressure distribution of oil films on journals, which carry loads, and their wear. In the past, there was no technology to successfully measure the pressure distribution of oil films on metal journals while engine in a moving vehicle is running⁽¹⁾⁻⁽³⁾. Therefore the author have developed a thin film sensor to measure the load distribution on metal journals⁽⁴⁾⁻⁽⁸⁾.

This study consists of three experiments. The first experiment was the measurement of the load on journals in a general aviation reciprocating engine using newly developed thin film sensors. The second was the measurement of the wear of the journal

bearing using a simulation test apparatus whose load distribution was controlled by servo valves to simulate the data obtained by the first experiment. The third was the measurement of the wear of a general aviation engine journal bearing for comparison with the data obtained in the second experiment.

It has been known from our experience that both wear patterns and wear rates differ for Start-stop driving conditions and Steady-state driving conditions. But there has been no study, within our knowledge, that identifies the wear patterns and wear rates under Start-stop driving conditions and Steady-state driving conditions independently, because wear particles generated under Start-stop driving conditions are carried over to the Steady-state driving stage and those particles cause excessive wear unless each test is conducted independently. Therefore this research was conducted in two stages. The number of wear particles was measured during Start-stop operation first, and then the tested engine was overhauled and the wear condition was inspected. After all the parts had been cleaned and inspected, the engine was reassembled and the number of wear particles was measured during Steady-state operation. These two-stage tests made it possible to distinguish the wear

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patterns and wear rates under Start-stop driving conditions from those under Steady-state driving conditions.

The first experiment was reported at the SAE World Congress & Exhibition held in Detroit in April 2009⁽⁹⁾, and then further experiments were continued. This paper is a revised version of the report based on the newly obtained data. Since I and my co-author presented the first report about the methods at the SAE World Congress in 2009⁽⁹⁾, the measurement techniques for obtaining pressure distribution on journal bearings have been improved. This paper provides an overview of our test and measurement system with additional test data.

2. First Experiment: Measurement of Pressure Distribution of Oil Film

2.1. Construction of Newly-Developed Sensor

The leads of conventional sensors are connected to pressure sensing surfaces. However, the leads of our new sensor are attached directly to metal side. The sensor has five pressure sensing points, each 0.8 mm in diameter. The five points are arranged in the radial direction. This structure makes it possible to measure the load distribution on a journal bearing on the metal part with the same width. An external view of the thin-film sensor attached to a crankshaft journal for the experiment is shown in Fig. 1.

The sensor is made of three layers: an insulation

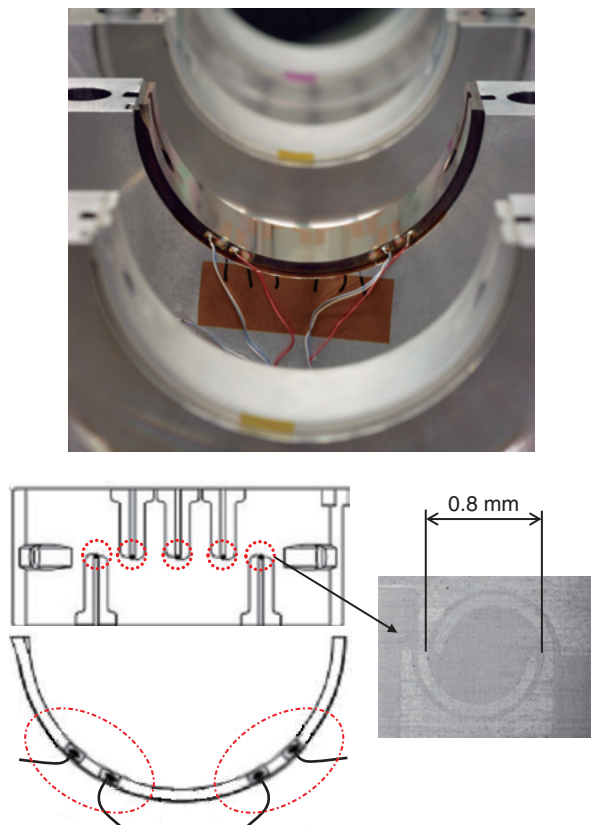


Fig. 1 External view of thin-film sensors

layer, a sensor layer, and an insulation layer on the lining. A cross-section is shown in Fig. 2.

For the calibration of the sensor, the change in its electric resistance was measured under various hydraulic pressures which were uniformly applied to the bearing surface in an autoclave. The temperature dependency was also characterized by varying oil temperature. Functions were curve-fitted to both pressure and temperature characteristics to convert the measured signal to physical quantities, and bearing load was obtained.

2.2. Pressure Measurement in Engine

A water-cooled horizontally-opposed four-cylinder general aviation engine with output of 230-hp was used for the tests. A reduction gear was placed between the engine and the propeller.

The reduction gear had a gear ratio of 1:2.08, which generated 2400 r/m with the propellers in operation. The engine displacement was 3500 cm³. Premium unleaded gasoline for automobiles was used for fuel. The lubricant for the engine was Ultra Mild 10W-30 Honda genuine engine oil. The connecting rod bearings on which oil film pressure was detected were TAIHO KOGYO SA250.

Two thin-film sensors were used for the tests. One was attached to Journal 1 between the case end and Cylinder 1, and the other to Journal 3 between Cylinders 2 and 3, as shown in Fig. 3. The measured loads on the journals at 3000 r/m were compared with the calculated loads.

2.3. Measurement Results of Load Distribution on Journal Bearings

Comparisons of the measured loads on bearings

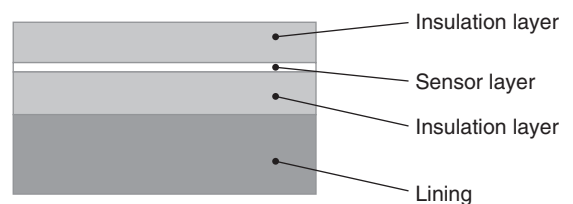


Fig. 2 Thin-film sensor in cross section

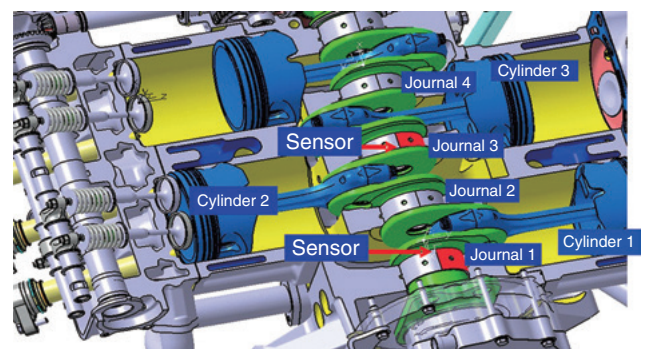


Fig. 3 Locations of thin-film sensors on crankcase

and the calculated loads are shown in Figs. 4 and 5.

The calculation of the loads was made on the assumption that the pressure would be carried uniformly by the total surface of the journal bearings. The measured loads on Journals 1 and 3 were less than half of the calculated ones.

The discrepancy may result from two assumptions made in calculations. One is that the rigidity of the bearing support and the rotary parts such as pistons and piston rods was not taken into account when the resultant force of the inertial load and the explosion load on the journal bearings were calculated, and the other is that the rotary shaft was treated as a beam. The measurements indicate that the loads on the bearings were reduced, because the rotary parts such as pistons and piston rods deformed like springs when the explosion load was received by the bearings. The results of measurement indicate that the size of journal bearings can be reduced by half. This is important to help engine makers reduce not only bearing cost but also the weight of engine.

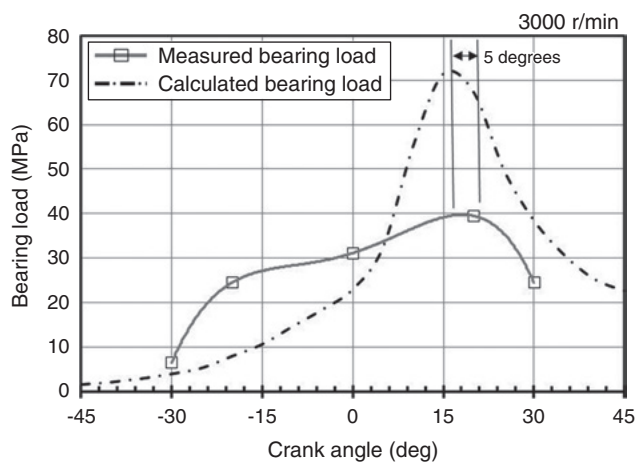


Fig. 4 Relationship between bearing loads and crank angle at peak load of #3 journal bearing

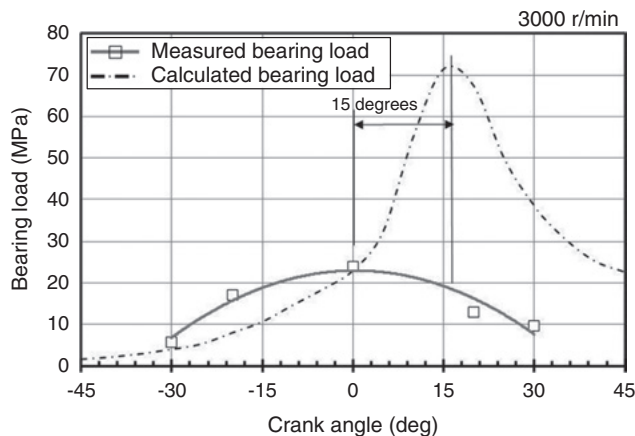


Fig. 5 Relationship between measured bearing load and calculated load and crank angle at peak load of #1 journal bearing

The shapes of the curves of the measured load are not sharp compared with those of the calculated ones. This is because the loads are spread over the journal bearing surface and because the sensor measures the load at five points in the radial direction, although the calculation shows the peak load only.

The difference in crank angle between the measured peak load and the calculated one for Journal Bearing 1 was large, because Journal Bearing 1 was influenced by the motion of Piston 1 only. On the other hand, the difference in crank angle between the measured peak load and the calculated one for Journal Bearing 3 was small, because Journal Bearing 3 was influenced by the motion of both Pistons 2 and 3.

3. Second Experiment: Wear Simulation Tests of Journal Bearing

3.1. Simulation Test Apparatus

In the past, it was common to examine the wear and the reliability of bearings through tests of a completed engine at the final stage. However, in order to design lightweight engines more efficiently, it is desirable to obtain fundamental data on the wear of journal bearing metal by simulating various loads on the journal bearings of an engine. Therefore a bearing test apparatus that can apply various loads to the journal bearings by servo valves was developed. Figure 6 shows the schematic arrangement of the bearing simulation test apparatus, by which bearing wear was examined using the data obtained by the sensors, which were attached to the bearings of the general aviation engine.

Figure 7 shows the construction of the inside of the test chamber with the thin-film sensors, the rotating shaft, the position of the crankcase journal, and the vibrator base, in which a newly developed high-speed hydraulic servo valve is installed.

The data obtained by the first experiment were incorporated into the computer of the simulation test

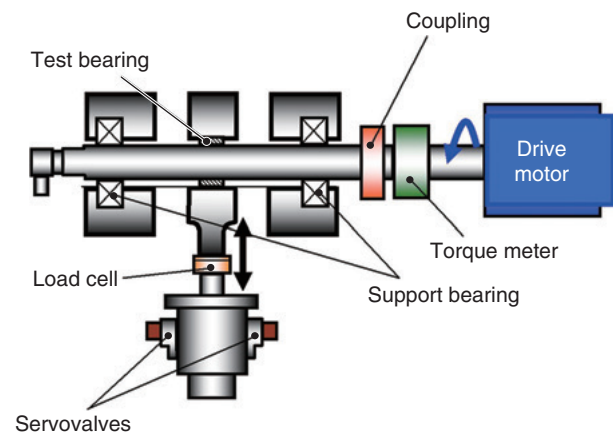


Fig. 6 Schematic arrangement of simulation test apparatus

apparatus, and the wear of the metal journals was monitored during the running of the simulation test apparatus. For the tests, the engine firing force and the simulated load on the journal bearing were adjusted to be identical. Fig. 8 shows an example of the load on the bearing at 70 MPa.

3.2. Initial Wear and Steady-State Wear

In conventional wear tests, the amount of wear was measured throughout the tests, which included both Start-stop tests and Steady-state operation, and was treated as Steady-state wear. However, it is known that the initial wear during the running-in period is greater than the wear during Steady-state operation. Therefore a long running test was conducted in order to keep the initial wear level within the margin of error.

Figure 9 shows the test period with the smallest influence of initial wear. In existing wear tests, the amount of initial wear tends to exceed that of steady wear.

For this reason, longer and more sufficient wear

tests were conducted. That is, Steady wear was measured by dismissing the initial wear as erroneous, and comparing the amount of wear before and after the test.

In our new method, the initial wear test and Steady-state wear test were conducted separately. After measuring the wear amount during the initial wear tests, the metal bearings were removed from the test apparatus and cleaned. Then the bearings were re-fitted to the apparatus for the Steady-state wear test. Consequently, our method not only reduced the initial test time, but also made it possible to verify the amount of wear during Steady-state operation.

An originally developed in-line wear particle counting system enabled the separation of these wear phases. As shown in Fig. 10, a portion of the oil from near the bearings containing wear particles flows into the branch line to the counter. The wear particles cover focused laser beams across the oil line and are detected as intensity deviations on a photo detector, whose outputs are processed and yield the number of particles of different sizes.

The oil sampling and particle counting were conducted every 3 minutes during the test.

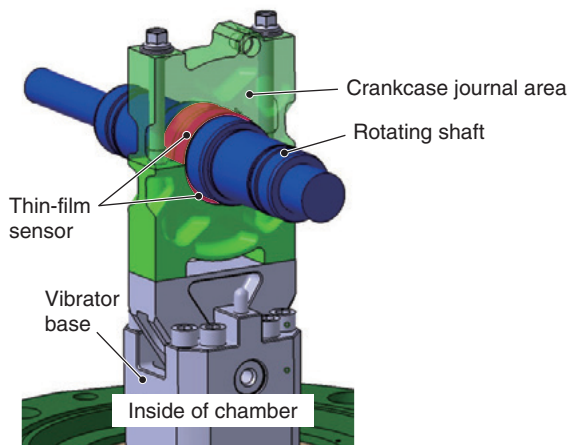


Fig. 7 Inside of chamber of bearing simulation test apparatus

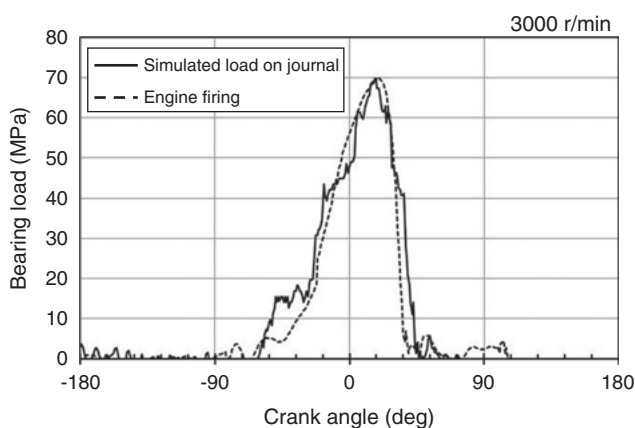


Fig. 8 Conversion data of bearing load value from thin-film sensor measurement data

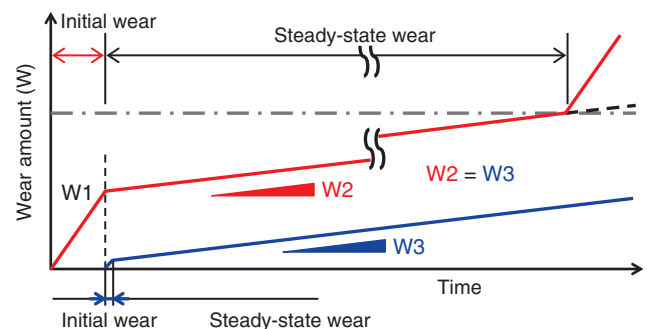


Fig. 9 Test period with small influence of initial wear

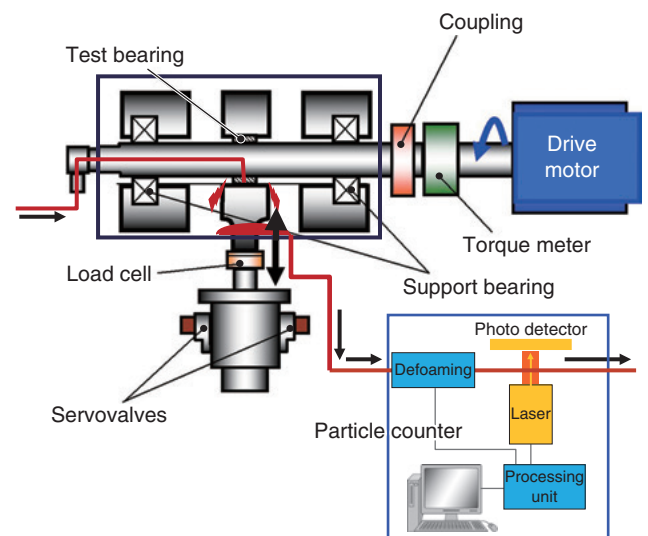


Fig. 10 Oil sampling location

The data were categorized into particle sizes larger than $10\ \mu\text{m}$ and of $10\ \mu\text{m}$ or smaller, and the change in number of particles during the test periods is shown in Figs. 11 and 12.

In the case of the initial wear test, the number of particles $10\ \mu\text{m}$ or smaller increased rapidly as soon as the test started. Then, it decreased as time elapsed until it became constant. But the number of particles larger than $10\ \mu\text{m}$ was almost constant during the initial wear test.

Figure 12 shows that the generation of particles larger than $10\ \mu\text{m}$ or smaller was low and almost constant throughout the steady-state wear test, different from the initial wear test. This suggests that few wear particles are generated in Steady-state wear, after the particles generated by initial wear have been completely removed.

The test results indicate that the wear of bearings is very low during normal operation and the reliability of bearings can be assured as long as the wear metals, which are generated during the initial running, are completely removed before commencement of Steady-state operation.

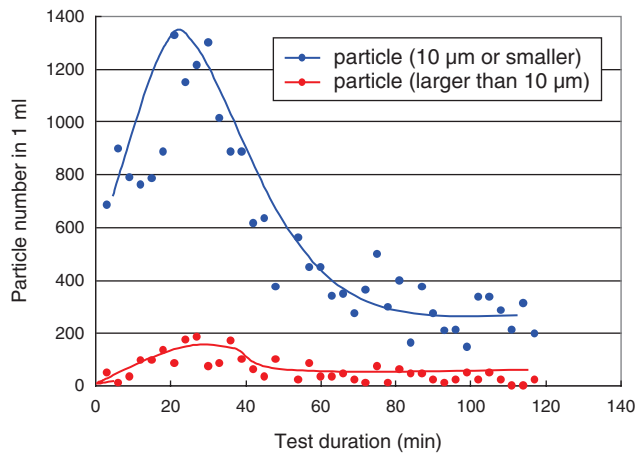


Fig. 11 Generation of initial wear particles

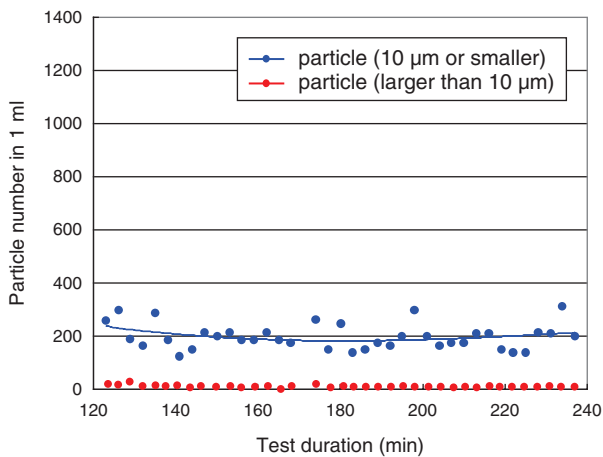


Fig. 12 Generation of Steady-state wear particles

4. Third Experiment: Start-Stop and Steady-State Wear Tests With a General Aviation Engine

4.1. Test Method

Figure 13 shows the flight simulation modes used for the tests. In order to verify the wear data obtained by the simulation test apparatus, confirmation tests were conducted using a general aviation engine, because general aviation engines are operated in simply programmed modes such as “Warm up,” “Take-off,” “Cruise,” “Landing” and “Cool down.” Therefore tests to evaluate the fatigue life of the crankshaft journal bearing were repeatedly conducted in these flight simulation modes.

The tests were carried out based on the flight simulation mode for an aircraft. The main shaft rotational speed and duration for the tests are shown in Fig. 14.

4.2. Results of Start-Stop Wear Test and Steady-State Wear Tests with a General Aviation Engine

After running 2-, 12-, 22- and 32-hour tests (Start-stop tests and Steady-state tests), the condition of the metal was examined under an optical microscope, and the wear of the journal bearing metal was measured with a roughness measurement gauge. The metal was set to the master reference plate of the roughness measurement gauge to measure the same point. The

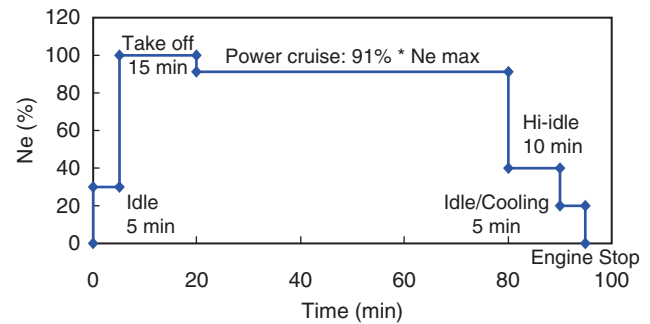


Fig. 13 Flight simulation modes of typical general aviation engine

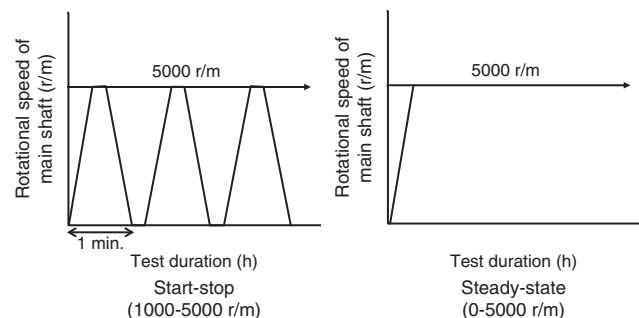


Fig. 14 Running modes

measured cross-sectional curve shows the wear at the center of the metal bearing where the wear was greatest.

In steady-state running mode, there was almost no change in the roughness curves before and after tests, while there was a slight change in the roughness curves in the Start-stop running mode showing some progression of wear, as shown in Fig. 15.

The surfaces of the journal bearings after a 32-hour test are shown in Fig. 16.

The photos in Fig. 16 show that the machining patterns were removed by the initial wear. The bearing surface after Steady-state operation was smooth, although that after Start-stop operation had a relatively deep and new groove, which was found after the 32-hour test. These photos indicate that wear during Start-stop operation is greater than that during Steady-state operation.

Figure 17 shows the number of discharged particles during the test in Start-stop running mode, where r/m varied from 0 to 1,000 and in steady-state running mode, where r/m was constant at 5,000.

Compared with steady-state running mode, the Start-stop running mode produced more wear particles from the beginning of the test, and it took a long time until the production of wear particles becomes

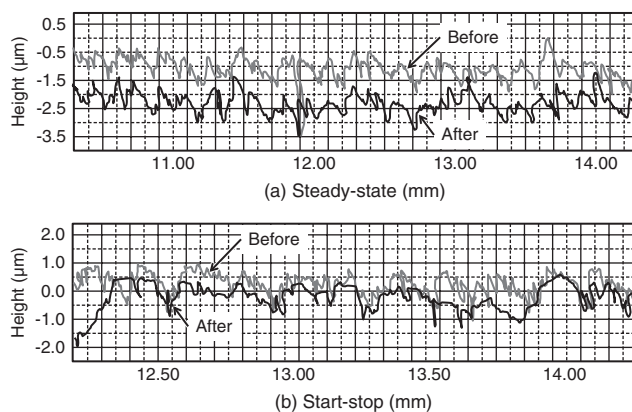


Fig. 15 Roughness curve before and after test

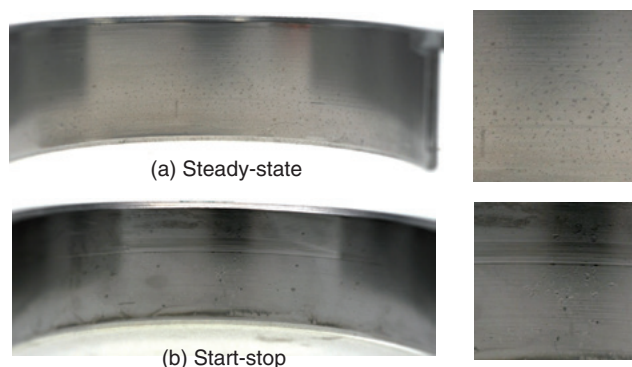


Fig. 16 Example of journal metal surfaces at sliding side after 32-hour test

stable.

In order to better understand wear during Start-stop operation and during steady-state operation, these wear data, which were obtained using the simulation test apparatus, were compared with those from endurance tests of a general aviation engine in a flying mode.

Figure 18 shows the wear prediction curves in three test modes, which were drawn on the basis of the test data.

The squares show the wear during Steady-state operation, the dotted line shows the wear during Start-stop operation, and the circles show the wear of the metal bearings during the endurance tests in a flying mode. Even though the amount of data was not enough to draw any conclusions, it suggests a general tendency that wear during the steady-state running test, which was conducted after removing the wear particles produced during the Start-stop test, is less than that during the actual engine endurance test and the Start-stop running test in that order respectively.

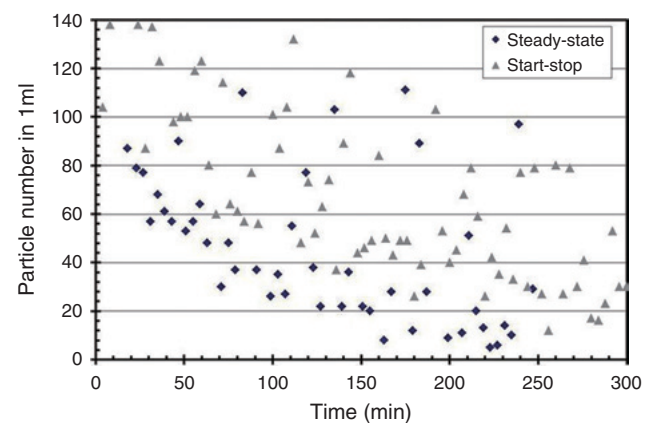


Fig. 17 Generation of particles during start-stop test and steady-state test (Steady-state: 5000 r/m, Start-stop: 0-1000 r/m, 5 min.x100 times)

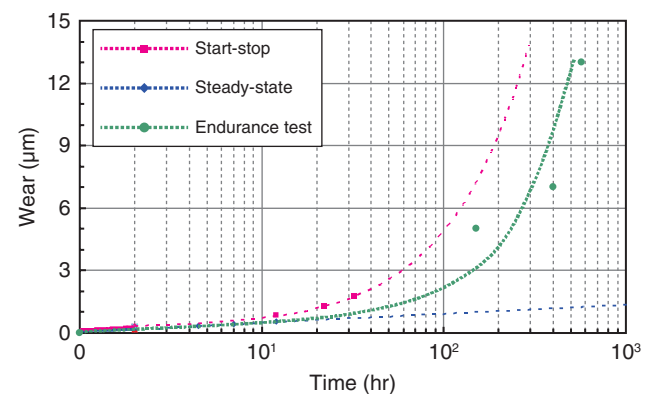


Fig. 18 Comparison of wear amount in three test modes

5. Conclusions

- (1) The journal load was measured in an actual running engine with thin-film sensors and the actual load in an actual engine was ascertained.
- (2) A bearing simulation apparatus made it possible to reproduce the actual load distribution, and wear tests of the metal bearings were able to be conducted.
- (3) The initial wear was differentiated from the Steady-state wear by measuring the generation of wear particles with a particle counter.
- (4) The study suggests that the reliability of engine bearings will increase if the wear particles generated during the initial running-in operation are completely removed.
- (5) The results of measurement of the loads on the journal bearings indicate some possibility of reducing the width of engine bearings.

In this paper, the new approach by the author, whereby initial and steady wear of the journal bearings in aero-plane engine can be divided, showed the validity for higher the accuracy and efficiency of endurance tests. The basic techniques, such as oil film pressure measurement, load simulation test apparatus and in-situ wear particle counting, are also applicable to other parts such as automobile engine bearings and enhance the development efficiency.

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