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Follow-up report on a new real-time condition monitoring method for engine bearings

Tribology

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ABSTRACT

The engine bearings, along with the lubricant between the shaft and the housing, support the smooth running of the engine. However, if the engine bearing cannot operate normally due to severe operation, the engine cannot operate. Therefore, the engine bearing is an important component for the engine.

Recently, it has become possible to control the engine at a high level; to monitor the running condition has become important in order to maximize the engine performance within the margin of the bearing condition.

By judging the condition of the bearing based on the monitored information, it is possible to avoid the occurrence of catastrophic damage on the bearing even when an unexpected load is applied in the severe running conditions of the engine. In other words, it leads to the use of sustainable engines.

In a previous study, a method for monitoring the condition of engine bearings was reported. The report presented the following findings: during a start-stop wear test on a bearing test rig, the oil supply was interrupted. And then, variations in vibration, temperature, torque, acoustic emission signals (AE signals), and contact electrical resistance were monitored. The findings revealed a pronounced correlation between the fluctuations in alloy temperature and AE signals, which are indicative of seizure damage.

This time, damage detection methods applicable beyond start-stop operations were investigated.

Furthermore, the investigation extended to bearing wear and fatigue damage, in addition to seizure damage. A significant correlation was observed between the root mean square value changes of the AE signal and the variations in bearing temperature, which is indicative of fatigue damage. Then, it was confirmed that the occurrence of serious damage can be avoided by performing recovery operation by this method, and the result is reported.

1 INTRODUCTION

Engine bearings, together with lubricating oil, ensure support smooth engine operation between the shaft and housing.

However, if the engine bearings fail to function property due to severe operating conditions, the engine may also fail. As such the engine bearings are important components.

It is now possible to control the engine at a high level, monitoring the operating condition has become crucial, which helps confirm the margin of the bearing safety and maximize the engine performance. By assessing the condition of the bearings based on the monitored data, catastrophic damage on the bearings can be prevented even when an unexpected load is applied during severe engine operation. Damage to engine bearings can be generally divided into three categories: seizure, fatigue, and wear. The definition of seizure varies depending on conditions and it is typically judged by criteria such as the occurrence of adhesion and an increase in torque. Some literature define seizure as a condition where the bearing is no longer retain its original performance, making the definition more practical.

It is also known that seizure occurs under different operating conditions. Figure 1 shows the friction test results of point contact type, summarized by Nakamura [1]. The results were originally compiled by the Industrial Materials Wear Research Group of the Organization for Economic Cooperation and Development (OECD). According to Figure 1, under slow sliding speed conditions, the boundary lubricant film breaks due to the transition from elastohydrodynamic lubrication to boundary lubrication, leading to seizure. On the other hand, at high sliding speed, seizure is considered to be a result of the unstable fracture of the elastohydrodynamic lubricant film. In other words,

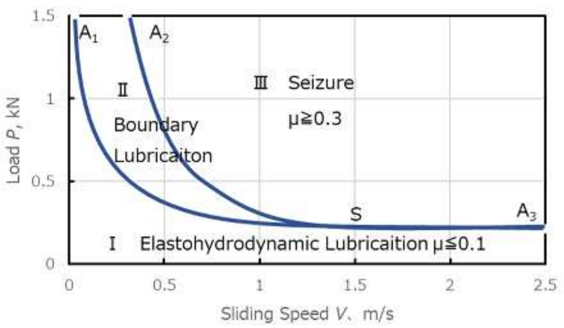

Figure 1. Critical film thickness ratio on general friction surface (reproduced by the author from Reference [1])

it is important to note that the seizure process differs depending on the operating conditions.

In the past, Hirano and Yamamoto conducted experiments on bearing seizure. Yamamoto [2] identified the following four seizure conditions:

1) Critical film thickness condition

When the thickness of the oil film decreases and the severity of the contact condition exceeds a certain critical value.

2) Critical temperature condition

When the surface temperature rises to the critical level temperature determined by the friction surface material and lubricating oil.

3) Critical friction loss condition

When mechanothermal disturbance and the μPV of the friction surface reach critical values.

4) Thermal instability condition

When generated frictional heat cannot be absorbed, breaking the thermal equilibrium on the friction surface.

Yamamoto's four conditions help in understanding the mechanism behind seizure and serve as a reference for implementing countermeasures in the event of damage. Fatigue damage is a phenomenon where small stresses, which do not cause fractures under static loading, can lead to damage, crack formation, and fractures when repeatedly applied to a material [3]. In aluminum alloy bearings, the strength decreases with increasing environmental temperature, making fatigue a potential concern. Cracks are initiated and propagated by the repeated loading of oil film pressure. Therefore, if changes can be detected when a crack occurs, it will enable early detection of damage. Abrasion is a phenomenon where material is gradually lost from the bearing surface due to friction. In engine bearings, the clearance increases as wear progresses, leading to greater oil leakage from the bearing and a subsequent drop in lubricating oil pressure throughout the engine. Additionally, when the overlay (a soft coating layer) is abraded and the underlying alloy is exposed, the bearing's ability to tolerate localised contact decreases. This also reduces the bearing's capacity to adapt to changing conditions, such as foreign particle contamination, which may ultimately lead to seizure.

Various detection methods for bearing damage have been studied. Many reports have used AE (Acoustic Emission) signals to monitor the condition of rolling bearings, however there are few studies focused on sliding bearings. Girtler et al. [4] reported on marine engine bearings, noting that RMS values of AE signals changed before and after fatigue, often increasing. They also reported that fatigue damage progressed slowly and could be evaluated through recorded amplitude and frequency analysis. Nagata et al. [5] conducted seizure tests on white alloy, Al-40%Sn alloy, and Al-40%Sn alloy with a polymer overlay using a plate-on-sleeve tester. They found that the RMS value of the AE signal correlated well with the friction force in the absence of an overlay. For the polymer overlay, the RMS value of the AE signal was more sensitive to changes in surface condition than the friction coefficient and temperature change during wear tests at startup and stop. Therefore, they reported that wear of the polymer overlay occurs before seizure in the seizure test. Koshima et al. [6] conducted a seizure test by forcibly stopping lubrication during repeated startup and stop tests. They reported that changes in bearing alloy temperature, torque, and contact voltage (used to judge contact between the bearing and the shaft), and the AE signal indicated abnormalities in the bearing at an early stage. Additionally, based on FFT analysis, the frequency peak observed at startup was found to match the frequency band of the peak observed during bearing damage caused by forcibly stopping lubrication. This makes frequency analysis effective for the early detection of bearing damage.

Measurement of the AE signal is often used to study fatigue. It is said that the occurrence of a crack initiates a burst AE signal with a short rise time. It has been reported that 'Risetime' and 'Duration' can be used to distinguish between plastic deformation (dislocation motion) and crack occurrence, based on the waveform parameters of the AE signal [7].

In this study, we examined and verified methods to detect damage caused by the steady rotation of dynamic loads and the step-up load of static conditions, which are different from the start-up and shutdown conditions reported previously. It was confirmed that serious damage can be avoided using these methods.

2 TEST METHOD

2.1 Testing machine

The test equipment consists of a test bearing in a rigid housing designed by Machida [8] and [9] along with a test shaft supported by four rolling bearings on both sides. The schematic diagram is shown in Figure 2. A hydraulic actuator installed in the lower connected to the gearbox via an electromagnetic clutch driven by a three-phase induction motor and is coupled to the test shaft through a torque meter. The feature of this testing machine is that it is

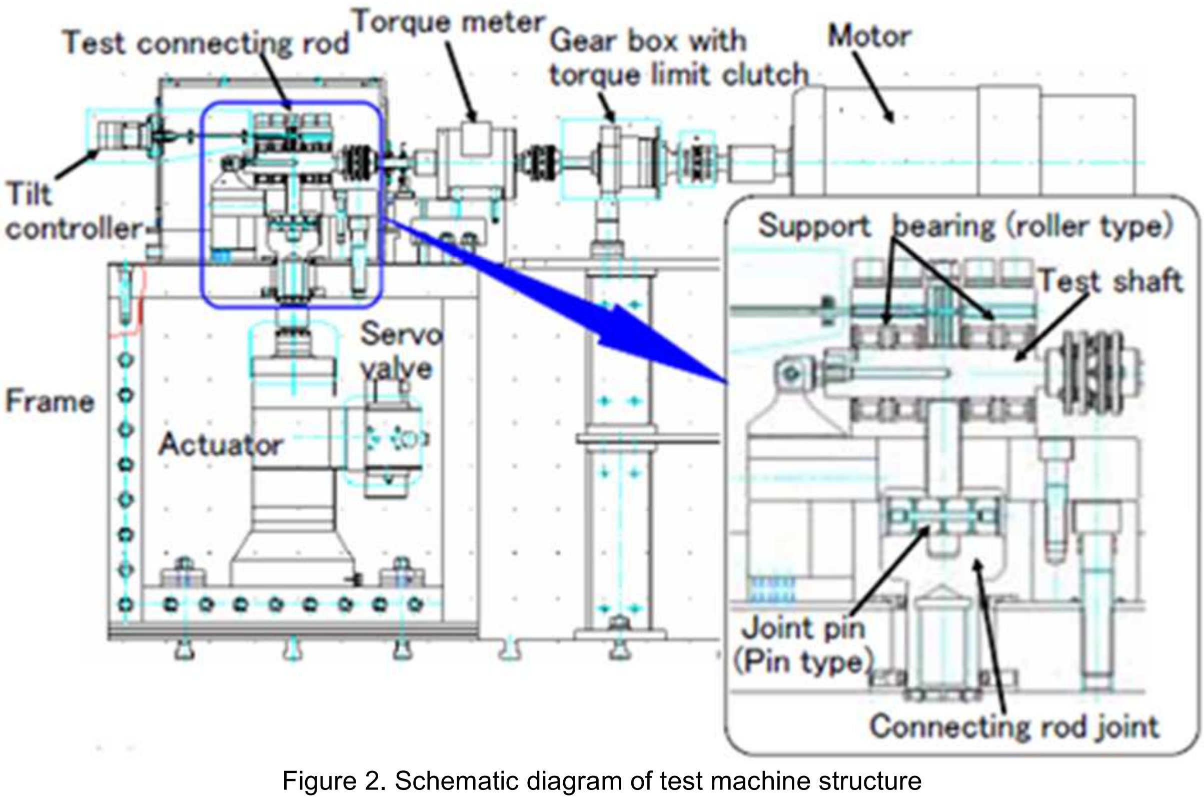

Figure 2. Schematic diagram of test machine structure

equipped with a mechanism that can control the alignment (uneven load) of the test bearing during the test. The system measures the temperature at both ends of the bearing alloy in the axial direction, evaluates the alignment condition based on the temperature difference, and automatically adjusts to the optimum alignment by moving the adjustment screw attached to the test housing using a stepping motor.

2.2 Definition of damage

In this study, each damage was defined as follows.

- Bearing Seizure: Seizure was defined as the condition in which the torque required to rotate the shaft rapidly increased.
- Bearing Fatigue: Fatigue was defined as the condition in which cracks were observed on the inner surface of the bearing. The confirmation of crack initiation was carried out using liquid penetrant testing.

2.3 Test Conditions

Operating conditions that could reproduce bearing damage were applied. For the seizure test, a method in which the rotational speed was kept constant and the load was increased by step-up (critical seizure operation mode) was used. For the fatigue test, a method in which the rotational speed was kept constant and the load was repeatedly applied (dynamic load operation mode) was applied.

2.3.1 Critical Seizure Operation Mode (Step-Up)

The critical seizure load test was conducted by gradually increasing the accumulated load until the seizure damage occurred, as shown in Figure 3. The rotational speeds were selected from 900 to 9000 rpm (for example, 900, 1800, 3600, 5400, 7200, and 9000 rpm). The hydraulic pressure of the test was set to 0.1 MPa..

2.3.2 Dynamic Load Operation Mode

In the dynamic load test, the test load was applied after the rotational speed was increased to the test rotational speed. A sine wave compression load was applied repeatedly to the test bearing. The pulsating load was applied, while maintaining a continuous compression load was continuously maintained. The minimum compression load was set to 3.5 kN.

2.4 Measurement parameters

Table 1 shows the parameters measured to evaluate phenomena correlated with bearing seizure and fatigue. Torque, vibration, and capacitance between the shaft and bearing alloy were measured at a sample rate of 1 kS/s to record the phenomena leading to seizure in detail. The temperature of the bearing alloy was measured at a sample rate of 10 S/s.

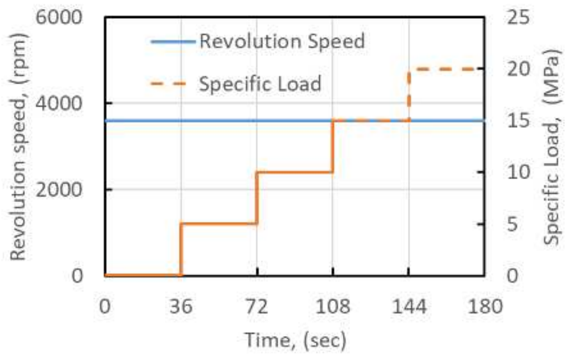

Figure 3. Schematic diagram of seizure test pattern

A broadband AE sensor was selected. AE signals were transmitted to an AE measurement device through a preamplifier. The AE signal was analyzed using software on this device, which can calculate various parameters. Figure 4 shows a schematic diagram of the AE signal. The threshold is set based on the noise level and other factors. The time from the point at which the threshold is crossed to the peak of the waveform is called Risetime, while the time from when the threshold crossing to the point where the signal returns to baseline is called Duration. The number of oscillations of the AE wave that exceed the threshold is referred to as Counts. The RMS value, which is the effective voltage, is used to assess the overall change in AE activity and is considered suitable for detecting bearing deformation. Signal Strength refers to the strength of AE signal.

Torque was measured using a flange-type torque meter with excellent response speed. The condition of oil film formation was evaluated by assessing the contact between the test shaft and the test bearing.

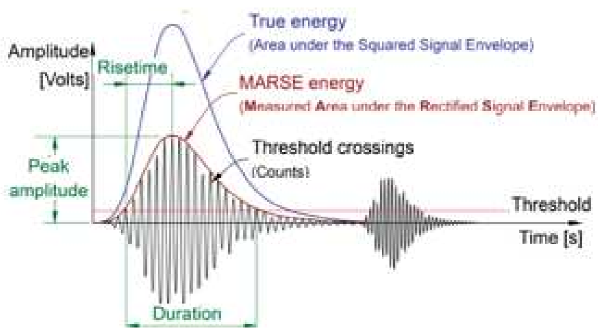

Figure 4. Schematic diagram of the threshold based hit detection and the AE features extracted from each hit.[10]

Temperature monitoring of the bearing is usually carried out by pressing a thermocouple against the rear surface of the bearing. however, for more accurate measurement, a hole of 1 mm depth was made on the side surface of the bearing, and the thermocouple was embedded. The measuring point of the oil inlet temperature is shown in Figure 5. Measurements were taken at a position 120 mm from the bearing surface. As will be described later, an additional measurement at a position 7 mm from the bearing surface was taken.

To assess the contact between the shaft and the bearing or the proximity between them, measurements were carried out using either contact electric resistance method or the capacitance method. Since the same circuit must be used for these measurements, simultaneous measurements cannot be performed. Therefore, either the contact electric resistance or the capacitance was measured. An insulating layer is formed between the bearing and the housing to provide electrical insulation. A slip ring was used to connect the electrical wiring to the test shaft.

The contact electric resistance was measured using the same method as previously reported [6]. The measured values were V_0 for the voltage in a completely floating state and V_c for the measured voltage. The contact ratio (CR) was calculated using the following equation:

$$CR = \frac{V_c}{V_0} \quad (1)$$

The electrostatic capacitance was measured using the circuit shown in Figure 6. When the clearance is (D), the sensor electrode area is (S), the dielectric constant of vacuum is (ε_0), and the relative dielectric constant of the oil is (ε_r), the electrostatic capacitance (C) is given by:

$$C = \frac{\varepsilon_0 \epsilon_r S}{D} \quad (2)$$

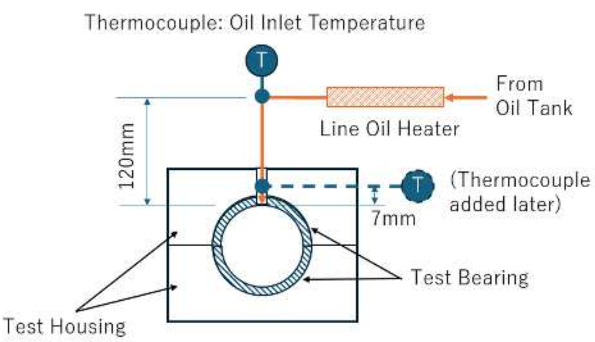

Figure 5. Schematic diagram of the oil inlet circuit from the line oil heater to the test bearing.

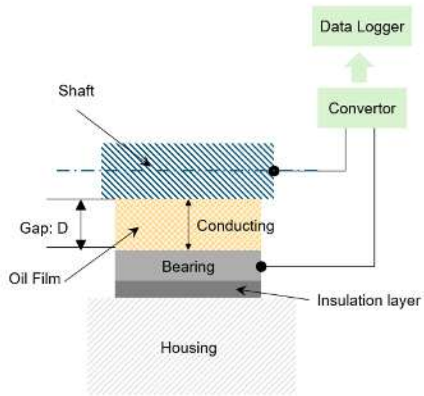

Figure 6. Schematic diagram of the electrical circuit to measure electrostatic capacitance of the oil film

This equation indicates that when the capacitance (C) is small, the clearance (D) is wide, and when the capacitance (C) is large, the clearance (D) is narrow. Ideally, the minimum oil film thickness could be calculated from this equation. However, this calculation was not performed because the bearing's shape is not perfectly round and changes under load.

2.5 Test Bearings

Table2 shows test bearings and test conditions.

3 TEST RESULTS AND DISCUSSION

3.1 Seizure Damage

Figure 7 shows the seizure test results for Cu-Bi alloy with Bi overlay. The vertical axis displays the bearing temperature, lubrication temperature, load, and torque from top to bottom, while the horizontal axis represents time. The bearing width is 15 mm, and the rotational speed is 6000 rpm. When the load exceeded 60 kN, the bearing temperature surpassed 300°C, and the torque rapidly increased, indicating seizure. The lubrication temperature was measured at a position approximately 120 mm from the bearing in the lubrication circuit (see Figure 5). A temperature rise of approximately 10°C was observed in the load step just before seizure.

Conversely, the bearing temperature increased rapidly after a rise of about 2°C was observed a few seconds earlier. The torque remained unchanged until the temperature spike occurred.

Therefore, by focusing on the temperature change at the oil inlet, it was thought that this could be useful for monitoring the precursor phenomenon of seizure. To measure the temperature more accurately, a thermocouple was installed at a position 7 mm from the bearing (see Figure 5), and the temperature of the oil being supplied was

Table 1 List of measurement parameters

Parameter	Unit	Sampling Rate	Remarks
Electric Contact Resistance or Electrostatic Capacitance	mV or pF	1kS/s	To check the formation status of oil film
Torque	Nm	1kS/s	
Acoustic Emission Signal (AE)	-		
Temperature of Bearing Alloy	℃	10S/s	Both bearing ends in the axial direction
Oil Inlet Temperature	℃	10S/s	

Table2 Test bearings and test conditions

Evaluation Purpose	Bearing Material	Circumferential speed	Bearing size
Seizure	Cu-Bi alloy with Bi overlay	16.7m/s (6000rpm)	ID53×15×1.5mm
	Al-Sn-Si alloy	1-25m/s (360-9000rpm)	ID53×5×1.5mm
Fatigue	Sn-Sb-Cu alloy	5, 10m/s (1364, 2728rpm)	ID70×9×5mm

monitored. The temperature at this position is hereinafter referred to as Oil Temp Oil Hole.

The temperature data from the seizure test performed at a rotational speed of 7200 rpm and a bearing width of 5 mm is shown in Figure 8. From the top to bottom, the vertical axis shows capacitance, load, torque, bearing temperature, oil temperature, and Oil Temp Oil Hole, while the horizontal axis represents time. A change in the Oil Temp Oil Hole is observed during the loading step before seizure occurs, with little change in the oil inlet temperature at the position of 120 mm. Seizure occurred when the temperature near the newly added bearing oil hole (Oil Temp Oil Hole) exceeded 120°C. Multiple tests were conducted, and the probability of seizure occurring due to this phenomenon was over 80%, indicating a high correlation with bearing seizure. Additionally, the temperature change up to seizure exceeded 30°C, with the temperature rising by 30°C in just 6 seconds, making it easy to monitor the condition.

It is known that exhaust oil temperature is monitored for bearings in turbines and large engines. There is a possibility that factors affect not only the exhaust oil temperature but also the oil inlet temperature when bearing seizure occurs. As a result of applying a high load, it is considered that the oil film thickness on the sliding surface became thinner, leading to increased shear heat generation in the oil. This, in turn, caused a change in the temperature of the oil in the oil supply piping due to oil convection.

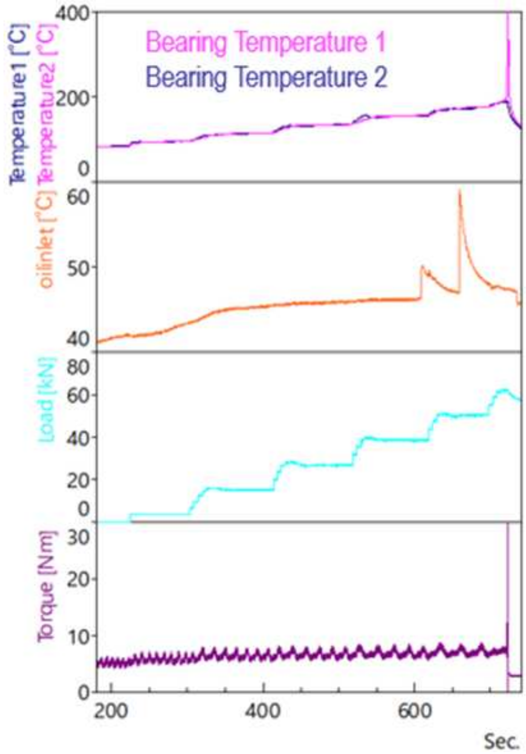

Figure 7. Measurement results of the seizure test at 6000 RPM for the Cu-Bi alloy bearing with Bi overlay

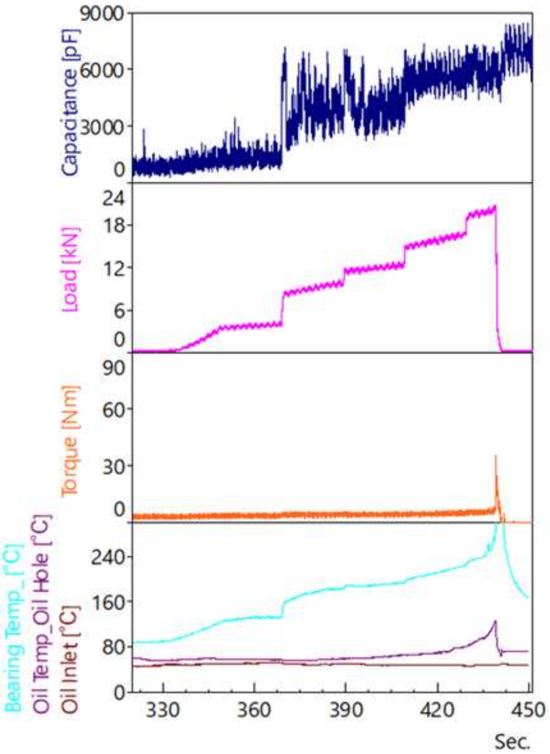

Figure 8. Measurement results of the seizure test at 7200 RPM for the Al-Si-Sn alloy bearing

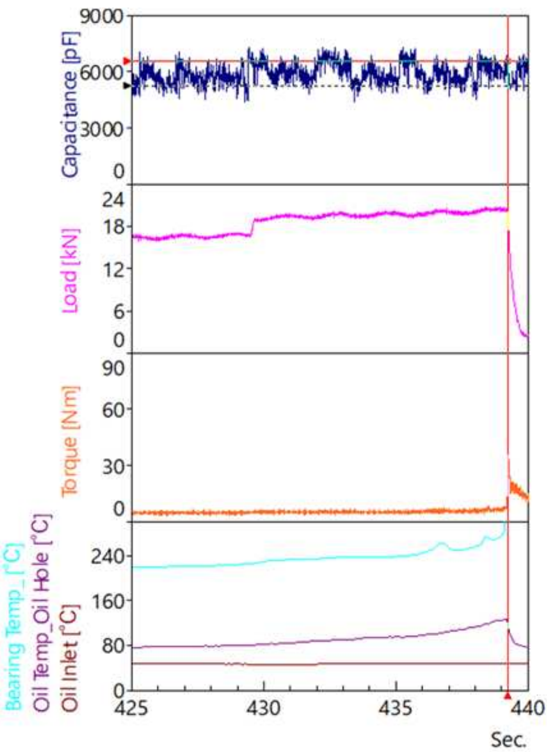

Figure 9. A graph of Figure 8 with the horizontal axis (time) expanded from 425 seconds to 440 seconds

For comparison with other measurement items, Figure 9 shows the magnified view of the values just before seizure, as presented in Figure 8. The timing of seizure and torque increase is slightly after the temperature rise of the bearing. Therefore, it is considered that seizure occurred following an event accompanied by a temperature rise (in this case, an increase in shear heat generation due to a decrease in oil film thickness). This tendency is similar to that observed in the Cu-Bi alloy with Bi overlay in Figure 7 during seizure. The capacitance remained high, indicating that the oil film was thin. It is considered that seizure under this condition was caused by an increase in shear heat generation and similar to the critical temperature condition described by Yamamoto [2]. However, the change in oil supply temperature occurred faster than the change in bearing temperature. This suggests that the true cause might be something other than the critical temperature (of the bearing surface) condition. In Figure 1, the seizure limit is shown, where seizure occurs without boundary lubrication on the high circumferential speed side.

In addition, a confirmation test was conducted to examine the phenomenon of temperature rise at the oil inlet just before seizure. The test was conducted at circumferential speeds ranging from 1 m/s to 25 m/s to determine whether this temperature rise occurred. For Al-Sn-Si bearings, this phenomenon was found to correlate with the circumferential speed, appearing when the speed exceeded 10 m/s. On the other hand, the correlation with the AE signal was confirmed in the region of slow circumferential speed. The data measured in the region of slow circumferential speed (10 m/s) are shown in Figure 10. The vertical axis shows the bearing temperature, load, CR (contact ratio), torque, and RMS value of the AE signal. Unlike the high circumferential speed condition, the torque gradually increased as the load increased. The contact ratio, which was measured to confirm the contact between the shaft and the bearing, also decreased as the load increased. Immediately before seizure, the contact ratio dropped to 0. Since a contact ratio of 1 indicates that the shaft and the bearing are completely separated, and 0 indicates that the shaft and the bearing are in direct contact, it is considered that the number of contact points between the shaft and bearing increased. Just before seizure, the torque, the RMS value of the AE signal, and the bearing temperature all increased, leading to seizure. At this point, there was no clear change in the oil inlet temperature and Oil Temp Oil Hole. It has been reported that the RMS value of the AE signal is related to the progress of wear, suggesting that seizure occurred due to wear. From the changes in the RMS value of the AE signal, the contact ratio, and the torque, the mechanism leading to seizure was considered as follows. As the load increases, the oil film thickness becomes thinner, increasing the chance of contact between the shaft and the bearing. As the load increases further, the oil film is lost, transitioning to mixed and boundary lubrication. Hydrodynamic lubrication is no longer effective, leading to strong contact and resulting in wear with severe plastic deformation. During this time, the RMS value, torque, and bearing temperature all increased. Since it was not possible to return to hydrodynamic lubrication, the torque continued to increase, resulting in the judgment of seizure. This condition is considered to correspond to the critical film thickness condition of Yamamoto's seizure criteria [2].

In other words, the mechanism of seizure is likely to vary depending on the circumferential speed. Therefore, a single technique may not be sufficient for bearing condition monitoring, and it is necessary to consider multiple techniques. This can be explained by referring to Figure 1 on seizure. Although the circumferential speed in this study is different from that in Figure 1, it is considered that this is due to different conditions such as the contact form (point contact and surface contact) of the specimens.

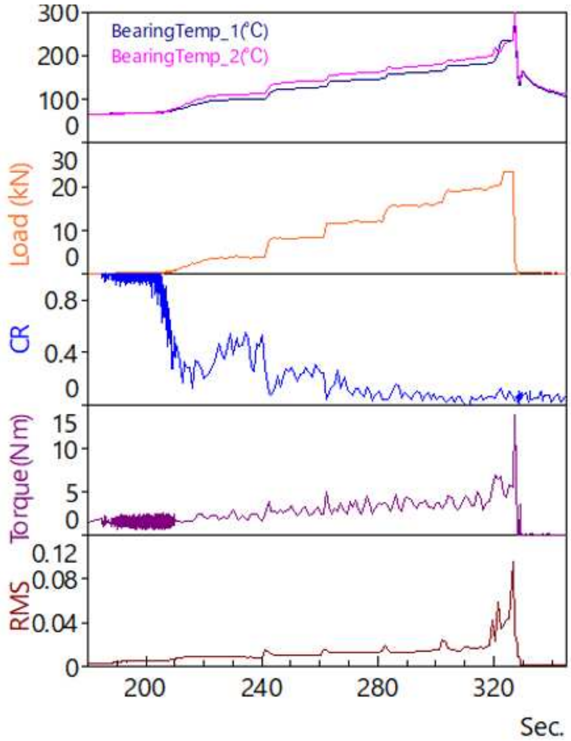

Figure 10. Comparison between the Contact Ratio and AE signal RMS value from seizure test result at 3600 rpm (10 m/s)

3.2 Fatigue Damage

To confirm the precursor phenomena of fatigue in engine bearings, continuous dynamic loading tests were performed using the bearing testing machine shown in Figure 2. The material tested was white alloy, which is widely used in marine engines. Figure 11 shows the appearance of the same bearing during and after the tests. The left photograph shows the bearing after the test, while the right photograph shows the results of liquid penetrant testing. No cracks were observed after the completion of 320,000 cycles. However, after a total of 820,000 cycles, cracks were observed in the bearing. The data collected during the test were analyzed, but no changes in torque or capacitance were detected. Next, AE signal measurement results were analyzed. Up to 320,000 cycles, no sudden AE signal events were observed. Figure 12 shows the analyzed results. From the top to bottom, the vertical axis shows the bearing temperature, RMS value of the AE signal, Strength of the AE signal, and Integrated Count Value of the AE signal. The RMS value, Strength, and Integrated Count Value all increased. This could be attributed to plastic deformation of the bearing alloy caused by repeated loading. Additionally, it is possible that repeated loading increased the bearing surface temperature, leading to the formation of new plastic deformation areas due to the progress of plastic flow. Finally, AE signals were analyzed for the results up to 820,000 consecutive cycles. During this period, several sudden AE signals were observed. An example is shown in Figure 13. The horizontal axis represents time (in microseconds), and the vertical axis represents the amplitude of the AE signal. An AE signal with a large amplitude was measured after 450 microseconds. The amplitude of this sudden AE signal is considered to indicate the development of a crack [7], suggesting that a crack has occurred and begun to develop. The Figure on the left of Figure 14 shows the analysis results of the AE signals up to 820,000 consecutive tests. From the top to bottom, the vertical axis shows the bearing temperature, RMS value of the AE signal, STRENGTH of the AE signal, and Integrated Count Value of the AE signal. The right side of Figure 14 shows the waveform measurement and frequency analysis results of the sudden AE signal, observed at the timing indicated by the vertical line on the Integrated Count Value in the left Figure. A peak in the RMS value is observed at the timing of the first sudden AE signal, but no peak is observed in the Strength value. The integrated value of the count of the AE signal shows a change in slope at the timing of the second sudden AE signal and becomes loose. In other words, the count of the AE signal decreases. In addition, strong values appear continuously in the Strength value, suggesting that the crack is progressing. The FFT analysis result of the sudden AE signal is shown on the right of Figure 14. In both cases, low frequencies below 200 kHz are strongly emitted. The occurrence of cracks suggests the presence of low-frequency components.

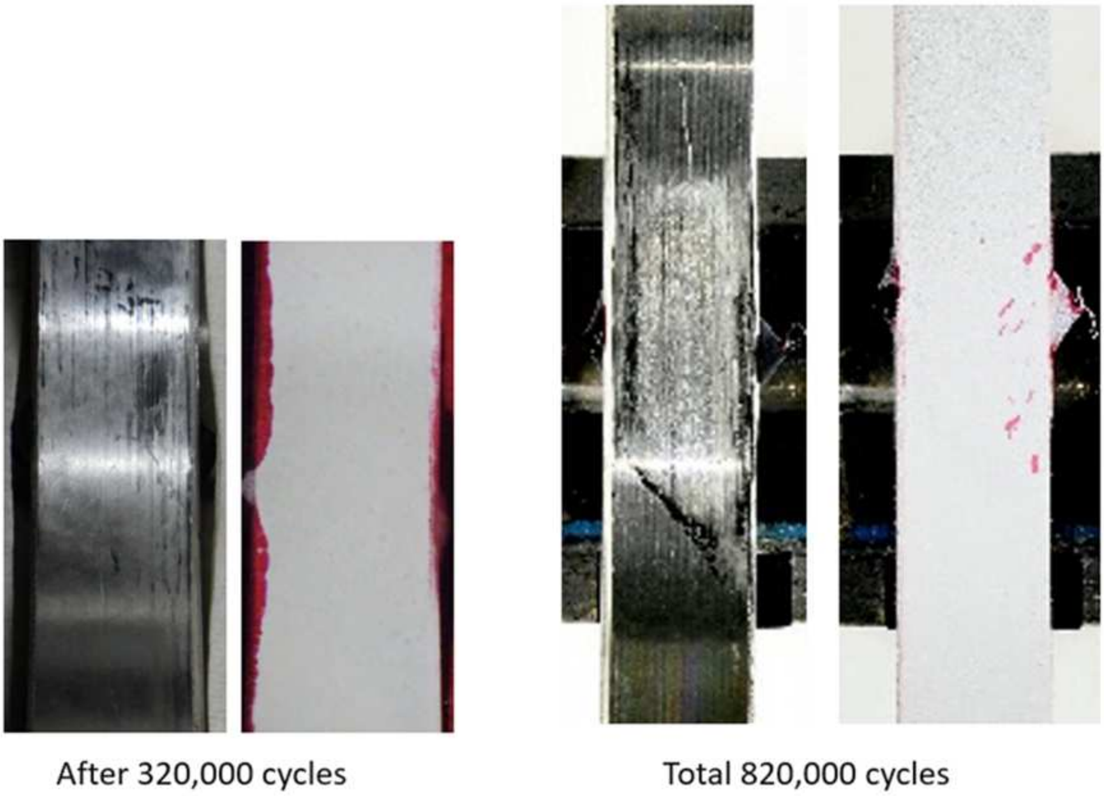

Figure 11. Appearance of the bearing after testing and results of the liquid penetrant test.

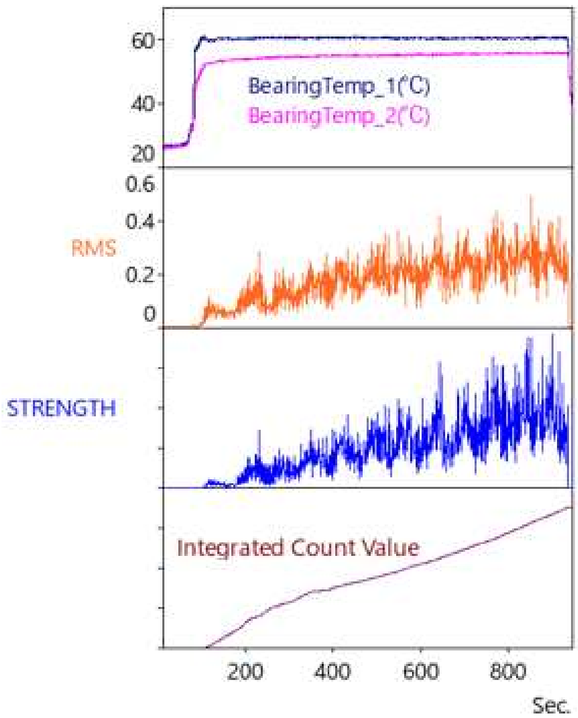

Figure 12. Changes in measured values during fatigue testing up to 320,000 cycles.

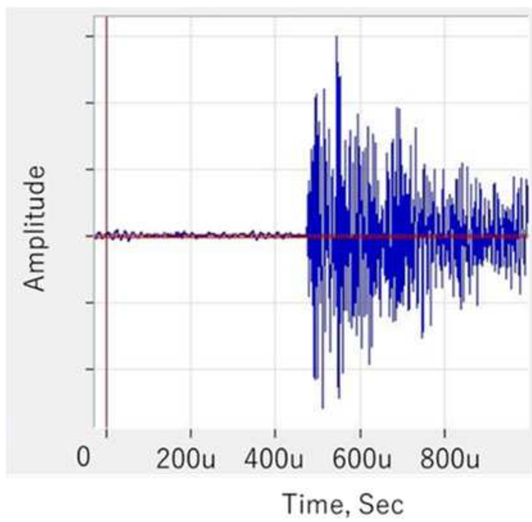

Figure 13. An abrupt AE signal waveform observed during testing.

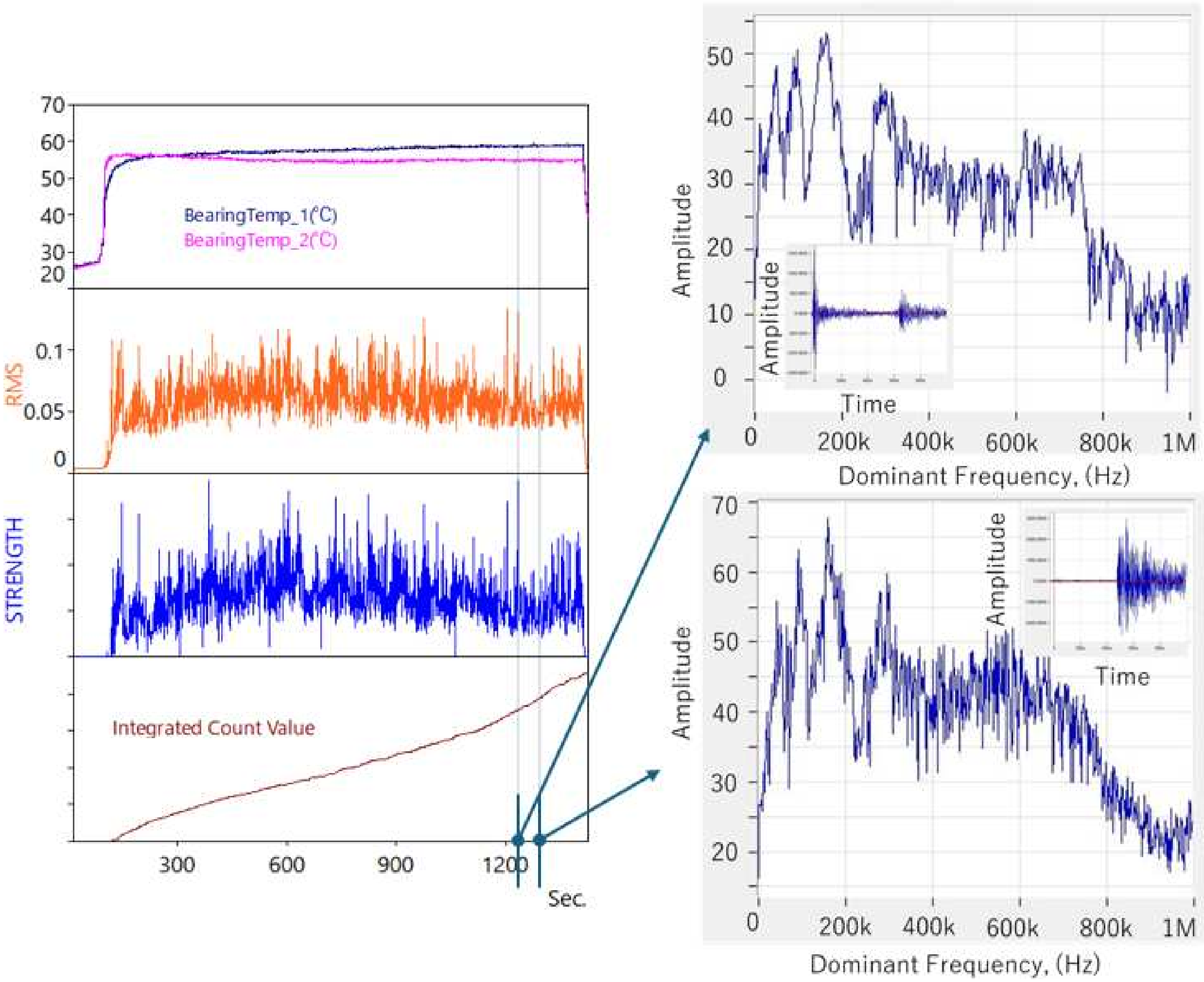

Figure 14. Relationship between measurement data during testing and the abrupt AE signal waveform. The right diagram is a time-frequency conversion diagram of the abrupt AE signal.

Figures 15-16 shows plots of Rise Time and Duration, which are parameters of the AE signal, associated with the sudden AE signal observed to the right of Figure 14. The presence of low frequency components is associated with crack formation, as suggested by the method of Mathis et al [7]. Figure 15 shows the results of up to 320,000 cycles, while Figure 16 shows the results of up to 820,000 cycles. In Figure 15 on the left (up to 320,000 cycles), there is almost no plot in the lower left area (where Rise Time and Duration are less than 100). In contrast, there is a plot in Figure 16 (up to 820,000 cycles). This region is considered to indicate the occurrence of cracks, suggesting that the occurrence of cracks can be detected from this Figure.

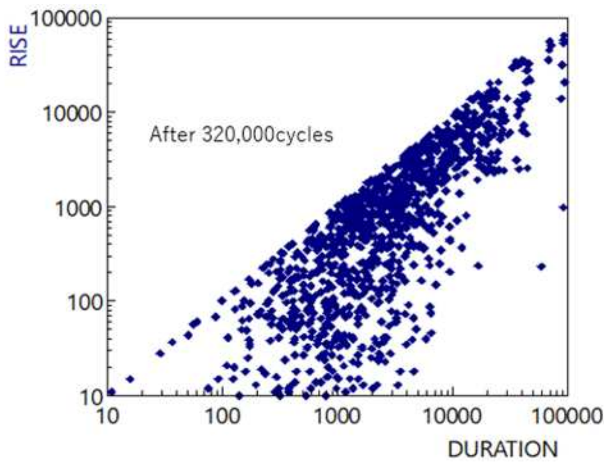

Figure 15. Risetime vs. duration cross-plot. (After 320,000cycles)

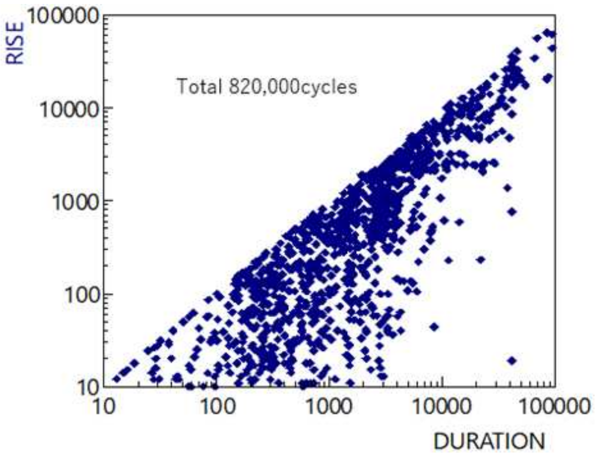

Figure 16. Risetime vs. duration cross-plot. (Total 820,000cycles)

On the other hand, in this test, a clear correlation between the change in RMS value and the occurrence of cracks could not be confirmed. It is considered more effective to detect the occurrence of cracks through the sudden AE signal.

3.3 Application to the Actual Engine

Since engine bearings support the crankshaft or connect the connecting rod to the crankshaft, extensive disassembly of the engine is required for open inspection, which is time-consuming. If the condition can be diagnosed without disassembly, it would significantly reduce man-hours.

However, the events measurable by the AE signal are limited to the occurrence of certain types of damage on the bearing surface and may not be suitable for monitoring seizure. In regions where the circumferential speed exceeds 10 m/s, monitoring the oil inlet temperature is effective for detecting precursor phenomena. In contrast, in regions where the circumferential speed does not exceed 10 m/s, the shear heating value of the oil is relatively low, and the heat generation from the shaft's rotation does not significantly contribute to seizure. Therefore, it is considered that the increase in oil film pressure due to increased load becomes the dominant factor, leading to oil film rupture and seizure. It is assumed that the shape change of the bearing caused by the oil film pressure at that point is detected as a change in the RMS value of the AE signal.

When applied to an actual engine, it is considered that more accurate information can be obtained by monitoring with multiple sensors, including the AE signal, oil drain temperature, oil inlet temperature, bearing temperature, and contact electric resistance.

4 SUMMARY

A method for detecting damage occurring under normal operation was examined and verified.

1 Occurrence of Seizure Damage

In regions where the circumferential speed exceeds 10 m/s, a precursor phenomenon of seizure can be detected by monitoring the temperature change at the bearing inlet. In this test system, 120°C was the threshold value.

In regions where the circumferential speed is less than 10 m/s, the changes in the RMS value of the AE signal was correlated with the seizure phenomenon.

2 About Fatigue Damage

The occurrence of a sudden AE signal was well correlated with the formation of cracks. Parameters of the AE signal, including Risetime and Duration, as well as Strength, were highly correlated with the formation of cracks.

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