Monitoring of Abnormal Vibration to Prevent Seizure of Crosshead Bearings

Tatsumi Kitahara*1; Hiroaki Yamamoto*2; Masaru Otsubo*2; Daisuke Nakahara*3

*1: Department of Mechanical Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka-shi, Fukuoka, 812-8581, JAPAN, E-mail: kitahara@mech.kyushu-u.ac.jp, Phone : +81-92-642-3456
*2: Department of Mechanical Engineering, Kyushu University, JAPAN
*3: Daido Metal Co., Ltd., Tendoh Shinden, Maehara, Inuyama-shi, Aichi, 484-0061, JAPAN

ABSTRACT

The crosshead bearing in large two-stroke diesel engines operates under severe lubrication conditions because hydrodynamic action is limited by low-amplitude, low-velocity oscillation under high specific load. The recent trend toward more compact engines with increased output raises the bearing specific load, thereby significantly increasing the lubrication severity. Therefore it is necessary to find a means to prevent tribological failure such as seizure. In this study, a technique for monitoring abnormal vibration was evaluated using a dynamically loaded bearing seizure test rig that is capable of simulating load patterns and relative oscillations of the crosshead bearing in actual engines. Vibration spikes occur around crank angles of ± 90 deg where the oscillating speed is zero during one cycle. When lubrication is impaired, an abnormal vibration spike caused by severe metal-to-metal contact is generated at a crank angle of approximately +90 deg, where the oil film thickness is a minimum. The frequency of this spike generation increases with the degree of impairment. If running-in is carried out immediately after detecting abnormal vibration, the bearing surface is conformed, thereby avoiding severe metal-to-metal contact damage. The detection of abnormal vibration can be an effective means to prevent seizure of the crosshead bearing.

1. Introduction

The crosshead bearing in large two-stroke diesel engines, as shown in Figure 1, operates under severe lubrication conditions, because it oscillates within a small angle at a low speed and is subject to a high specific load. The crosshead bearing has several axial oil-grooves on the loaded surface to promote oil film exchange with bearing oscillation. However, because the development of a thick oil film by hydrodynamic action is impaired by these oil-grooves, the bearing is more prone to damage by tribological failure such as seizure. The recent trend towards more compact engines with increased output raises the bearing specific load, thereby further increasing the severity of operating conditions. Therefore, it is necessary to find a means to prevent seizure 1)-5).

A technique to monitor vibration using an accelerometer has already been adopted to detect the tribological degradation on many surfaces in cases of rolling bearings, gears and piston rings6)-9). For high-speed fluid film bearings, vibration monitoring has been commonly used to diagnose unstable motion such as oil whirl and oil whip. For crosshead bearings, however, there are very few reports on monitoring techniques to detect the very beginning of severe metal-to-metal contact prior to complete seizure. If careful running-in could be carried out immediately after detecting incipient abnormal vibration, the surface damage that would otherwise be caused by metal-to-metal contact will be reduced. Any damage that does occur will be more likely to recover. Detection of

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abnormal vibration could therefore be an effective means of preventing seizure, and thereby improving the reliability of crosshead bearings.

In the present study, seizure tests were carried out using a dynamically loaded bearing test rig that is capable of simulating the load pattern and relative oscillation of the crosshead bearing in actual engines. During the tests, bearing vibration, surface temperature and oil film resistance were monitored until seizure occurred. A technique for monitoring abnormal vibration was evaluated to allow the critical level of impaired lubrication to be identified. The effect of running-in just after detecting abnormal vibration was also evaluated.

2. Test Procedure

Figure 2 shows a schematic diagram of the test apparatus. The test journal ①, with a diameter of 100mm, was supported on each side by roller bearings ③, and was oscillated within a small angle ($2\psi = 55$deg) by an oscillation device ④. The test bearing ② was subject to a cyclically fluctuating load applied vertically by an oil pressure ram ⑤. The lubricating oil was supplied to the test bearing at a constant temperature of 60℃ by an oil feed pump ⑩.

Figure 3 shows typical changes in the specific load $P_w$, defined as the bearing load divided by the bearing projected area, and the oscillation angular velocity $\omega$ during one cycle. The specific load reached a maximum of $P_{w\text{max}}$ at 0 deg crank angle, i.e. top dead center. The oscillation angular velocity $\omega$ was zero at both -90 deg and +90 deg crank angles, and maximum at 0 deg and 180 deg crank angles, i.e. top and bottom dead center. Although the bearing and the load direction were fixed and the journal itself oscillated in the test apparatus, the test conditions of load pattern and relative oscillation were similar to those for crosshead bearings in actual engines.

Figure 4 shows the major dimensions of the bearing used in the tests. The test bearing, with a diameter of 100mm and a width of 100mm, had four axial oil-grooves at a pitch angle of 45 deg. The lining material was white metal without overlay. The test journal was made of unhardened S55C carbon steel, and its sliding surface was finished to a center line average height $Ra$ of 0.12μm. The bearing clearance ratio $c/r$ ($c$: radial clearance, $r$: journal radius) was set to either 0.0001 or 0.0005. The lubricating oil was SAE10W additive-free engine oil.

During the tests, bearing vibration, bearing surface temperature and oil film resistance were continuously measured until seizure occurred. Seizure was caused by either stopping the oil supply or raising the specific load gradually. The vibration in the direction of oscillation was measured using a piezoelectric accelerometer attached to the bearing housing as shown in Figure 5. The temperature at the center of the bearing was measured using a thermocouple placed at a depth of 0.5 mm below the
bearing surface.

The electrical resistance of the oil film between the bearing and the journal was measured to evaluate the extent of oil film formation. Figure 6 shows the electrical circuit. A voltage of 273 mV was applied to the bearing, which was electrically insulated from the bearing housing, while the journal was earthed. As shown in Figure 7, the output voltage $E$ varies between 0 mV and 273 mV depending on the electrical resistance of the oil film $R$. When the oil film is thick enough to avoid metal-to-metal contact, the electrical resistance of the oil film is infinite. This results in an output voltage of 273 mV. As the extent of metal-to-metal contact increases with decreasing oil film thickness, the electrical resistance of the oil film decreases, thereby causing the output voltage to drop to 0 mV.

3. Test Results and Considerations

3.1 Abnormal vibration in seizure test with the oil supply closed off

3.1.1 Characteristics of vibration signal

Seizure tests in which the oil supply was closed off were carried out to allow a study of the effect of impaired lubrication. Before stopping the oil supply, running-in was carried out under constant conditions of $N=300$ rpm, $\phi=55$ deg and $P_{\text{max}}=18$ MPa.

Figure 8 shows the typical changes in the vibration acceleration $V$ and the output voltage $E$ during one cycle. Under a normal lubrication condition obtained before stopping the oil supply, as shown in Figure 8 (a), two vibration spikes occurred around crank angles of -90 deg and +90 deg where the oscillation speed was zero during one cycle. This is probably because the friction spike at the reversal of the sliding direction created some stick-slip phenomenon. Figure 8 (a) also shows a typical variation in the output voltage $E$ during one cycle. When the oil film was thick enough to create a condition of no metal-to-metal contact, which existed around bottom dead center under conditions of low specific load and high oscillating speed, the electrical resistance of the oil film was very high, resulting in an output voltage of 273 mV. Because the oil film thickness reduced towards boundary lubrication from around top dead center under a heavily loaded condition to 90 deg crank angle under a very low speed condition, the electrical resistance of the oil film decreased, resulting in an output voltage of 0 mV. The oil film formation ratio $F$ over one cycle was estimated from equation (2), as shown in Figure 9.

Figure 8 (b) shows the vibration acceleration $V$ and the output voltage $E$ obtained at 570 seconds after the oil supply was stopped. Because the lubrication condition became more severe with time after stopping the oil supply, a thick oil film could not be formed, resulting in an output voltage of 0 mV throughout one cycle. An increase in the vibration spike occurred at a crank angle of approximately +90 deg. However, a significant increase in the vibration amplitude was not

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evident at other crank angles. Figure 8 (c) shows the vibration acceleration $V$ and the output voltage $E$ obtained at 790 seconds after stopping the oil supply, immediately before seizure occurred. The vibration spike increased significantly at a crank angle of approximately +90deg. However, the vibration amplitude at all other crank angles increased only slightly.

Figure 10 shows the calculated oil film thickness $h_{min}$ during one cycle\(^{[2]}\). The oil film thickness is not at its lowest at 0 deg crank angle where the specific load is maximum, but reaches a minimum just after +90 deg crank angle where the oscillation speed is zero. The oil film thickness becomes a maximum at a crank angle of approximately -120 deg, just before the bearing specific load begins to increase. The oil film obtained at +90 deg crank angle is lower than at -90 deg crank angle. It is considered that this is why the abnormally increased vibration spike occurred at this timing (+90 deg crank angle) in the cycle when lubrication was impaired.

Figure 11 shows the vibration acceleration $V$ monitored continuously throughout 10 cycles. Under the normal lubrication condition before stopping the oil supply, the cyclic variation of the vibration signal was very similar throughout all 10 cycles. At 570 seconds after the oil supply was stopped, an abnormally increased vibration spike could be seen in six of the ten cycles, identified by a broken line, while the amplitude of the vibration spike was unchanged in the other four cycles. This demonstrated that the oil film breakage and its recovery were repeated at the very beginning of severe metal-to-metal contacts. However, because the degree of the oil film breakage was more extensive at 790 seconds, just before seizure occurred, complete oil film recovery could not occur, thereby creating the abnormally increased vibration spikes in all 10 cycles.

3.1.2 Detection of abnormal vibration

Based on the characteristics of the vibration signal described above, abnormal vibration was evaluated to detect the very beginning of severe metal-to-metal contacts before seizure occurred. Figure 12 shows the definition of abnormal vibration. The vibration spikes at +90 deg crank angle obtained under the normal lubrication condition before stopping the oil supply
was set to $V_0$. The vibration spike $V_m$ was increased by stopping the oil supply, thus impairing lubrication. The threshold level $V_{cr}$ was determined as $1.2V_0$. When the vibration spike $V_m$ exceeded the threshold level $V_{cr}$, the vibration spike was defined as abnormal. The occurrence ratio $X$ was defined as the number of times the abnormal vibration occurred, expressed as a percentage of the total number of cycles.

Figure 13 shows the changes in surface temperature $T$, oil film formation ratio $F$, root mean square (RMS) value of vibration acceleration $V_{rms}$ and abnormal vibration occurrence ratio $X$ as a function of time after stopping the oil supply. The values of $T$ and $V_{rms}$ increased rapidly at 770 seconds, immediately before seizure occurred. It is too late to prevent seizure after detecting the rapid increase in these values. Therefore, monitoring of the bearing surface temperature and the RMS of vibration cannot be effective in preventing seizure.

On the other hand, the oil film formation ratio $F$ dropped to 0% around 200 seconds after stopping the oil supply, even when only relatively mild contacts occurred. Because the hydrodynamic oil film is very thin in crosshead bearings, a rapid decrease in the oil film resistance caused by mild contacts can occur frequently. Therefore, it is difficult to predict seizure based on a rapid decrease in the oil film resistance.

When the abnormally increased vibration spike caused by severe metal-to-metal contacts is generated
frequently, the possibility of seizure becomes very high. An increase in the abnormal vibration occurrence ratio \( X \) to more than 50\% means that the rate of the oil film breakage is more significant than that of recovery. Therefore, the unacceptable level of the abnormal vibration occurrence ratio was set to 50\%. As shown in Figure 13, the abnormal vibration occurrence ratio reached 50\% at 470 seconds after the oil supply was stopped, while the bearing surface temperature \( T \) and the RMS of vibration remained very stable. The monitoring of abnormal vibration allows the critical level of impaired lubrication to be identified, thereby preventing seizure.

3.2 Abnormal vibration in seizure test with increasing specific load

One further seizure test, in which the lubrication condition was impaired by gradually raising the specific load, was carried out. This test also used the above mentioned vibration monitoring technique. Before the test, running-in was performed under constant conditions of \( N=300\text{cpm}, \ 2\phi=55\text{deg} \) and \( P_{\text{max}}=20\text{MPa} \). The maximum specific load \( P_{\text{max}} \) was then raised at a rate of 0.2 MPa / 30 seconds until seizure occurred. Figure 14 shows the changes in the vibration acceleration \( V \) as the maximum specific load \( P_{\text{max}} \) was raised from 20 MPa to 24.2 MPa. Under the normal lubrication condition obtained at a low specific load of 20 MPa, as shown in Figure 14 (a), the vibration spikes occurred around crank angles of -90 deg and +90 deg where the oscillation speed was zero. When the maximum specific load increased to 23.2 MPa, as shown in Figure 14 (b), an abnormally increased vibration spike was generated at a crank angle of approximately +90 deg. However, at all other crank angles, no significant increase was evident. When the maximum specific load increased to 24.2 MPa, immediately before the development of seizure, as shown in Figure 14 (c), the vibration spike increased significantly.

Impaired lubrication severity was evaluated by means of the abnormal vibration occurrence ratio \( X \) as shown in the previous section. The vibration spike obtained under the normal condition at a low specific load of 20 MPa was determined as \( V_\phi \). The threshold level \( V_\phi \) was set to 1.2 \( V_\phi \). When the vibration spike exceeded the value of \( V_\phi \), it was defined as abnormal. The occurrence ratio \( X \) was defined as in Section 3.1.2 above.

Figure 15 shows the changes in surface temperature \( T \), oil film formation ratio \( F \), root mean square value of vibration \( \text{RMS} \) and \( X \) by raising maximum specific load.
acceleration $V_{nm}$ and abnormal vibration occurrence ratio $X$ when the maximum specific load $P_{w_{max}}$ was increased. The values of the surface temperature $T$ and the RMS of vibration $V_{rms}$ increased rapidly at the specific load of $P_{w_{max}}=24$ MPa immediately before seizure occurred. The oil film formation ratio $F$ dropped to 0% at a relatively low specific load of $P_{w_{max}}=21.8$ MPa. Therefore, it is difficult to adopt these lubrication parameters to diagnose the onset of seizure. The abnormal vibration occurs frequently at the specific load of $P_{w_{max}}=23.2$ MPa, thereby causing the abnormal vibration occurrence ratio $X$ to reach 50%. This demonstrates the beginning of severe metal-to-metal contacts leading to seizure.

In the following section, the effect of the running-in immediately after detecting the abnormal vibration was evaluated.

### 3.3 Effect of running-in just after detecting abnormal vibration

The operation was modified to promote running-in immediately after the abnormal vibration occurrence ratio $X$ exceeded 50%. The rate of increase of specific load was reduced from 0.2 MPa / 30 seconds to 0.2 MPa / 240 seconds, as shown in Figure 16. Figure 17 shows the changes in surface temperature $T$, oil film formation ratio $F$, root mean square value of vibration acceleration $V_{rms}$ and abnormal vibration occurrence ratio $X$ when the operation was modified. The abnormal vibration occurrence ratio reached 50% at a specific load of $P_{w_{max}}=22.2$ MPa, at which point the operation was modified to promote running-in. Because running-in was carried out immediately after detecting the abnormal vibration, the bearing surface conformed, thereby avoiding severe metal-to-metal damage. As a result, seizure no longer occurred when the specific load of $P_{w_{max}}=24.2$ MPa was reached. The monitoring of abnormal vibration can be an effective means to detect incipient lubrication degradation, and thereby prevent seizure of crosshead bearings.

### 4. Conclusions

From experiments conducted to evaluate the onset of abnormal vibration to prevent seizure of the crosshead bearing, the following conclusions were obtained:

1. Vibration spikes occur around crank angles of -90 deg and +90 deg where the oscillating speed is zero during one cycle. When lubrication is impaired, an abnormal vibration spike caused by severe metal-to-metal contact is generated at a crank angle of approximately +90 deg, where the oil film thickness is a minimum. The frequency of this spike generation increases with the degree of impairment.

2. It is impossible to detect the very beginning of severe metal-to-metal contacts based on the rapid increase in bearing surface temperature and the RMS value of vibration. It is also difficult to predict the likelihood of seizure based on a sudden
decrease in oil film resistance.

(3) Avoidance of bearing seizure is best achieved by limiting the abnormal vibration occurrence ratio to 50%.

(4) If running-in is carried out immediately after detecting abnormal vibration, the bearing surface is conformed, thereby avoiding severe metal-to-metal contact damage.

(5) Detection of abnormal vibration can be an effective means to prevent seizure of crosshead bearings.

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