Lubrication performance analysis of the connecting rod bearing based on AVL EXCITE

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Abstract. The lubrication state of connecting rod bearing has influence on the reliability and lifetime. It is necessary to analyze the lubrication state of connecting rod bearing to evaluate and design the lubrication performance. The connecting rod bearing hydrodynamic lubrication simulation model was set up for 9XX diesel engine and journal bearing fatigue test-rig at Glacier Vandervall. The effect of maximum oil film pressure, minimum oil film thickness and maximum asperity contact pressure on the lubrication performance were studied. Then the lubrication states of connecting rod bearings under different working conditions were discussed based on two test machines. The results are of great significance for analyzing the lubrication performance of connecting rod bearings and the reliability of bearings.

Keywords: Connecting rod bearings; AVL EXCITE; lubrication state; EHD; Lubrication performance

1. Introduction
As one of the most critical elements in diesel engines, journal bearings are applied to support load and transform the reciprocating motion of the pistons into the rotary motion of the crankshaft [1]. According to the survey, bearing failure incidents have accounted for 24.4% of engine failure incidents and cost [2]. If the connecting rod bearing runs for a long time in a poor lubrication state, the asperity contact will occur between the bearing and the journal, which causes to severe bearing failure [3]. Therefore, it is necessary to study the lubrication performance of the connecting rod bearing, this can provide guidance for improving the reliability and service life of the bearing in actual industry.

The researches of the bearing lubrication performance analysis usually simplify the geometry model and obtain the lubrication states using the Reynolds equation derived from Navier-Stokes equations and continuity equations [4-5]. However, there are still some limitations as follows: firstly, the lubricant viscosity is assumed to the constant neglecting the influence of viscosity changing on the lubrication performance [6-7]. Secondly, the elastic deformation of the bearing and the journal is not considered in some articles [8]. Furthermore, some researchers ignore the effect of surface topography parameters on lubrication characteristics [9-10]. Therefore, in this paper, considering the factors of the lubricant viscosity, the elastic deformation, and the surface topography, the lubrication performance of the connecting rod bearing in 9XX diesel engine and journal bearing fatigue test-rig at Glacier Vandervall is discussed, the lubrication states of connecting rod bearings under different working conditions in two devices are compared to provide technical support for bearing lubrication performance analysis and the design of the working conditions.
2. Theory

2.1. Averaged Reynolds equation

The full oil film interaction is solved by the averaged Reynolds equation, which considers the influence of roughness amplitudes. The specific formula is as follows [11]:

\[
\frac{\partial}{\partial x} \left( -\frac{h_r}{12\eta} \frac{\partial P}{\partial x} + \frac{u_t + u_s}{2} h_r \right) + \frac{\partial}{\partial y} \left( -\frac{h_r}{12\eta} \frac{\partial P}{\partial y} \right) + \frac{\partial h_r}{\partial t} = 0
\]

(1)

where \( h_r \) denotes the real clearance considering roughness heights of journal and bearing. \( P \) is the hydrodynamic pressure and \( x, y \) represents the circumferential and axial direction respectively. \( H \) indicates the oil viscosity.

2.2. Lubricating oil properties

The Vogel equation [12] is applied to describe the relationship between the oil viscosity and oil temperature in the simulation model:

\[
\eta(T) = Ae^{\frac{B}{T+C}}
\]

(2)

where \( A = 0.198 \text{ mPa·s}, B = 736.69 \degree C, C = 88.9 \degree C \) for oil Shell Rimula R3 Multi 10W-30 in this paper. \( T \) is the oil temperature.

2.3. Asperity contact interaction

Asperity contact interaction exists when asperity summits of two nominal flats rub each other. The Greenwood and Tripp model is used to evaluate the behaviour of asperity contact. The asperity contact pressure is calculated as:

\[
P_{ac} = KE^* F_{5/2} (H_s)
\]

(3)

where the elastic factor \( K \) is set to 0.003. \( F_{5/2}(H_s) \) stands for the form function and \( E^* \) is the composite elastic modulus, as listed in Eq. (4) and (5):

\[
F_{5/2}(H_s) = \begin{cases} 
4.4086 \times 10^{-4} (4 - H_s)^{6.804} & H_s < 4 \\
0 & H_s \geq 4 
\end{cases}
\]

(4)

\[
E^* = \frac{1}{\left( \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{1/2}}
\]

(5)

where \( H_s \) is the non-dimensional summit clearance, \( \nu_1 \) and \( \nu_2 \) are Poisson ratio of bearing material and shaft material respectively, \( E_1 \) and \( E_2 \) are Young modulus of bearing material and shaft material respectively.

2.4. Lubrication conditions

Generally, the film thickness ratio is designed as a criterion for the determination of lubrication condition. It is calculated as follows:

\[
\lambda = \frac{h_{min}}{\sqrt{\sigma_1^2 + \sigma_2^2}}
\]

(6)

where \( h_{min} \) represents the minimum oil film thickness. \( \sigma_1 \) and \( \sigma_2 \) are surface roughness of bearing and journal respectively. According to the range of the film thickness ratio, journal bearing lubrication regimes are divided into three kinds: boundary lubrication (\( \lambda \leq 1 \)), mixed lubrication (\( 1 < \lambda < 3 \)), hydrodynamic lubrication (\( \lambda \geq 3 \)).
3. Simulation

The connecting rod big-end bearings of 9XX diesel engine and journal bearing fatigue test-rig at Glacier Vandervall are modelled by AVL EXCITE to study the lubrication performance. The modeling process is as follows: firstly, the geometric model of the connecting rod assembly is established in Solidworks, which includes the connecting rod, the connecting rod small-end bearing, and the connecting rod big-end bearing. Then the geometric model is meshed in hypemesh software. The tetrahedral mesh is used for the connecting rod model and the hexahedral mesh is applied for the small-end and big-end bearing models. Based on the mesh model, the finite element model is obtained by Abaqus solver. Finally, in AVL EXCITE, the connecting rod dynamic model is built and the information of the finite element model is input. The simulation models of two devices are shown in Figure 1. By setting the simulation parameters and adding the hydraulic cylinder pressure, the lubrication characteristics can be obtained. In this paper, the lubrication performance of 9XX diesel engine under two cylinder pressure conditions and journal bearing fatigue test-rig under a maximum cylinder pressure of 40Mpa is calculated. Table 1 lists the simulation parameters. The plots of the hydraulic cylinder pressure of two devices are shown in Figure 2.

| Parameter                              | 9XX diesel engine | Journal bearing fatigue test-rig at Glacier Vandervall |
|----------------------------------------|-------------------|--------------------------------------------------------|
| Hydraulic cylinder type               | four-stroke       | two-stroke                                             |
| The number of hydraulic cylinders     | 20                | 1                                                      |
| Hydraulic cylinder diameter (mm)      | 230               | 130                                                   |
| Stroke (mm)                           | 230               | 0.76                                                   |
| Shaft rotational speed (rpm)          | 1405/1455         | 3000                                                  |
| Shaft diameter (mm)                   | 158               | 52.7                                                   |
| Bearing width (mm)                    | 62                | 29.62                                                  |
| Lubricating oil supply pressure (bar) | 8                 | 6                                                      |
| Inlet oil temperature (℃)             | 90                | 70                                                     |
| Shaft surface roughness (μm)          | 0.63              | 0.2                                                    |
| Bearing surface roughness (μm)        | 0.2               | 0.45                                                   |

Figure 1. The simulation models: (a): the finite element model of the connecting rod assembly of 9XX diesel engine; (b): the finite element model of the connecting rod assembly of journal bearing fatigue test-rig at Glacier Vandervall; (c): the dynamic model.
4. Results and discussion

4.1. The simulation results in 9XX diesel engine

For 9XX diesel engine, the lubrication performance of the connecting rod bearing under two working conditions is evaluated. Figure 3 shows the peak oil film pressure (POFP) and the minimum oil film thickness (MOFT) plots of the connecting rod bearing in 9XX diesel engine. Figure 4 shows the peak asperity contact pressure (PASP) distribution diagram. The simulation results of 9XX diesel engine are listed in Table 2. It can be found that when the shaft rotational speed is set at 1405rpm, the maximum POFP and minimum MOFT of the connecting rod bearing under 80% load are 116.2Mpa and 0.77μm, respectively. The calculated film thickness ratio is 1.165. Therefore, the bearing runs in mixed lubrication. The slight asperity contact distributes in the range of 100°~120° of the upper connecting rod bearing. The maximum PASP is 18.4Mpa. While for the working conditions of 1455rpm and 100% load, the maximum POFP and the minimum MOFT are 139.8Mpa and 0.51μm, respectively. The film thickness ratio decreases to 0.772. The bearing lubrication state changes from mixed lubrication to boundary lubrication. The asperity contact still appears on two sides of the bearing. However, the degree of the asperity contact is more serious and the maximum PASP is increased to 44.6Mpa.

**Table 2. Simulation results of 9XX diesel engine.**

| Parameter               | 1405rpm, 80% load | 1455rpm, 100% load |
|-------------------------|-------------------|--------------------|
| Minimum MOFT (μm)       | 0.77              | 0.51               |
| Maximum POFP (Mpa)      | 116.2             | 139.8              |
| Maximum PASP (Mpa)      | 18.4              | 44.6               |
| Film thickness ratio    | 1.165             | 0.772              |
| Lubrication condition   | Mixed lubrication | Boundary lubrication |

**Figure 2.** The plots of the hydraulic cylinder pressure: (a): 9XX diesel engine; (b): journal bearing fatigue test-rig at Glacier Vandervall.

**Figure 3.** The simulation results of the connecting rod bearing in 9XX diesel engine: (a): the peak oil film pressure (POFP); (b): the minimum oil film thickness (MOFT).
4.2. The simulation results in journal bearing fatigue test-rig

For journal bearing fatigue test-rig at Glacier Vandervall, the lubrication performance of the connecting rod bearing under three shaft rotational speeds (3500rpm, 4000rpm, and 4500rpm) and three relative clearances (1‰, 2‰, and 3‰) is discussed. The simulation results are summarized in Table 3.

According to the simulation results of Table 3, it can be found that at the same relative clearance, the maximum POFT and the minimum MOFT gradually increases with the increase of the speed. When the relative clearance is set at 1‰, the POFP and MOFT of the connecting rod bearing under different shaft rotational speeds are shown in Figure 5. The obtained film thickness ratios indicate that the bearing lubrication state is mixed lubrication and is not affected by the change of the speed. When the relative clearance is set to 2‰, the bearing lubrication state changes from boundary lubrication to mixed lubrication with the increase of the speed. The lubrication performance is improved. While for the relative clearance of 3‰, the increase of the speed does not affect the bearing lubrication state, which remains boundary lubrication. Therefore, in order to ensure the reliability and the service life of the connecting rod bearing in journal bearing fatigue test-rig, the speed should not be too low. In addition, when the relative clearance is 2‰, the bearing lubrication performance can be improved by increasing the speed.

While at the same speed, the maximum POFT gradually increases and the minimum MOFT gradually decreases with the increase of the relative clearance. Simultaneously, the bearing lubrication state changes from mixed lubrication to boundary lubrication. The lubrication performance is improved. When the speed is 3500rpm, the POFP and MOFT of the connecting rod bearing under different relative clearances are shown in Figure 6. Hence, it is necessary to choose an appropriate relative clearance to ensure better lubrication performance of the bearing. The relative clearance should not be too large.

![Figure 4](image_url)

**Figure 4.** The peak asperity contact pressure (PASP) distribution diagram of the connecting rod bearing in 9XX diesel engine: (a) 1405rpm, 80% load; (b) 1455rpm, 100% load.

![Figure 5](image_url)

**Figure 5.** The simulation results of the connecting rod bearing in journal bearing fatigue test-rig at Glacier Vandervall under the relative clearance of 1‰ for different speeds: (a): the peak oil film pressure (POFP); (b): the minimum oil film thickness (MOFT).
The simulation results of the connecting rod bearing in journal bearing fatigue test-rig at Glacier Vandervall at 3500rpm for different relative clearances: (a): the peak oil film pressure (POFP); (b): the minimum oil film thickness (MOFT).

**Table 3.** Simulation results of journal bearing fatigue test-rig at Glacier Vandervall.

| Load (Mpa) | Shaft rotational speed (rpm) | Relative clearance | Minimum MOFT (μm) | Maximum POFP (Mpa) | Film thickness ratio | Lubrication condition       |
|------------|------------------------------|--------------------|-------------------|-------------------|---------------------|-----------------------------|
| 3500       | 1%                           | 0.83               | 91.4              | 1.687             |                     | Mixed lubrication           |
| 3000       | 2%                           | 0.47               | 112.6             | 0.955             |                     | Boundary lubrication        |
| 4000       | 3%                           | 0.30               | 139.8             | 0.610             |                     | Boundary lubrication        |
| 4500       | 1%                           | 0.93               | 91.8              | 1.890             |                     | Mixed lubrication           |
| 3500       | 2%                           | 0.51               | 112.8             | 1.037             |                     | Mixed lubrication           |
| 4000       | 3%                           | 0.32               | 140               | 0.650             |                     | Boundary lubrication        |
| 4500       | 1%                           | 1.02               | 92.5              | 2.073             |                     | Mixed lubrication           |
| 3500       | 2%                           | 0.54               | 113.5             | 1.098             |                     | Mixed lubrication           |
| 4000       | 3%                           | 0.33               | 140.3             | 0.671             |                     | Boundary lubrication        |

4.3. The comparison results

Based on the simulation results in Table 2 and Table 3, it can be found that for 9XX diesel engine, the minimum MOFT and the maximum POFT at 1405rpm and under 80% load are 0.77μm and 116.2Mpa, respectively. While for journal bearing fatigue test-rig, under the fixed load condition, the minimum MOFT and the maximum POFT at 4500rpm and a relative gap of 2‰ are 0.54μm and 113.5Mpa, respectively. The minimum MOFT values of two devices differ by 0.23μm and the maximum POFT values are close. Besides, the lubrication states of two devices are mixed lubrication. So it can be considered that the lubrication performance of two devices is close. Similarly, when the connecting rod bearing of 9XX diesel engine runs at 1455rpm and under 100% load, the minimum MOFT and the maximum POFT are 0.51μm and 139.8Mpa, respectively. While for journal bearing fatigue test-rig, under the fixed load condition, the minimum MOFT and the maximum POFT at 4500rpm and a relative gap of 3‰ are 0.33μm and 140.3Mpa, respectively. The minimum MOFT values of two devices differ by 0.18μm and the maximum POFT values are similar. The lubrication states of two devices are boundary lubrication. Therefore, under the corresponding working conditions of two devices, the lubrication performance is similar. The equivalent working conditions can provide guidance for the bearing lubrication performance evaluation in different devices.

5. Conclusion

In this paper, the lubrication performance of the connecting rod bearings in 9XX diesel engine and journal bearing fatigue test-rig at Glacier Vandervall is studied by AVL EXCITE. The main conclusions are as follows:
For 9XX diesel engine, the connecting rod bearing runs in the mixed lubrication under 80% load when the speed is 1405rpm. The lubrication state changes to boundary lubrication when the connecting rod bearing runs at 1455rpm under 100% load. Under two working conditions, the asperity contact appears between the connecting rod bearing and the shaft, which is distributed in the range of 100°-120° upper shell angle.

For journal bearing fatigue test-rig at Glacier Vandervall, under the same hydraulic cylinder pressure and relative clearance, the maximum POFT and the minimum MOFT gradually increases with the increase of the speed. When the relative clearance is set to 2‰, the bearing lubrication performance can be improved with the increase of the speed.

For journal bearing fatigue test-rig at Glacier Vandervall, under the same hydraulic cylinder pressure and speed, the maximum POFT gradually increases and the minimum MOFT gradually decreases with the increase of the relative clearance. The bearing lubrication performance can be improved.

The bearing lubrication performance of 9XX diesel engine at 1405rpm under 80% load are similar to that of journal bearing fatigue test-rig at Glacier Vandervall at 4500rpm and a relative clearance of 2‰ under a maximum cylinder pressure of 40Mpa. The lubrication states are mixed lubrication; While the bearing lubrication performance of 9XX diesel engine at 1455rpm under 100% load are similar to that of journal bearing fatigue test-rig at Glacier Vandervall at 4500rpm and a relative clearance of 3‰ under a maximum cylinder pressure of 40Mpa. The lubrication states are boundary lubrication.

In future work, the influence of different surface roughness parameters, lubricating oil temperature, and viscosity on the lubrication performance of the connecting rod bearing will be studied in detail. Simultaneously, for 9XX diesel engine and journal bearing fatigue test-rig at Glacier Vandervall, the equivalent parameters corresponding to similar lubrication states, such as surface roughness, lubricating oil temperature, and viscosity will be calculated and compared.

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