Effects of Rotational Conditions on Performance of Gear Unit Pinion Bearing

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Tapered roller bearings are mainly used in rotating parts of gear units on railway vehicles. In order to prevent bearing seizure and to improve gear unit reliability, it is important to ensure appropriate clearance between bearings. Bearing clearance changes from its initial value as vehicles travel due to atmospheric temperatures and variation in the initial values in the gear unit assembly, which affects bearing performance. In this research, an actual gear unit was subjected to bench rotation tests under various bearing clearances and various atmospheric temperatures. Bearing temperature and torque were measured, and changes in bearing clearance were estimated.

Key words: gear unit, pinion, machine element, tapered roller bearing, bearing clearance

1. Introduction

In Japan, most gear units for power transmission in railway vehicles (electric cars) employ one-stage speed reducers, and use tapered roller bearings for the rotating parts [1]. Two tapered roller bearings are installed on the pinion shaft, which are referred to as pinion bearings, to support the pinion shaft against the gear case. Similarly, two tapered roller bearings are installed in the axle, which are referred to as gear bearings, to support the gear case. These bearings are lubricated with gear oil spread by the gear. Among these bearings, the rotational speed of the pinion bearings is higher than that of the gear bearings, so the sliding speed at the contact surface between roller ends and inner ring flanges of the pinion bearings is higher than that of the gear bearings. In the pinion bearings, therefore, seizure may occur by metal-to-metal contact from inadequate lubrication between roller ends and inner ring flanges [2]. In order to prevent pinion bearing seizures, it is important to appropriately manage bearing clearances. Although this bearing clearance is usually adjusted in a specified range when assembling gear units, this initial clearance value can change due to temperature changes in peripheral parts of the bearings as vehicles travel [3, 4].

The authors of this paper have already reported the behavior of bearing temperatures and torque under various rotational conditions, lubricating conditions, and bearing clearances by performing basic rotational tests of pinion bearings [5]. On the other hand, the previous research was conducted under circulating lubrication with gear oil, therefore there are many unverified items about the performance and the behavior of pinion bearings mounted on an actual gear unit which are lubricated with gear oil spread by the gear. Therefore, in this study, the effects of initial bearing clearance and atmospheric temperature on the bearing temperature and torque were investigated in bench rotation tests on an actual gear unit. In addition, the behavior of bearing clearance during the rotation of gears was estimated from the temperature changes on peripheral parts of bearings [6].

2. Test apparatus

2.1 Test rig of gear unit

Figure 1 shows the test rig of a gear unit used in this study. This rotation testing machine has the structure in which a pinion shaft is rotated by a motor through a coupling, using an actual gear unit as a specimen. The gear unit is attached to an axle and supported by two bearings at both ends of the axle and a torque reaction rod. Blowers are installed in the vicinity of the gear unit and the support bearings to cool them.

The specifications of the gear unit are shown in Table 1, and a schematic view of the gear unit is shown in Fig. 2. The reduction gear mechanism was composed of helical gears with a left-hand

![Fig. 1 Test rig of gear unit]

![Fig. 2 Schematic view of testing gear unit]

| Table 1 Specification of testing gear unit |
|------------------------------------------|
| Material of gear case | Aluminum alloy |
| Material of housings | Carbon steel |
| Material of pinion and pinion shaft | Alloy steel |
| Dimensions of pinion bearings | (Tapered roller bearing) |
| Outside: Φ150 mm × Bore: Φ70 mm × Width: 38 mm |
pinion and a right-hand gear. The pinion shaft was installed with pinion bearings on both sides of the pinion, which supported the pinion shaft against the gear case. The axle was installed with gear bearings on both sides of the gear, which supported the gear case against the axle. The inner rings of the pinion bearings were fitted to the pinion shaft, and the inner rings of the gear bearings were fitted to the axle. On the other hand, the outer rings of these bearings were fitted to the housings which were fastened to the gear case. The gear case was made of aluminum alloy, and gear oil was stored inside.

2.2 Measuring items

While the gear unit is operating, the temperatures, and the rotational speed and the torque of the pinion shaft can be measured (Fig. 3). The temperatures were measured at the outer diameter surfaces of the pinion bearings and the gear bearings, the surface of the gear case, the gear oil, and the atmosphere. These were all measured with thermocouples. The rotational speed of the pinion shaft was measured with a photoelectric rotation detector. The torque of the pinion shaft was obtained by calculation using the current value of the motor. Furthermore, the temperature at the end of the pinion shaft was measured with a small temperature data logger (Fig. 4).

2.3 Test bearing

In this study, we focused on the pinion bearing (hereinafter referred to as “bearing”). The outer ring, inner ring, and rollers were made of high-carbon chromium bearing steel. The cage was made of low-carbon steel. The bearing clearance (combination clearance in the axial direction of the two bearings) could be changed by inserting shims of various thicknesses between the gear case and the pinion housing (Fig. 5).

3. Test method

The rotation tests were performed under the constant conditions shown in Table 2. Figure 6 shows the rotational pattern of the pinion shaft. Maximum rotational speed of the pinion shaft is 6,000 min⁻¹. This rotational speed corresponds to a vehicle speed of approximately 320 km/h. The gear case and the support bearings were air-cooled when the rotational speed of the pinion shaft was 200 min⁻¹ or higher.

Under the constant conditions shown in Table 2, the axial clearance of the pinion bearings and atmospheric temperature were variously changed. They are shown in Fig. 7. Since the gear case and the pinion shaft were made of different materials shown in Table 1, the bearing clearance varied depending on the temperature of the gear unit. In this paper, the bearing clearances are shown as values by converting the measured values at assembling to the values at 20°C.
4. Temperature change of each part of the gear unit and torque of pinion shaft

4.1 Influence of the bearing clearance

Figure 8 shows the temperature change of each part of the gear unit and torque of the pinion shaft from the start of rotation to 3,600 s for the tests with different bearing clearances under conditions where the atmospheric temperature was close to 20°C. Regardless of the test conditions, the temperature measured at the end of the pinion shaft was the highest among the temperatures of each part, and increased rapidly from the start of rotation to approximately 600 s as the bearing clearance was smaller. In particular, when the bearing clearance was 0.06 mm, it reached about 80°C in 600 s after the start of rotation, and after a pause in the temperature increase, it rose slowly again. This is thought to be due to an increase in frictional resistance and rolling viscous resistance inside the bearing. The increase in these resistances resulted from the widening of a load contact zone and an increase in the number of loaded rollers due to a relatively small clearance. Although it is not as apparent as the trend of temperature at the end of the pinion shaft described above, the temperature rise in the outer ring of the bearing immediately after the start of rotation was more rapid on both the motor side and the counter motor side bearings as the bearing clearance was reduced. The tendency described above weakened further at the temperature of the gear case surface and gear oil. These trends may be attributed to the main heat source in the tests being the pinion bearings, and the temperature rise of the inner rings being the greatest [7, 8]. The torque of the pinion shaft reached its maximum value immediately after the start of rotation, then decreased, and became almost constant after about 1,000 s. The maximum value of the torque of the pinion shaft increased as the bearing clearance decreased. Although the torque of the pinion shaft included other torques than the torque of the pinion bearings (for example, the torque of the gear bearings and the stirring resistance of gear oil), it was confirmed that the torque of the shaft increased as the bearing clearance decreased in the rotation test performed by the authors with only the pinion bearings [5]. For this reason, it is considered that the bearing clearance has the most influence on the above torque difference.

4.2 Influence of the atmospheric temperature

Figure 9 shows the temperature change of each part of the gear unit and torque of the pinion shaft from the start of rotation to 3,600 s for the tests with different atmospheric temperatures under conditions where the bearing clearance was close to 0.11 mm. Regardless of the conditions, the temperature measured at the end of the pinion shaft was the highest among the temperatures of each part, and increased rapidly from the start of rotation to about 600 s as the atmospheric temperature was lower. In particular, when the atmospheric temperature was 9.1°C, it reached about 80°C in 600 s after the start of rotation, and after the rising stopped a while, it rose slowly again. This is thought to be due to an increase in rolling viscous resistance and stirring resistance of gear oil inside the bearing, caused by relatively low atmospheric temperature. In the rotation test performed by the authors with only the pinion bearings, it has been confirmed that the heating amount from the bearings increases when the gear oil temperature drops and its viscosity rises, which explains the trend of the temperature rise above [5]. The trends of temperature changes of the outer rings of bearings, gear case, and gear oil were the same as those described in Section 4.1. The torque of the pinion shaft reached its maximum value immediately after the start of rotation, then decreased, and remained almost constant after about 1,000 s. The maximum value of the torque of the pinion shaft increased as the atmospheric temperature decreased. This is because the viscosity of gear oil increased as the atmospheric temperature decreased, and the rolling viscous resistance inside the bearing and the stirring resistance of gear oil increased.

4.3 Temperature at the end of the pinion shaft and torque of the pinion shaft

As described in Section 4.1 and Section 4.2, the difference in
the test conditions most clearly affects the temperature at the end of the pinion shaft. In particular, it was found that the temperature rise from the start of rotation to about 600 s varies greatly depending on the test condition. Therefore, from the results of each test condition shown in Fig. 7, the maximum rate of increase in the temperature at the end of the pinion shaft (temperature rise per 10 s) is summarized in a contour diagram with respect to the initial bearing clearance $E_{P_{20}}$ (Axial clearance of pinion bearings shown in Fig. 7) and atmospheric temperature, and shown in Fig. 10. The white area in the diagram is the area for which data was not obtained because the rotation test was not performed. The maximum rate of increase in the temperature at the end of the pinion shaft tends to increase as $E_{P_{20}}$ decreases and the atmospheric temperature decreases. In particular, when $E_{P_{20}}$ is smaller than 0.14 mm, the maximum rate of increase in the temperature at the end of the pinion shaft increases rapidly as $E_{P_{20}}$ decreases.

It was found that the difference in the test conditions also affects the torque of the pinion shaft. Therefore, from the results of each test condition shown in Fig. 7, the maximum value of the torque of the pinion shaft is summarized in a contour diagram with respect to the initial bearing clearance $E_{P_{20}}$ and atmospheric temperature, and shown in Fig. 11. The maximum value of the torque of the pinion shaft tends to increase as $E_{P_{20}}$ decreases and the atmospheric temperature decreases.

5. Study on change of bearing clearance due to temperature change

As shown in Section 4, the temperature of each part of the gear unit greatly changes immediately after the start of rotation. For this reason, the bearing clearance changes due to the thermal expansion of each part of the gear unit. There is a concern that a seizure of the bearing may occur when the bearing clearance decreases to 0 mm. Therefore, the change in the bearing clearance is estimated from the temperature change in each part of the gear unit.

5.1 Method for calculating bearing clearance

By simplifying the structure around the pinion bearings of the gear unit shown in Fig. 2 (Fig. 12), we calculated the bearing clearance $E_P$ during the operation of the gear unit, using (1) that takes
into account only the axial thermal expansion of each component.

\[
EP = EP_{20} + (t_c - 20) \cdot \alpha_c \cdot L_c - (t_h - 20) \cdot \alpha_h \cdot (L_c - L_b) - (t_s - 20) \cdot \alpha_s \cdot L_b
\]

where \(EP_{20}\) is the initial bearing clearance shown in Fig. 7, \(t_c\), \(t_h\), and \(t_s\) are the temperatures of the gear case surface, the pinion bearing housing, and the pinion shaft, \(\alpha_c\), \(\alpha_h\), and \(\alpha_s\) are the coefficients of thermal expansion of the gear case, the pinion bearing housing, and the pinion shaft. \(L_c\) is the distance between the housing fastening surfaces of the gear case, and \(L_b\) is the distance between the bearing centers. Since the temperatures of the pinion bearing housings are not directly measured, the temperature of the outer ring of the bearing near the housing (average value of the temperatures of the two bearings) is used, and the temperature of the pinion shaft is used for the temperature of the shaft end.

5.2 Calculation result of bearing clearance

Figures 13 and 14 show the bearing clearances calculated by (1) for the test results shown in Figs. 8 and 9. After about 600 s from the start of rotation, where the temperature rises in each part of the gear unit, the bearing clearance increases mainly due to the difference in the coefficient of thermal expansion between the gear case and the pinion shaft. However, for about 600 s from the start of rotation, the bearing clearance decreases with rotation, and this tendency is more pronounced as the initial bearing clearance is smaller (Fig. 13) and the atmospheric temperature is lower (Fig. 14). This is because, in the initial stage of rotation, the temperature of the pinion shaft \(t_s\) accompanying the rotation of the bearing rises faster than the temperature of the gear case \(t_c\), and the thermal expansion of the pinion shaft becomes larger than the thermal expansion of the gear case. The trend whereby the bearing clearance first decreases after the start of rotation then increases agrees with the trend confirmed by the rotation test performed by the authors with only the pinion bearings [5]. As described in Section 4, when the initial bearing clearance was the smallest and the atmospheric temperature was the lowest, the temperature at the end of the pinion shaft increased rapidly in the initial stage after the start of rotation, and after the rising stopped a while, it rose slowly again. It is thought that this is because the bearing clearance (EP value) started to increase and the heat generation was suppressed after the heat generation of the bearing increased due to the decrease in the bearing clearance.

As shown in Figs. 13 and 14, the bearing clearance varies during the rotation of the pinion shaft. There is a concern that when the bearing clearance decreases the most the temperature of the bearing rises rapidly which may result in seizure of the bearing. Therefore, from the results of each test condition shown in Fig. 7, the minimum values of the actual bearing clearances \(EP_{\text{min}}\) obtained by (1) are summarized in a contour diagram with respect to the initial bearing clearance \(EP_{20}\) and atmospheric temperature, and shown in Fig. 15. Figure 16 shows the value obtained by subtracting \(EP_{\text{min}}\) from the initial bearing clearance \(EP_{20}\), that is, the maximum decrease in bearing clearance during rotation.

When compared at the same atmospheric temperature, the smaller \(EP_{20}\) becomes, the smaller \(EP_{\text{min}}\) is. Further, when compared with the same \(EP_{20}\), the lower the atmospheric temperature is, the smaller the \(EP_{\text{min}}\) is. In addition, the maximum decrease in bearing clearance tends to increase as \(EP_{20}\) decreases and the atmospheric
temperature falls. In the range in which the test was performed, the maximum decrease in bearing clearance was a relatively large 0.05 mm or more under the conditions where $EP_p$ was 0.10 mm or less and the atmospheric temperature was 10°C or less.

6. Conclusions

The findings obtained through this study are summarized below.

1. The temperature measured at the end of the pinion shaft is the highest among the temperatures of each part, and increases more rapidly from the start of rotation to about 600 s as the initial bearing clearance is smaller and the atmospheric temperature is lower. Therefore, the maximum rate of increase in the temperature at the end of the pinion shaft (temperature rise per 10 s) also increases as the initial bearing clearance is smaller and the atmospheric temperature is lower.

2. The maximum value of the torque of the pinion shaft tends to increase as the initial bearing clearance is smaller and the atmospheric temperature is lower.

3. The bearing clearance during the operation of the gear unit is calculated using the temperature change of each part. As a result, it was found that the bearing clearance decreases with rotation for about 600 s from the start of rotation, and this tendency is more pronounced as the initial bearing clearance is smaller and the atmospheric temperature is lower.

4. The minimum value of the bearing clearance during the operation of the gear unit decreases as the initial bearing clearance is smaller and the atmospheric temperature is lower.

References

[1] Ezaki, Y., Terasawa, H. and Wada, T., “Vibration Analysis for Tapered Roller Bearing Fatigue Prevention,” *Journal of System Design and Dynamics*, Vol. 6, No. 5, pp. 665-675, 2012.

[2] SKF, Bearing damage and failure analysis, p. 70, 2017.

[3] Johns, T.M., “Application Guide for Tapered Roller Bearings in Aluminum Differential Housings,” *SAE Transactions, Journal of Passenger Cars*, Vol. 107, Section 6, pp. 1610-1624, 1998.

[4] Hayashi, Y., Zenbutsu, M. and Suzuki, H., “Analysis of Fluctuations in Bearing Preload and Optimal Design of Tapered Roller Bearings for Pinion Shaft Support in Differential Gearboxes,” *SAE Transactions, Journal of Passenger Cars: Mechanical Systems*, Vol. 110, Section 6, pp. 1042-1049, 2001.

[5] Takahashi, K., Suzuki, D. and Nagatomo, T., “Investigation of factors affecting the performance of pinion bearing for gear unit of railway vehicle,” *Transactions of the JSME*, Vol. 85, No. 876, p. 19-00181, 2019 (in Japanese).

[6] Takahashi, K., Suzuki, D. and Nagatomo, T., “Effects of bearing clearance and atmospheric temperature on performance of pinion bearings of railway vehicles,” *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, Vol. 14, No. 4, p. 20-00048, 2020.

[7] Otaki, Y. and Haruyama, T., “Study on non-contact temperature measurement by temperature sensitive paint for roller end face of tapered roller bearing,” *Proceedings of Tribology Conference 2018 Spring Tokyo*, pp. 108-109, 2018 (in Japanese).

[8] Xianwen, Z., Hao, Z., Xu, H., Xin, L. and Qingkai, H., “Investigation on thermal behavior and temperature distribution of bearing inner and outer rings,” *Tribology International*, Vol. 130, pp. 289-298, 2019.

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