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Influence of the Carrier Pinhole Position Errors on the Load Sharing of a Planetary Gear Train

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Load sharing among planetary gears, one of the design variables, has a significant influence on the performance and service life of a gearbox. This study involved simulating and testing the design parameters related to load sharing among planetary gears. In this regard, the influence of errors in the carrier pinhole position on the load sharing among the planetary gears was analyzed. The results showed that the difference between the simulation results using the model and the laboratory test results was less than 10%. Furthermore, similar tendencies were observed according to the magnitude of the load applied to the planetary gears. As for the design parameters affecting load sharing, the service life of a gearbox containing planetary gears can be extended by using a floating system as opposed to a non-floating system. In addition, reduced planetary pin diameter and increased planetary bearing clearance leads to appropriate load sharing among the planetary gears and increases the service life and floating effect of the gearbox.

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1. Introduction

Gearboxes are widely used for the purpose of transmitting power as components in various industries. Considerable effort has been directed at producing lighter and smaller gearboxes by optimizing their volumes, and improving their service lives.

The use of a planetary gear train constitutes a way to reduce the volume of a gearbox by enabling multiple planets to share the load of the transmitted power, an approach that has several advantages. The extent to which the load is uniformly shared among the planet gears is an important design variable of a planetary gear train because it affects the strength and service life of the gearbox. Especially, load sharing among planetary gears has a significant influence on the bending strength and the contact stress of the gears, etc..[1,2]

Kahraman et al. analyzed the effect of load sharing on planetary gears according to the flexibility of the ring gear and the variation in the input torque by floating one element among the sun gear, carrier, and ring gear of a single-stage planetary gear train with three or four planetary gears.[3-5] Singh used a simulation model of a single-stage planetary gear train and considered the tangential and radial error in the carrier pinhole position due to the increased number of planet gears to examine load sharing.[6] Link used a gearbox model for a wind turbine system to accurately analyze the load-sharing characteristics among the planet gears and suggested that the flexibility of the carrier, ring gear, and housing be considered.[7] Lacava confirmed the effect of load sharing on the orbit of the sun gear by conducting a test and simulation using a gearbox for a 750-kW-class wind turbine system.[8]

Previous studies analyzed the effects of planetary gear floating, ring gear flexibility, input torque variation, and flexible pin application from the perspective of load sharing by arbitrarily setting positional errors in one or two pinholes of the carrier using a single-stage planetary gear train with three to six planet gears. However, few studies have been reported in which load sharing was verified by carrying out analyses and tests by considering the errors in the carrier pinhole position of planetary gearboxes in industry.

In this study, load sharing among the planet gears was analyzed using

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both simulation and a practical test based on the errors in the carrier pinhole position of a planetary gearbox. This enabled us to investigate the extent to which the design parameters affect the load sharing. A planetary gearbox simulation model was developed using commercial software, and the developed simulation model was compared with the results of the study by Singh.[6] The analysis was performed by measuring the errors in the carrier pinhole of a manufactured carrier using three-dimensional (3D) measuring instruments. Four sets of measured results, ranging from maximum to minimum values, were applied to the simulation model. The simulation model was verified by performing an analysis and by comparing the results with those of previous studies. The analysis was conducted by applying six errors in the pinhole position of the analyzed carrier to the verified simulation model, and by comparing the results with the test results obtained by the authors in a previous study.[9] The verified simulation model was used to investigate the effects of the floating and non-floating systems, planet pin diameter, and bearing clearance, all of which affect load sharing among the planetary gears, from the perspective of the service life of the gearbox.

2. Verification of the Planetary Gearbox Simulation Model

2.1 Simulation model

The planetary gearbox was an 82.2-kW-class gearbox fitted with a two-stage planetary gear train as shown in Fig. 1. The planetary gear train was composed of sun gears, planetary gears, ring gears, and carriers. The number of planet gears in each stage was six.

The planetary gearbox was modeled using commercial software[10] by considering all elements constituting the gears, carriers, shaft, bearings, and housing. The macro-geometry and micro-geometry of the gears, the variation in the meshing stiffness of the gear and the bearings, and the effects of gravity were also considered.[11-14] Furthermore, the sun gears and the first stage ring gear were modeled as a floating type in which five degrees of freedom (F_x, F_y, F_z, M_x, and M_y) in addition to the torque were not fixed.

2.2 Analysis of load sharing according to the carrier pinhole position errors

The results obtained with the simulation model were compared with those of Singh[6] using commercial software. Based on the rated power of the planetary gearbox, 82.2 kW, the input rotational speed was 86 rpm at the first-stage carrier, and the output rotational speed was 67.4 rpm in the counterclockwise direction at the second-stage carrier.

To verify the load sharing according to the errors in the pinhole position of the planetary gearbox, the analysis was conducted under ideal conditions in which no pinhole position error existed in the carrier. Additionally, a (+) 50 μm error in the pinhole position was introduced at one of the pinholes. Here, the (+) pinhole position error refers to an error that exists in the right direction with respect to the center of the pin.

Load sharing among the planet gears was analyzed by measuring the load applied to each planet gear and using the ratio of the load shared by each planet gear to the input load. Fig. 2 shows the load sharing results of the four analysis models. A represents the results of the developed simulation model and B the results of the study by Singh.

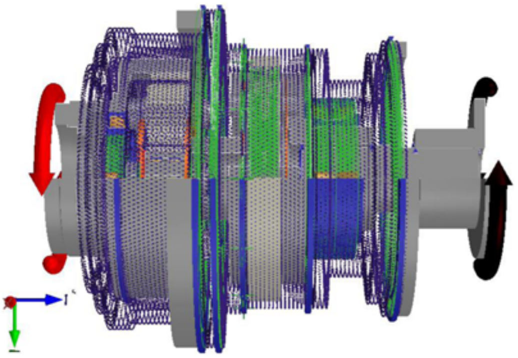

Fig. 1 Simulation model of the planetary gearbox

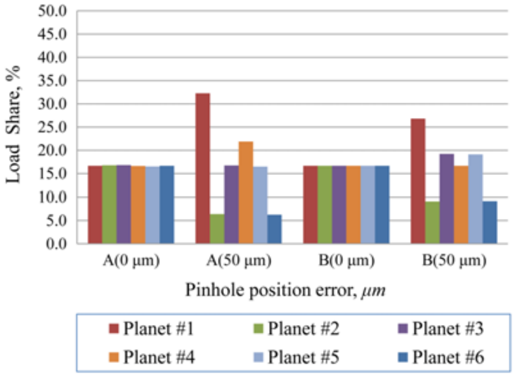

Fig. 2 Load sharing analysis of planet gear

As A (0 μm) and B (0 μm) did not have a carrier pinhole position error, the loads among the planet gears were uniform. A (50 μm) exhibited the largest load for planet gear 1 with a (+) pinhole position error, and the second largest load was determined for planet gear 4 located at 180° with respect to planet gear 1. The next largest loads were applied to planet gears 3 and 5 located on both sides of planet gear 4. The smallest loads were applied to planet gears 2 and 6 located on both sides of planet gear 1. B (50 μm) showed the largest load for planet gear 1, and the second largest loads for planet gears 3 and 5 located near the 180° position with respect to planet gear 1. The third largest load was applied to planet gear 4 located at 180° with respect to planet gear 1.

The order in which the shared load magnitudes were applied differed slightly and the magnitudes were also different. The magnitudes of the shared loads and their order were judged to vary according to the stiffness of the carrier, planet pin, bearing, and housing constituting the planetary gear train and the input power of the gearbox. In addition, Singh's results were based on a single-stage planetary gear train model whereas those of the developed simulation model were based on a model of a planetary gearbox system. Thus, the results of the analysis of each stage of the planetary gear train are believed to have affected the results of the system model. In terms of the overall tendency, however, when the carrier pinhole position error was (+), the largest load was experienced by the planet gear with the pinhole position error. The second largest loads were found in the planet gears located at or near 180° to the planet gear with the pinhole position error, and the smallest loads were found in the planet gears located on both sides of the planet gear with the pinhole position error. These findings indicate

Table 1 Pinhole position error of carrier

Case	Pinhole position error, μm					
	#1	#2	#3	#4	#5	#6
1	80	0	0	0	0	0
2	40	0	0	40	0	0
3	40	0	0	-40	0	0

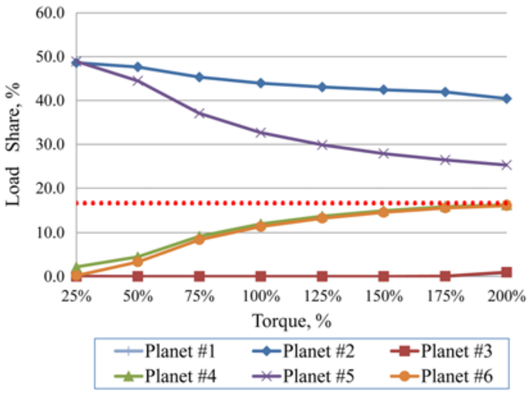

Fig. 3 Load sharing analysis of Case 1 (floating type)

that the developed simulation model and the results of Singh's study show similar tendencies.

2.3 Analysis of the influence of input torque on load sharing in the planetary gearbox

Considering the maximum value 80 μm, median value 40 μm, and minimum value 0 μm among the pinhole position errors of the manufactured carrier, three analysis models for load sharing among the planet gears were prepared. Table 1 provides the errors in the carrier pinhole positions for the three analysis models. The load sharing among the planet gears was analyzed by increasing the torque in increments of 25% from 25 to 200% based on the rated torque of the planetary gearbox (9,119.25 Nm).

The results in Fig. 3 were obtained by locating the carrier pinhole position error of (+) at Pin 1, and in the case of counterclockwise rotation, gear meshing was first observed in planet gear 1 and then in planet gear 4 as load sharing occurred. In addition, as the torque applied to the planetary gearbox increased, load sharing tended to further improve. In other words, when the torque was 25%, 97.5% of the total load was shared by planet gears 1 and 4, but it decreased to 65.7% when the torque was 200%. In this instance, 32.5% of the total load was shared by planet gears 3 and 5 located on both sides of planet gear 4.

The results in Fig. 4 were obtained by introducing errors in the carrier pinhole position of (+) at Pin 1 and 4, and in the case of counterclockwise rotation, gear meshing was first observed in planet gears 1 and 4. As the torque increased, the load sharing ratio of planet gear 1 varied as 48.0%, 49.0%, 49.3%, 46.7%, 42.0%, 38.4%, 35.7%, and 33.5%, and that of planet gear 4 was 50.0%, 49.9%, 49.9%, 47.1%, 42.3%, 38.6%, 35.8%, and 33.7%. The load sharing ratios of planet gears 2 and 6 and planet gears 3 and 5 were 8.2% even when the torque was 200% because of the influence of planet gears 1 and 4.

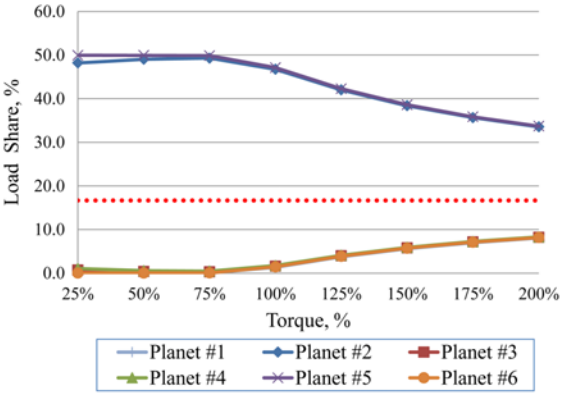

Fig. 4 Load sharing analysis of Case 2 (floating type)

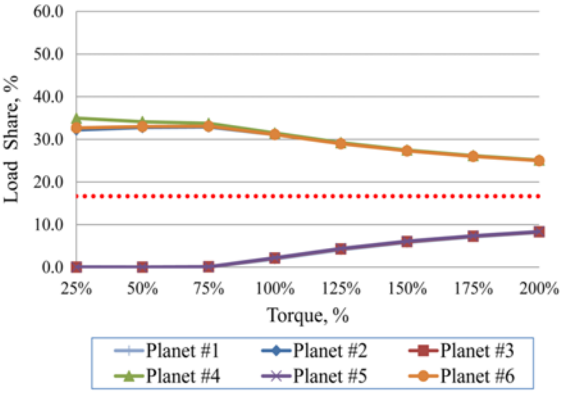

Fig. 5 Load sharing analysis of Case 3 (floating type)

The results in Fig. 5 were obtained by locating the carrier pinhole position error (+) at Pin 1 and (-) at Pin 4, and in the case of the counterclockwise rotation, the first gear meshing occurred in planet gear 1. As the torque increased, the load-sharing ratio of planet gear 1 decreased. In addition, the load was supposed to be shared by planet gear 4; however, as it was in the (-) position, the load was shared by planet gears 3 and 5 located on both sides of planet gear 4, and the remaining load was shared by planet gears 2 and 6.

The load applied to each planet gear varied according to the errors in the carrier pinhole position. As the torque applied to the planetary gearbox rose, load sharing among the planet gears improved. A tendency similar to that of the load sharing test results of Bodas and Hayashi, who used a single-stage planetary gear train, was observed.[5,15]

3. Test Setup for Verifying the Model of the Planetary Gearbox Simulation

Details of the measurement of the errors in the carrier pinhole positions and the test stand for measuring the load sharing in the planetary gearbox were presented in the authors' previous study.[9]

3.1 Carrier pinhole position errors

The errors in the pinhole positions of the manufactured carrier were measured using the 3D measuring instruments shown in Fig. 6.

The errors in the carrier pinhole positions were calculated using the average values of the errors on the front and rear sides of the carrier

Fig. 6 View of the 3D measuring instruments

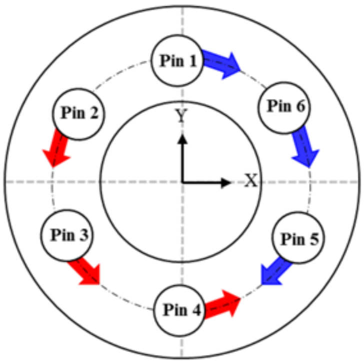

Fig. 7 Arrangement used to analyze the results of the measured carrier

Table 2 Measurement of carrier pinhole position error

Number	Pinhole position error, μm		
	Front side	Rear side	Average
Pin 1	54.1	71.5	62.8
Pin 2	-32.6	0.5	-16.1
Pin 3	-85.0	-72.3	-78.6
Pin 4	-55.8	-68.3	-62.0
Pin 5	39.6	15.7	27.7
Pin 6	84.5	79.2	81.8

Fig. 8 Test rig of planetary gearbox

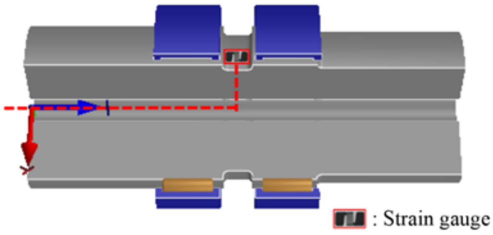

Fig. 9 Geometry of planet pin with strain gauges

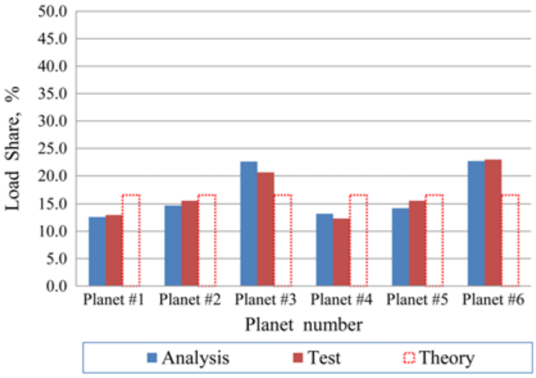

Fig. 10 Comparison between analysis and test results

according to the arrangement shown Fig. 7 and are listed in Table 2. In the results of the analysis of the carrier pinhole position errors, the (+) errors are represented by blue arrows and the (-) errors by red arrows with respect to the clockwise direction. The maximum (+) pinhole position error of the carrier was 81.8 µm at Pin 6 and the maximum (-) pinhole position error was 78.6 µm at Pin 3. These measured values were used in the planetary gearbox simulation model to analyze the load sharing among the planet gears.

3.2 Test setup for measuring the load sharing of the planetary gearbox

The test stand for determining the load sharing among the planet gears was designed to closely approximate the mounting and operating conditions of planetary gearboxes. In addition, to ensure easy control and accurate test measurements, a dynamometer was used with the test stand as shown in Fig. 8.

The planet pins were designed as hollow shafts for the purpose of measuring load sharing among the planet gears, as shown in Fig. 9, and strain gauges were attached to the grooves created in the middle of the pins in the axial direction. Strain gauges were attached to the six planet pins of the planetary gear train and were used to measure the load sharing.

4. Verification of the Planetary Gearbox Simulation Model and Load Sharing Parameters

4.1 Analysis and tests of load sharing among the planet gears according to the errors in the carrier pinhole positions

The errors in the carrier pinhole positions were analyzed using a 3D measuring device and these values were applied to the planetary gearbox simulation model. This model was used to analyze load sharing among the planet gears. The analysis and tests were conducted at 100% torque based on the rated power indicated in Section 2.2.

Fig. 10 shows the results of applying the six carrier pinhole position errors. The load applied to each planet gear is shown as the ratio to the input load. The theoretical load-sharing ratio for each of the six planet gears is 16.6%. The analysis using the simulation model showed that the loads applied to planet gears 1 to 6 were 12.6%, 14.7%, 22.6%, 13.2%, 14.2%, and 22.7%, respectively, and the test results showed that the loads were 13.0%, 15.6%, 20.6%, 12.3%, 15.6%, and 23.0%.

Thus, the differences between the analysis results and the test results were 2.8%, 5.5%, 9.6%, 7.1%, 8.8%, and 1.2% based on the analysis results. The results were calculated by using Eq. (1). These differences are believed to have been caused by the influence of the manufacturing and assembly errors of the components of the planetary gearbox.

$$Error,\% = \frac{(Analysis - Test)}{Test} \times 100 \tag{1}$$

Even though no error other than that in the carrier pinhole position was used in the simulation model, the actual product showed a phase change due to the error in the pinhole position of the two carrier discs, the pitch and run-out errors of the gear, the tooth thickness error, and the error in the interference fit of the carrier and the planetary pin.

4.2 Influence of the parameters affecting the load sharing of the planetary gearbox on its service life

To investigate the influence of the design parameters of the planetary gearbox on its service life, the effects of the parameters including the floating and non-floating systems, planet pin diameter, and planet bearing clearance were studied. In the industrial field, gearboxes are designed either with a floating or a non-floating system. This parameter was selected to examine the influence of the design method on the service life. The parameters of the planet pin diameter and the planet bearing clearance were previously studied for each parameter.[16-21] These parameters, however, were selected because insufficient information existed on their influence on each other.

The conditions in the floating system were such that the five degrees of freedom (F_x, F_y, F_z, M_x, and M_y) of the first-stage sun gear were not fixed, but these five degrees of freedom were fixed for the non-floating system.

The diameter of the planet pins was selected based on the 60-mm diameter of the manufactured planet pins such that the strength of the planet pins could be one or higher. Furthermore, as the diameter of the planet pins changed, the planet bearings were also selected. Bearings with similar dynamic loads to those of conventional bearings were selected. The dynamic loads of the bearings were considered because the loads and dynamic loads applied to the bearings are related to the calculation of the service lives of the bearings. The product number of the planet bearings was RNA49/52R, and C1, CN, and C4 were selected as the clearance of the planet bearings. The analysis was conducted at 100% torque based on the rated power indicated in Section 2.2, and detailed conditions for each design parameter are listed in Table 3. For the analysis, the service life of the planetary gearbox was examined based on the highest value of the load in each planet gear.

The graph in Fig. 11 shows the change in the service life of the planetary gearbox according to the design parameters.

Table 3 Details of design parameters

Design parameter	Case	Note
Type	Floating	-
	Non-floating	$F_{x,y,z} = 10^{12}$ N/mm, $M_{x,y} = 10^{12}$ Nmm/rad
Pin diameter (Bearing type: Needle roller)	30 mm	NA6906 (Dynamic load rating: 4.90×10^4 N)
	45 mm	NKS45 (Dynamic load rating: 4.55×10^4 N)
	60 mm	RNA49/52R (Dynamic load rating: 4.91×10^4 N)
Bearing clearance (Bearing designation: RNA49/52R)	C1	12.5 μm
	CN	55 μm
	C4	95 μm

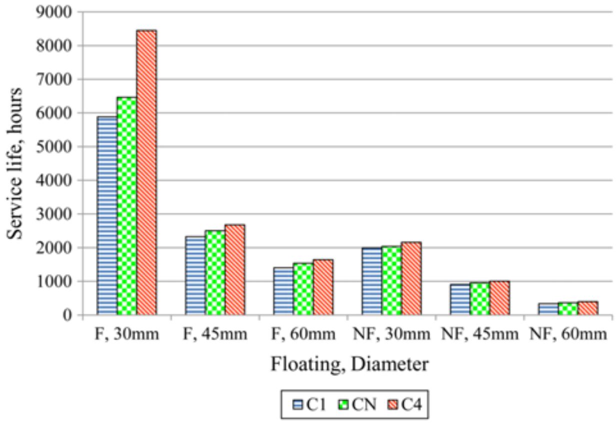

Fig. 11 Service life according to the variation in the design parameters

The service life of the planetary gearbox is inversely proportional to the load-sharing factor representative of the load sharing among the planetary gears.[21] When the load-sharing factor decreases, the service life of the planetary gearbox shows a tendency to increase. For the floating type with a pin diameter of 30 mm and the bearing clearance C4 in Fig. 11, the load-sharing factor was 1.87. The factor was 2.26 when the floating was changed to non-floating under the same conditions, 2.39 when the pin diameter was changed from 30 mm to 60 mm, and 1.92 when the bearing clearance was changed from C4 to C1.

The service life of the gearbox was longer in the floating system than in the non-floating system. This seems to be because relative movement of the planetary gear train did not occur in the non-floating system because the five degrees of freedom of the sun gear and the ring gear were assigned fixed values. As the diameter of the planet pins increased, the service life of the gearbox tended to decrease. This seems to be because the displacement of the planet pins increased while the loads applied to the planet pins remained the same. An increase in the planet bearing clearance improved the service life of the gearbox and the influence was larger in the floating system than in the non-floating system.

The overall tendencies showed that the service life of the floating system was longer than that of the non-floating system. It was found that a decrease in the diameter of the planetary pins and an increase in the clearance of the planet bearings improve the service life and floating effect of the planetary gearbox.

5. Conclusions

This study used the errors in the carrier pinhole positions of a manufactured planetary gearbox to determine the load sharing among the planet gears. These results were compared with the results of previous studies using the developed simulation model. The load-sharing tendency was examined using both the simulation model and the results of practical tests. In addition, the design parameters affecting load sharing among the planet gears were studied using the simulation model. The results of the study are summarized below.

In the planetary gearbox simulation model, when the error in the carrier pinhole position was (+), the largest load occurred in the planet gear with the pinhole position error, and the next highest load appeared in the planet gears at or near 180° to the planet gear with the pinhole position error. The smallest load was found in the planet gears located on both sides of the planet gear containing the pinhole position error. These results were similar to those of a previous study[6] based on a single-stage planetary gear train.

As the torque applied to the planetary gearbox containing the errors in the six carrier pinhole positions increased, the load sharing ratio among the planet gears tended to improve.

The difference between the simulation model and the test results was less than 10%. This error seems to have been caused by the phase error between the two carrier discs, the pitch and run-out errors of the gears, the tooth thickness error, and the error caused by the interference fit of the carrier and planetary pin. Moreover, the order in which the magnitudes of the loads were applied to each planet gear showed the same tendency except for planet gears 1 and 4.

As for the parameters affecting the load sharing of the planetary gearbox, the service life of the gearbox was longer in the floating system than in the non-floating system. This was attributed to the absence of relative movement of the planetary gear train in the non-floating system because the five degrees of freedom of the sun gear and ring gear were fixed. As the diameter of the planet pins increased, the service life of the gearbox tended to decrease. This seemed to be because the displacement of the planet pins increased while the loads applied to the planet pins remained the same. An increase in the planet bearing clearance improved the service life of the gearbox and the influence was greater in the floating system than in the non-floating system.

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