FAILURE PHENOMENONS AND THEIR ROOT CAUSES IN PLANETARY GEAR SYSTEMS

Lászlo, Kovács, Budapest University of Technology and Economy,
Műegyetem rkp. 3-5, Budapest, Hungary
Mihály, Kozma, Budapest University of Technology and Economy,
Műegyetem rkp. 3-5, Budapest, Hungary

Abstract: *Planetary gear systems are well-known and widely used in almost every field of industry, because of their high load carrying capacity and efficiency, compared to ordinary gear drive systems. Using some types of planetary gear systems, very high gear ratios can be realized in one step. In contrary to these benefits, the complex structure of planetary gear systems make them more sensitive to manufacturing errors and improper maintenance. There are some special failure phenomenon, which are special for planetary gear systems. In this article, these phenomenon are analyzed.*
Keywords: *planetary gear, failures, dual planet gears, efficiency*

1. INTRODUCTION

Planetary gear drives are used in a diverse field of applications, mainly in automotive and measurement industries, and nowadays, they spread across different fields of industry. Because of internal load distribution between more gear pairs, the load density is quite high, and, using some special planetary gear drives, high gear ratio can be achieved in one step. These good characteristics make planetary gears a good choice for both high power and space-constrained applications. Planetary drives with improved precision are also used in manufacturing and robotics industries. Complex planetary gears can be used as gearshifts for power transmission systems. Planetary gear constructions with more degree of freedom can also be used as differentials, power addition and control systems.
The efficiency of simple planetary drives with small gear ratio is often better, than efficiency of ordinary gear drives with similar parameters. However, the high gear ratio types – usually with dual planet gears – have lower efficiency, which largely depends on the lubrication of gear meshes and the conditions of bearings.
The failures of ordinary and planetary gear drives are similar, but – because of more complex internal structure – planetary gears are more sensitive to damages. To achieve good efficiency for high gear ratio planetary drive systems, the applied construction of bearings and the proper lubrication is critical. At very high gear ratios and extreme conditions, improper lubrication can cause instant lock-up of planetary gear, making it inoperable. This article presents the characteristic failures of different planetary gear systems.

2. FAILURES IN PLANETARY GEAR SYSTEMS

Planetary gear systems are subject to the same failures as ordinary gear drives:

- Failure of gear meshes (tooth break or pitting)
- Failure of bearings

Besides these well-know failure situations planetary drives, having dual planet carriers, with high gear ratio are subject to lock-up. This failure situation occurs, when the efficiency of planetary gear drive falls below 0, because of improper bearing function, or lack of effective lubrication of gear meshes. In this case, the gear teeth of planetary drive are not broken.

3. LOAD DISTRIBUTION

High load carrying capacity of planetary gear drives is achieved by distribution of load across more gear pairs. Usually – depending on the construction – three or more gear pairs transmit the power through a planetary gear system. Ideally, the load of each gear mesh is the same. However, because of manufacturing inaccuracies and elastic deformation owing to applied load this ideal condition never occurs, the load of each gear mesh is different.

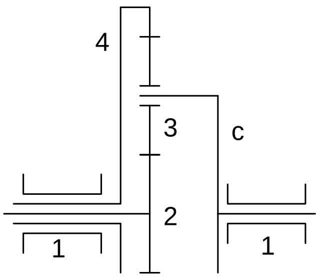

Fig. 1. Structure of a simple planetary gear drive

Load distribution problems occur in all types of planetary gear drives. The structure of the most widely used planetary gear system is shown on Fig. 1. This simple planetary gear drive consists of one sun gear (2), a ring gear (4), a carrier (c) and several planet gears (3).

Manufacturing inaccuracies can include center distance deviations, and gearing deviations. According to dynamic models developed by PRODKI, JARCHOW and LAMPARSKI [1], gearing deviations have little influence on dynamic effects in transmissions, if they remain within the limits of DIN quality class 6.

The effect of center distance deviations can be neglected, if they do not consume the backslash allowed by clearings of bearings. If bearing clearances are consumed, then load of gear meshes and bearings can exceed nominal values several times, shortening the life expectancy of transmission and causing high decrease in efficiency during operation.

4. EFFICIENCY PROBLEMS

The efficiency of a planetary gear drive depends on the structures of planetary gear drives, and on lubrication conditions of gear pairs and bearings. In case of simple planetary gear drives (Fig. 1.), the power is transmitted by both gear pairs and rotation of carrier. In this case the power transmitted by gear meshes is smaller than power transmitted by planetary drive.

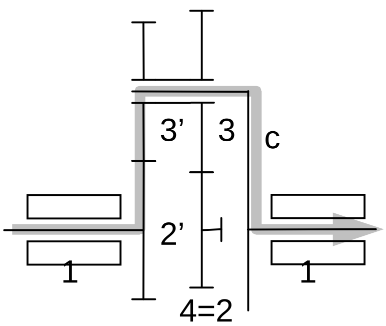

Fig. 2. Structure of the External-External drive

For this reason these simple planetary gear drives are less sensitive to gear lubrication and bearing conditions than ordinary gear drives.

However, this is not the case for dual planet gear drives. In these types of planetary gear drives, in certain operation conditions, the power transmitted by gear meshes can exceed enormously the power transmitted by the whole gear drive, because of internal power circulation, especially for large gear ratios.

Dual planet can be built from both internal and external gear meshes, the typical types are the following:

- External-external (Fig. 2.) with two sun gears, one of them fixed to housing.
- Internal-internal with two ring gears, one of them fixed to housing.
- External-external with one sun gear and one ring gear.

The external-external and internal-internal dual planet drives mentioned above can be complemented by and additional ring or sun gear. In this case the transmission works as a two-stage transmission built from a simple and an external-external or internal-internal planetary gear drive, respectively.

The advantage of dual planet transmissions is their high gear ratio. However, as gear ratio increases, the load of gear meshes and bearings of planet gears also increases. The gear ratio of external-external gear drives depends on the difference of the working diameters of 3 and 3' planet gears. As this difference decreases, the gear ratio is increased.

Using a series of external-external planetary gear drives the dependence between gear ratio and efficiency is demonstrated.

Axle distance (a)	250 mm
Number of planet gears (N)	3
Mean diameter of planet gear bearings (d_b)	30 mm
Friction coefficient between tooth surfaces (μ_g)	0.05; 0.07
Contact angle (α)	20°

Table 1. Main characteristics of external-external planetary drives used for calculations

Tooth number are selected according to Formulas 1-3:

$$z_{3'} = z_3 - 1 \qquad (1)$$

$$z_2 = z_{3'} \qquad (2)$$

$$z_{2'} = z_3 \qquad (3)$$

By using these selection criteria, the 2-3 and 2'-3' gear meshes use the same gears. The tooth number z_3 is running from 15 to 250. The gear ratio of the planetary gear drive can be calculated by Formula 4:

$$i = \frac{1}{1 - \frac{z_3}{z_2} \cdot \frac{z_{2'}}{z_{3'}}} \qquad (4)$$

The gear ratio of this planetary gear drive is always negative because of the change in direction of rotation. On diagrams –i is displayed for clarity.

4.1. Power loss from gear meshes

The efficiency of gear meshes are calculated by method presented by Niemann [2] using friction coefficients listed in Table 1. The calculation was carried out for two friction coefficients in order to show the effect of different friction coefficients, as even a small change in friction coefficient can cause large difference in gear mesh loss.

The efficiency of planetary gear drive is calculated by the Formula 5:

$$\eta = \frac{1}{i\left(1-\left(1-\frac{1}{i}\right)\frac{1}{\eta_{23}\cdot\eta_{2'3'}}\right)} \qquad (5)$$

This efficiency calculation is for gear mesh efficiencies only. The result of calculations is presented on Fig. 3.

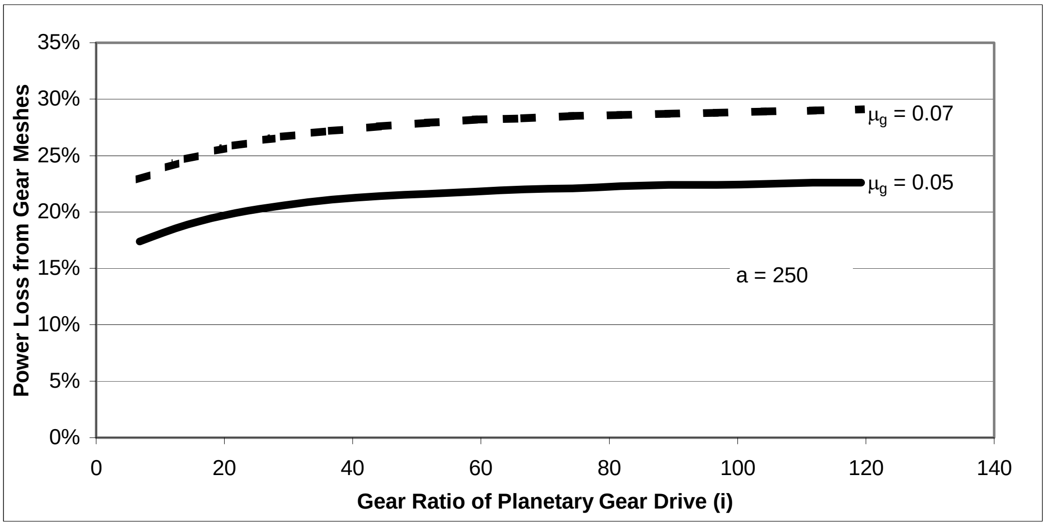

Fig. 3. Power loss from gear meshes for different gear ratios and friction coefficients

4.2. Power loss from bearings

The bearing loss cannot be neglected, because of the high bearing loads. Calculations are made for both needle roller bearings and sliding bearings. During calculations, only the power loss from planet gear bearings are taken into consideration.

The radial force on bearings from 3 and 3' gears can be calculated by the following formulas:

$$F_{r3} = \frac{1}{a\cdot\cos(\alpha)}\frac{d_{w3'}}{d_{w3}-d_{w3'}}\cdot M_{in} \qquad (6)$$

$$F_{r3'} = \frac{1}{a\cdot\cos(\alpha)}\left(\frac{d_{w3'}}{d_{w3}-d_{w3'}}-1\right)\cdot M_{in} \qquad (7)$$

where $d_{w3'}$ and d_{w3} are the working diameters of gears 3' and 3, respectively; M_{in} is the input torque of planetary gear drive.

The radial load of bearing is the sum of load calculated by formula 6. and 7.

$$F_r = \frac{1}{a\cdot\cos(\alpha)}\left(2\frac{d_{w3'}}{d_{w3}-d_{w3'}}-1\right)\cdot M_{in} \qquad (8)$$

The torque of bearings are calculated by the following formula:

$$M_b = 0.5\cdot\mu_b\cdot F_r\cdot d_b \qquad (9)$$

where μ_b is the friction coefficient for bearing.

The power loss from bearing depends on the bearing torque and the rpm of bearings:

$$\upsilon_b = n_b \cdot M_b \quad (10)$$

The rpm of bearings can be calculated from the rpm of input shaft of planetary gear drive:

$$n_b = n_{in} \cdot \frac{z_{2'}}{z_{3'}} \quad (11)$$

By formulas 8-11. the power loss from bearings are calculated by the following way:

$$P_b = n_{in} \cdot \frac{z_2}{z_3} 0.5 \cdot \mu_b \cdot d_b \frac{1}{a \cdot \cos(\alpha)} \left(2 \frac{d_{w3'}}{d_{w3} - d_{w3'}} - 1 \right) \cdot M_{in} \quad (12)$$

The power loss of bearings can be calculated as a percentage of power flowing into the planetary gear system, which is $n_{in} \cdot M_{in}$. The decrease in efficiency caused by bearings is:

$$\upsilon_b = \frac{z_2}{z_3} 0.5 \cdot \mu_b \cdot d_b \frac{1}{a \cdot \cos(\alpha)} \left(2 \frac{d_{w3'}}{d_{w3} - d_{w3'}} - 1 \right) \quad (12)$$

Calculations are carried out for needle roller bearings. The coefficient of friction for needle roller bearings by SKF [3] is μ_b=0.0025.
The efficiency of external-external planetary gear drives resulting from gear and bearing efficiency calculations is presented on Fig. 4.

4.3. Starting problems of a planetary gear drive equipped with sliding bearings

When starting the planetary gear drive, the hydrodynamic lubrication conditions are not built up instantly. For this reason the efficiency of the planetary gear drive at start is lower, than the running efficiency. For dual planet drives, it can cause lock-up of drive system, and makes its start impossible.
For evaluating the starting conditions, Formula 12. can be used. The μ_b friction coefficient for bearing in this case will be the friction coefficient of sliding bearing materials, for calculations
μ_b=0.05 value is supposed by recommendations of SKF catalogue [3]. The efficiency calculations presented on Fig. 5. show, that around the gear ratio of 62, efficiency falls below zero. High gear ratio external-external planetary gears equipped with sliding bearings can lock-up at start time, however, their operating efficiency would allow them to work.

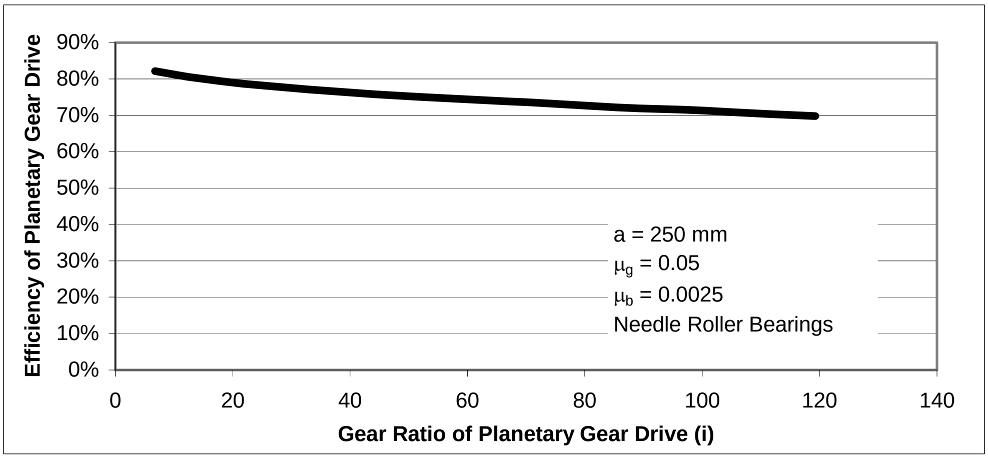

Fig. 4. Efficiency of planetary gear drives equipped with needle roller bearings, for different gear ratios

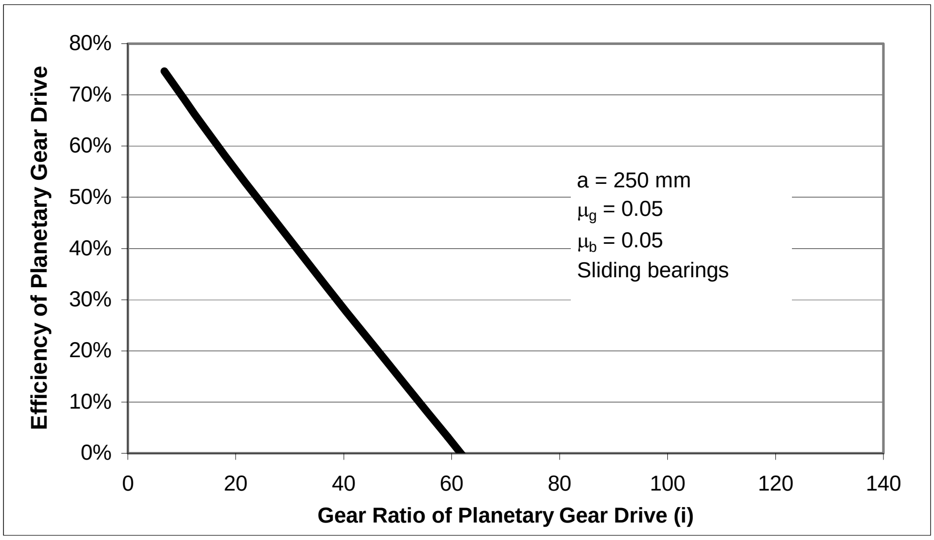

Fig. 5. Starting efficiency of planetary gear drives equipped with sliding bearings, for different gear ratios

5. CONCLUSION

Planetary gears are subject to a number of special failure phenomenon, compared to ordinary gear drives. These failures are:

- uneven load distribution, which causes overload of some gear meshes and bearings;
- lock-up of planetary gear drives, which can occur in planetary gear drives with dual planet gears, especially at high gear ratios.

The lubrication conditions of bearings and gear meshes highly influences the efficiency of the drive system. Another important factor in gear system efficiency is the operating conditions of bearings. If bearings run under ideal operating conditions, their contribution to losses of gear drives is significant, but small compared to gear mesh losses. When bearings have lubrication problems – like hydrodynamic sliding bearings at start – their power loss can make the gear system inoperable.

7. ACKNOWLEDGMENT

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