The load sharing structure design and FE analysis of planetary gearbox with flexible pin

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Abstract. The paper first introduced the unequally load sharing in the planetary gear set and explained the cause of unequally load sharing in traditional design. Then a new floating structure of planetary gear with flexible pin has been designed to improve unequally load sharing of planetary gear set. In order to verify the flexible pin structure effects on the load sharing, two integrated finite element models have been built. Each one consists of two coupled planetary gear sets. One finite element model has been built with flexible pin structure and the other with fixed pin. The same load and boundary conditions have been applied to the two different finite element models. After analysis, the vonmises stresses of different parts such as ring gear, planetary gear, bearing and pin etc. in two different models have been compared. From the analysis result verification, the maximum vonmises stress of flexible pin of planetary gear set is much higher than that of planetary gear set with fixed pin in different mesh position. Although it is in the design range of material strength, its increase indicates that flexible pin structure makes the higher unequal mesh load of planetary gear shared with other pinions, the deflection of flexible pin make the load sharing with other pinions possible. Whereas the maximum vonmises stresses of other parts such as ring gear, planetary gear, bearing and sun gear decreases in a certain degree with the flexible pin deflection. It really indicates that the effect of flexible pin in the planetary gear set is obvious against fixed pin. When the higher unequally sharing load becomes smaller, maximum vonmises stresses of all planetary gear set parts except flexible pin become smaller and safer.

1. Introduction
Planetary gear sets can provide more power density than countershaft gear pairs. The planetary gear box can be designed with smaller size whereas transmits more torque power with planet gear branch parallel power paths. Each planetary gear mesh transmits one share of whole torque, therefore significantly reduces the gearbox size.

However the advantage of planetary gear sets is weakened if planetary gear does not equally share the torque load. Often is the case that one planetary gear meshes share much more load than other planetary gear meshes due to transmission error, which is caused by planetary gear manufacturing, assembly, misalignment and deformation etc. Many factors affect the planetary gear transmission error and it lead to the planetary gear unequal load sharing.

The locations of planet gear centres are limited in a fixed range in a traditional planetary gearbox. When the planetary gears mesh with sun or ring gear, the planetary gear bearing pins almost cannot deflect due to its ends fixed in the carrier. The total meshing force between planetary gears cannot be equally shared among them though they actually share the transmitted torque together. Sometimes the
sharing loads are seriously unequal because of TE including planetary gear backlash, manufacture error, assemble error, misalignment, deflection etc.

This can be explained in the figure 1 with magnified mesh points in local meshing contact area. When \( a_1 \) planetary gear begin to mesh or contact with sun and ring gear, the other \( a_2 \) and \( a_3 \) planetary gears are still not contacting its mating gear. That means the torque transmitted at that moment is largely loaded through \( F_1 \) meshing force. The other two meshing force \( F_2 \) and \( F_3 \) are very small or zeros. This leads to seriously unequally load for the \( a_1 \) planetary gear and limits the torque transmission ability of whole planetary gear set. Therefore the reliability of whole transmission system is greatly reduced or even damaged by this unequal gear meshing force.

![Figure 1: The unequally load sharing among planetary gears [1]](image1)

2. The design methods of the load sharing in the planetary gearbox

The traditional design in the planetary gearbox often adopts more planetary gears in the one planetary gear set. It seemly indicates that each planetary gear is loaded with less torque and increases the planetary gear safety coefficient according to the static design. However it cannot resist the much larger unequally load caused by transmission error. With the planetary gear pin fixed in the carrier (figure 2a), it cannot counteract the maximum unequal load from meshing gear through bending deflection of pin because the pin's two ends are fixed.

Whereas the flexible pin can bend with one end impended. It counteracts the maximum unequal gear meshing force through flexible pin’s deflection and share its maximum gear meshing force with other planetary gears, where pinion's meshing point moves along the mesh line and coordinates with other pinions and makes large unequal sharing load small till it is equally shared with others.

![Figure 2: the fixed and flexible pin structure design](image2)
flexible pin is designed and improve the traditional planetary gear sets with equally load sharing. Next paragraphs are the flexible structure design and its finite element strength analysis.

### 3. The improved planetary gear set design with flexible pin structure

Through flexible pin principle explanation in figure 2, planetary gear set should be designed with flexible bearing pin in planetary gear set. Traditional design often makes both bearing pin two ends fixed on the carrier. That makes the pin hardly deformable. There is no space for pin to deflect in either ends because they are tightly assembled on the carrier. That is why more and more flexible pin structures are designed in various applications. The improved planetary gear set with flexible structure is designed in figure 3. The finite analysis model of two planetary gear set with flexible pin has been built; load cases with torque and speed are applied for the strength analysis. The validation results are obtained and flexible pin effect on planetary gear load sharing is obvious.

![Figure 3 The improved planetary gear set with flexible pin structure](image)

1 Sub Carrier 2 Copper Cushion 3 Needle bearing 4 U-type flexible pin 5 Carrier 6 Screw 7 Oil plug 8 Planetary gear 9 Screw 10 Bolt 11 Ring-shape cushion 12 Flexible pin linkage

### 4. The strength analysis for improved structure of planetary gear set with flexible pin

The two planetary gear set models have been built with fixed and flexible pins. Comparing is made with two different structures and the results indicate that the planetary gear set with flexible pin has lower maximum vonmises stress on the planetary gear bearing, pin, ring and planetary gears than fixed pin case. The design with flexible pin makes the largest gear mesh force become small and shared with other planetary gears through its pin deflection. The whole planetary gear set load sharing with flexible pin gets much better than without it.

![Figure 4 FE model of two planetary gear sets](image)  ![Figure 5 Flexible pin structure FE model](image)

**4.1. The needle bearing strength analysis results**

The needle bearing maximum vonmises stresses of planetary gears with flexible or fixed pins are shown in figure 6.
The maximum vonmises stresses (Mpa) of planetary gear bearing needle at different location in the whole meshing cycle are as follows.
874.39, 902.83, 901.38, 899.41, 886.4, 874.18, 899.39, 901.55, 902.81, 879.16, 896.05.

The maximum vonmises stresses (Mpa) of needle of planetary gear bearing at its different location in the whole meshing cycle with flexible pin are as follows.
555.07, 567.69, 73.38, 565.86, 561.51, 564.07, 566.27, 567.67, 575.17, 559.49, 565.55.

4.2. The planetary gear strength analysis results
The comparison of maximum vonmises stresses on the planetary gear with fixed pin and flexible pin are shown in figure 7. The maximum vonmises arises on the initial contact of gear mesh.

The maximum vonmises stresses (Mpa) of planetary gear with fixed pin are shown as follows.
(255.86), 211.42, 195.31, 191.64, 197.84, 207.94, 205.12, 195.76, 195.64, 221.18, 251.12.

The maximum vonmises stresses (Mpa) of planetary gear with flexible pin are shown as follows.
(260.01), 208.71, 174.61, 177.88, 195.12, 207.16, 201.53, 158.18, 177.34, 227.29, 248.67.

From above analysis, one conclusion can be made that among all the maximum vonmises stresses in different planetary gear mesh positions, the maximum vonmises stresses of planetary gear with flexible pin become smaller than that of planetary gear with fixed pin except for the initial gear meshing contact position and few other gear meshing positions.

The fact that maximum vonmises stress becomes smaller indicates that the flexible pin of planetary gear has greater effects than that of fixed pin on the planetary gear load sharing in almost all gear mesh positions. It really decrease the maximum vonmises stress of planetary gears.

The other maximum vonmises stresses of planetary gear (255.9 Mpa and 260.16 Mpa, 221.18 Mpa and 227.29 Mpa can be compared from above) are probably related with transmission errors caused by manufacture error, assemble error, gear mesh deformation or the initial mesh contact impact etc. and the two stresses differences are very small.
4.3. The ring gear strength analysis results

The ring gear maximum vonmises stress with flexible pin in different mesh positions are shown in figure 8 and the ring gear maximum vonmises stress without flexible pin in different position in shown in figure 9.

![Figure 8 Maximum vonmises of ring gear without flexible pin](image1)

![Figure 9 Maximum vonmises of ring gear with flexible pin](image2)

From above comparison the effect with flexible pin on the maximum vonmises stress of ring gear is obvious. The maximum vonmises stress of ring gear with flexible pin in different mesh position decreases from figure 8 to figure 9 accordingly.

4.4. The planetary gear pin strength analysis results

The fixed pin and flexible pin of planetary gear needle bearing are different. The maximum vonmises stresses of planetary gear needle bearing with flexible pin is much larger than that of planetary gear needle bearing with fixed pin. The pin maximum vonmises is totally different from planetary gear, ring gear and sun gear. The increase of maximum vonmises stress with flexible pin indicates that the flexible pin deflect or deform much more than that fixed pin. It actually deforms much more and makes ring-pinion gear mesh or sun-pinion gear much more equally shared the total meshing loads.

The maximum vonmises stress of planetary gear bearing pin with flexible pin structure or without are shown in figure 10 in the initial meshing position.

![Figure 10 Maximum vonmises of planetary gear bearing pin](image3)

The maximum vonmises stresses (Mpa) of flexible pin of planetary gear in different gear meshing positions after analysis are as follows:

474.24, 489.44, 488.81, 489.77, 479.45, 475.67, 489.68, 488.71, 490.16, 477.62, 486.74.
The maximum vonmises stresses (Mpa) of fixed pin(without flexible pin) of planetary gear in different gear meshing positions after analysis are as follows:
123.41, 127.11, 126.91, 126.58, 125.04, 123.24, 126.59, 126.94, 127.08, 124.01, 126.15.

5. Conclusion
From the analysis results above the conclusion can be made that maximum vonmises stress of flexible pin of planetary gear set is much larger than that of planetary gear set without flexible pin in different meshing position. Although the maximum vonmises stress is under design range of material strength, its increase indicates that the structure of planetary gear set with flexible pin makes the larger unequally meshing load of planetary gear shared with other planetary gears, whereas the deflection of the flexible pin make the sharing of the large unequal load with other planetary gear possible for the maximum vonmises stress of flexible pin is much larger the fixed pin. This can be validated from above analysis results. The effect of flexible pin in the planetary gear set can also be proved with the decreasing of maximum vonmises stress on the planetary gear, needle bearing and ring gear.

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