Load Sharing Behavior in Planetary Gear Set

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Abstract. The objective of this paper is to study the effects of meshing phase between planets, the effects of the gravity of carrier and the planet position error on the load sharing behavior in planetary gear set. These effects will be studied numerically under the stationary condition and will be validated experimentally by a back-to-back planetary gear test bench. In this test bench, strain gauges are installed on each planet's pin hole in order to compare strains in the pinhole of each planet.

Keywords: Planetary gear, load sharing, meshing phase, gravity, planet position error.

1 Introduction

Planetary gear can transmit higher power because they use multiple power paths formed by each planet branches. This allows the input torque to be divided between the *n* planet paths, reducing the force transmitted by each gear mesh.

Under ideal conditions, each planet path carries an equal load. Nevertheless, planetary gears have inevitable manufacturing and assembly errors. So, the load is not equally shared amongst the different sun-planet and planet-ring paths, which can be a problem in terms of both dynamic behavior and durability.

Many researchers have done significant works on the subject of planetary gear load sharing. Their works were based on transmission modeling and assessed by experimental tests. Kahraman (Kahraman, 1994) used a discrete model to study the influence of carrier pin hole and planet run-out errors on planet load-sharing characteristics of a four-planet system under dynamic conditions. He employed later (Kahraman, 1999) a planet load-sharing model to determine the static planet

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load sharing of four-planet systems and presented experimental data for validation of the model predictions. Iglesias (Iglesias et al, 2013) studied the effect of planet position error on the load sharing and transmission error. Singh (Singh, 2005) found that the tangential pin position error has a greater effect on the load sharing than the radial pin position error. Ligata (Ligata et al, 2008) proved experimentally that for the same amount of error, the degree of inequality in the planet load-sharing behavior increases with the number of planets in the system. Guo and Keller (Guo and Keller 2012) presented a three-dimensional dynamic model which take into account to the addressing gravity, bending moments, fluctuating mesh stiffness, nonlinear tooth contact, and bearing clearance. They validated this model against the experimental data.

In this paper, the effects of meshing phase, the gravity and the error position of the pin hole of planets on the load sharing characteristics are studied numerically and validated experimentally with back-to-back planetary gear.

2 Description of the Test Bench

The test bench is composed of two identical planetary gear sets with the same gear ratio (Fig. 1). The first planetary gear is a “test gear set” and the second planetary gear is a “reaction gear set” having a free ring. An arm is fixed on this ring and allowing the introduction of external load ((Hammami et al 2015) and (Hammami et al 2014a)).

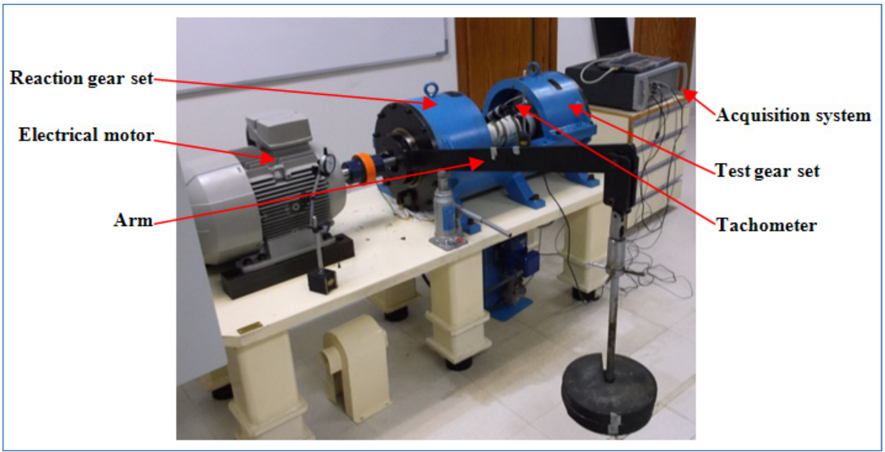

Fig. 1 Back-to-back planetary gear test bench

The two planetary gears are connected back-to-back in order to provide a mechanical power circulation: the sun gears of both planetary gear sets are connected through a common shaft and the carriers of both planetary gear sets are connected to each other through a rigid hollow shaft (Hammami et al 2014b).

In order to compare the load sharing between the tests planets, three strain gauges are installed in the pin holes of each planet in the tangential direction of the test carrier (Fig. 2).

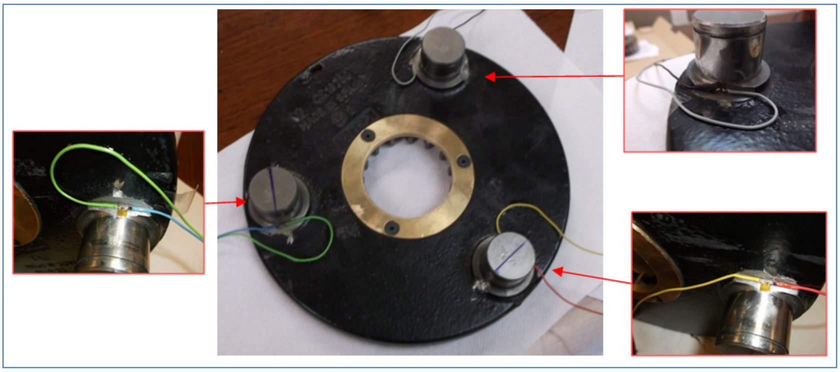

Fig. 2 Strain gauges mounted in each pin hole of the test carrier planets

The wires from the strain gauges are connected to the acquisition system through a hollow slip ring (HBM SK5/95) which is installed with the hollow shaft that connects the carriers (Fig.3).

Strains gauges are used in quarter bridge configuration.

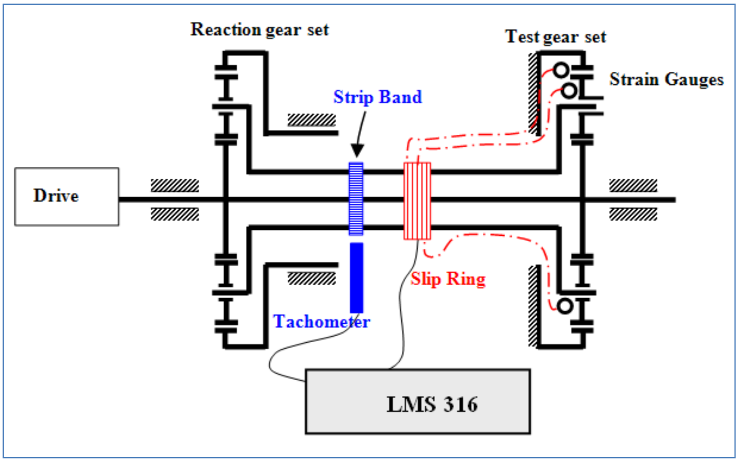

Fig. 3 Instrumentation layout

Strain signals registered by strain gauges will be acquired by Programmable Quad Bridge Amplifier module (PQBA) of the acquisition system "LMS SCADAS 316 system". This module can support four channels of strain transducers, piezo-resistive or variable capacitor sensors. Every channel is connected by 6 poles LEMO connector.

The data will be processed with the software "LMS Test.Lab" to visualize time history of strains.

Additionally, an optic tachometer (Compact VLS7) is combined with pulse tapes along the axe in order to measure its instantaneous angular velocity. It was placed along the hollow shaft of carriers.

3 Numerical Results

The effect of meshing phase, the gravity of planets carrier and the position error of planets on the load sharing behavior is studied in this part.

First of all, we define the planet load sharing ratio (LSR) as the ratio of the meshing torque due to sun-planet(i) and ring-planet(i) meshes of planet (i) by the meshing torque of all planets.

$$L_{Pi} = \frac{T_{mesh\,(Pi)}}{\sum_{i=1}^{n} T_{mesh\,(Pi)}} \tag{1}$$

3.1 *Effect of Meshing Phase*

For the case of equally spaced planets and in phase meshes gear (sun planets and ring planets), the planet load sharing factor is equal to 1/N (N: number of planets).

In our case, planets are equally spaced and gear meshes functions are sequentially phased.

$$\frac{Z_j \psi_i}{2\pi} \neq n \quad \text{and} \quad \sum_{i=1}^{N} Z_j \psi_i = m\pi \qquad (j = r, s) \tag{2}$$

Z_j is the number of tooth of the gear (j). ψ_i is the angle position of the planet (i). n and m are integer.

The gear meshes stiffness of ring-planets gear pairs (Fig. 4) and sun-planets gear pairs are modeled using the finite element model (Fernandez Del Rincon et al 2013).

The dynamic response is computed according to the procedure given in (Kahraman, 1994) and the load sharing ratio is computed according to equation (1). Fig.5 shows the planet load sharing ratio for the nominal position of planets (faultless system) for 100 N.m of input torque and for speed of motor 165 rpm.

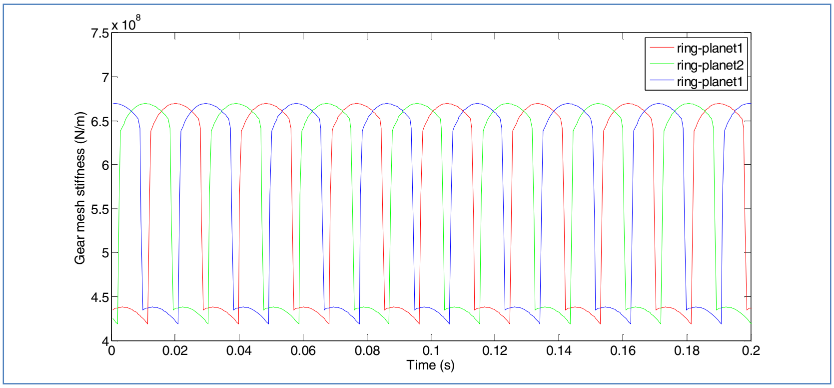

Fig. 4 Gear mesh stiffness ring-planets

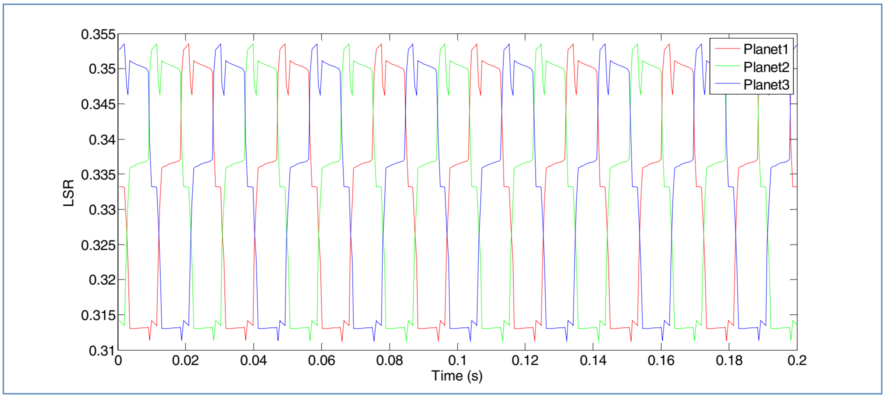

Fig. 5 Planet load sharing ratio for the nominal position of planets

In this case, the LSR for all planets fluctuates slightly around the 1/N value (N=3: number of planets) because the number of tooth in contact changes. The fluctuation of LSR of each planet is the same with a phase shift of 2π/3. This phase is induced by the fact that gear mesh sun-planets and ring-planets are sequentially phased.

3.2 Effect of Gravity of Carrier

The gravity of carriers has effect on the distances between ring-planets and sun-planets so that they are variable during the running of gearbox. Then, the values of gear mesh stiffness decrease as the distance between gears (sun-planets and ring-planets) increase and vice versa.

Fig.6 shows the evolution of gear mesh stiffness ring-planet1 during one period of rotation of carrier with effects of gravity of carrier. This period can be divided into four subperiods:

- The first subperiod : where the planet 1 is in the upper position. The values of gear mesh stiffness are low.
- The second subperiod where the planet 1 is in an intermediate position in (the left). The values of gear mesh stiffness are medium.
- The third subperiod where the planet 1 is in a lower position. The values of gear mesh stiffness are high.
- The fourth subperiod where the planet 1 is again in an intermediate position (the right). The values of gear mesh stiffness are medium.

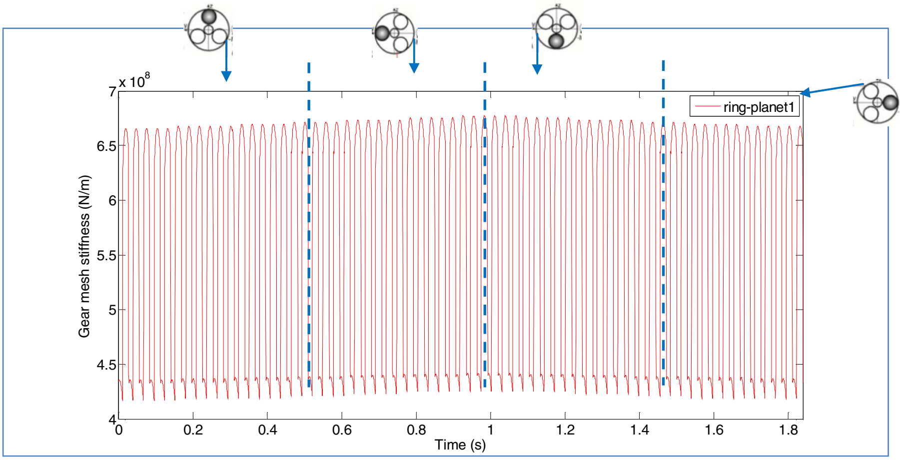

Fig. 6 Evolution of gear mesh stiffness ring-planets with gravity effects

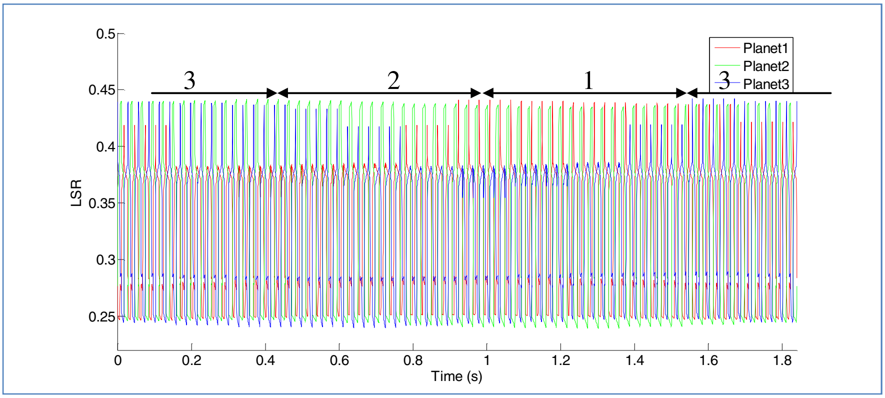

Fig. 7 Planet load sharing ratio with gravity effects

The gravity of carrier will lead to a periodic fluctuation of the maximum amplitude of gear mesh stiffness with a period corresponding to that of the rotation of the carrier Tc. The higher values of the gear mesh stiffness of ring-planets are successively on the planet 3 then planet 2 then planet 1.

Fig.7 shows the evolution of LSR during one period of rotation of carrier. This period is divided into three sub-periods of Tc/3. For each sub-period, the LSR of each planet does not oscillate with the same amplitude; there is always a planet that will include the maximum (planet1then planet2 then planet3).

3.3 Effect of Planet Position Error

If a planet has an error "e" on the position of its pin hole, and all other planets are at their ideal position, then the force due to this error is given by (Singh, 2010):

$$F_e = K_{eff}.e \tag{4}$$

K_{eff} is the cumulative stiffness due to meshing stiffness of the contact at the sun–planet K_{ps} and planet–ring K_{pr}, and the planet bearing stiffness K_b.

K_{eff} is defined as (Ligata et al, 2009):

$$\frac{1}{K_{eff}} = \frac{1}{K_b} + \frac{1}{K_{ps} + K_{pr}} \tag{5}$$

In our case, the planet 1 has an error "e_1=62µm" and the planet 2 has an error "e_2=-60µm". The LSR in this case is represented in Fig.8.

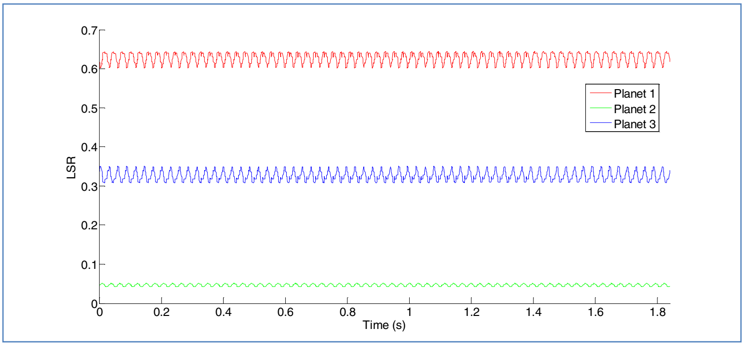

Fig. 8 Planet load sharing ratio with planets position errors

The position errors of planets 1 and 2 have an important effect in the LSR. Planet 1 which has a positive error anticipates the contact, being preloaded before planets 2 and 3 begin to transmit load; whereas planet 3 which has a negative error is preloaded after planet 2 and 1.This defects are in tangential direction and they have an effect more important in the LSR than the effect of gravity of carrier which is a variable radial error (Bodas and Kahraman 2004).

4 Correlation with Experimental Results

Strain-time histories for three planets system having errors "e_1=62µm" and "e_2=-60µm" are shown in Fig.9. It is clear that the positioning error has an important effect in the strain of each pin hole of planet.

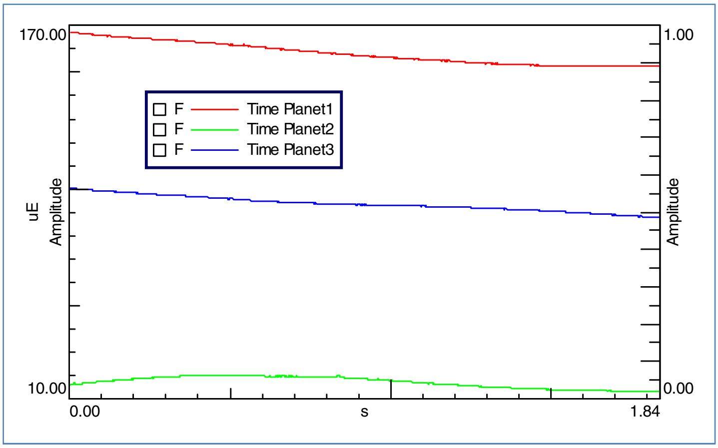

Fig. 9 Variation of the measured planets strains for the speed motor 165 rpm

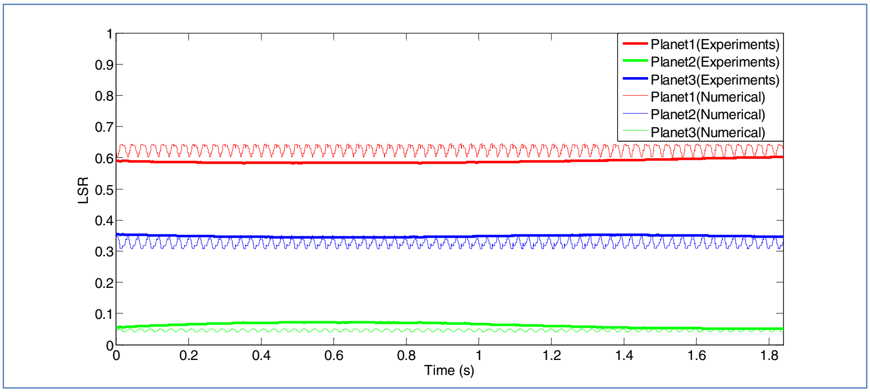

Fig. 10 Evolution of measured and calculated LSR

The computational results of the load sharing ratio are compared to the measured LSR (Fig. 10). In general, the calculated load sharing agrees with the measured data. In fact, the planet position errors have an important effect. In addition, a slight deviation of the load sharing evolution due to the effect of gravity of carrier is observed on the numerical and experimental results whereas the effect of meshing phase is observed only in the numerical results because the recorded signals presents noise due to the contact between brushes and slip ring. So, a signal processing was necessary.

5 Conclusion

In this paper, the planets load sharing behaviour is studied and correlated with those obtained experimentally using strain gages on planets of a back-to-back planetary gear test bench.

The effect that planets are sequentially phased is included to the model and as results; the load sharing ratio for all planets fluctuates slightly around the 1/N value. The time evolution of LSR of each planet bends a little bit every Tc/3 by the effect of gravity of carrier. However, the planets position errors have an important effect on the LSR of each planet. The final numerical results with the three effects agree with the measured strains on planets.

Future investigation will be focused mainly on the planets load sharing under non-stationary condition (run-up and run-down regimes).

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