Planet Load Sharing Behavior During Run Up

Ahmed Hammami, Alfonso Fernandez Del Rincon, Fakher Chaari, Fernando Viadero Rueda and Mohamed Haddar

Abstract The objective of this paper is to study the effects of meshing phase between planets and the planet position error on the load sharing behavior in planetary gear set during run up regime. These effects will be studied numerically and will be validated experimentally through a back-to-back planetary gear test bench by comparing strains in the pinhole of each planet.

Keywords Planetary gear · Load sharing · Run up · Meshing phase · 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.

A. Hammami (✉) · F. Chaari · M. Haddar
Laboratory of Mechanics, Modeling and Production (LA2MP),
National School of Engineers of Sfax, BP1173–3038 Sfax, Tunisia
e-mail: ahmed.hammami2109@gmail.com

F. Chaari
e-mail: fakher.chaari@gmail.com

M. Haddar
e-mail: mohamed.haddar@enis.rnu.tn

A. Hammami · A. Fernandez Del Rincon · F. Viadero Rueda
Department of Structural and Mechanical Engineering, Faculty of Industrial and Telecommunications Engineering, University of Cantabria,
Avda de los Castros s/n, 39005 Santander, Spain
e-mail: alfonso.fernandez@unican.es

F. Viadero Rueda
e-mail: fernando.viadero@unican.es

T. Fakhfakh et al. (eds.), *Advances in Acoustics and Vibration*,
Applied Condition Monitoring 5, DOI 10.1007/978-3-319-41459-1_16

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

Many significant works on the subject of planetary gear load sharing have been done. These works were based on transmission modeling and assessed by experimental tests. 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 load sharing of four-planet systems and presented experimental data for validation of the model predictions. Iglesias et al. (2013) studied the effect of planet position error on the load sharing and transmission error. Singh (2005) found that the tangential pin position error has a greater effect on the load sharing than the radial pin position error. 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 (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.

All works on the subject of planetary gear load sharing are in the static, quasi-static or stationary operations.

In this paper, the effects of meshing phase and the error position of the pin hole of planets on the load sharing characteristics are studied during the run up regime numerically and validated experimentally through 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 allowing the mechanical power circulation (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. 2014a, b). The two planetary gears are connected back-to-back: 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. 2014c).

Three strains gauges are used in quarter bridge configuration in order to compare the load sharing between the tests planets. They are installed in the pin holes of each planet in the tangential direction of the test carrier (Fig. 1).

The wires from the strain gauges are connected to the Programmable Quad Bridge Amplifier module (PQBA) of the acquisition system "LMS SCADAS 316

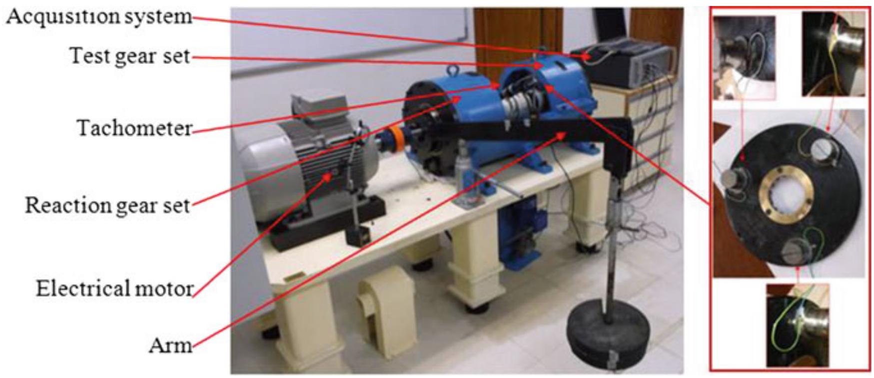

Fig. 1 Back-to-back planetary gear test bench

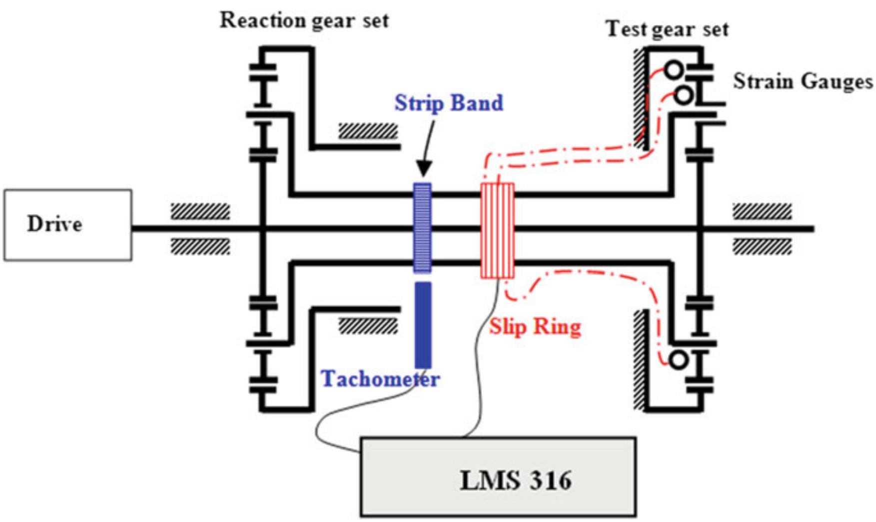

Fig. 2 Instrumentation layout

system" through a hollow slip ring which is installed with the hollow shaft that connects the carriers (Fig. 2).

Additionally, an optic tachometer (Compact VLS7) which is placed along the hollow carriers' shaft measure its instantaneous angular velocity.

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

3 Numerical Results

In this part, effects of meshing phase and the position error of planets on the load sharing behavior are studied during the run up regime. The variation of speed during this regime is controlled by the frequency converter "Micromaster 440" which commands linearly the variation of the rotational speed of motor as shown in Fig. 3.

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.

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

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.

For run up regime, the period of mesh stiffness function decrease as speed increases (Khabou et al. 2011; Viadero et al. 2014). Meshes stiffness between gears

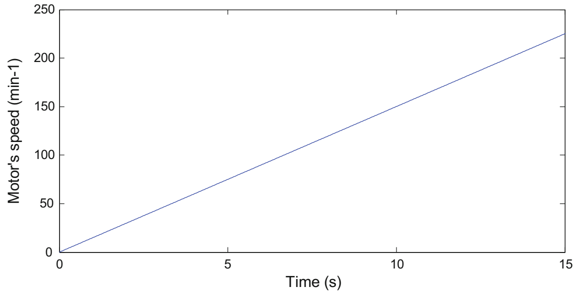

Fig. 3 Evolution of the motor's speed during run up

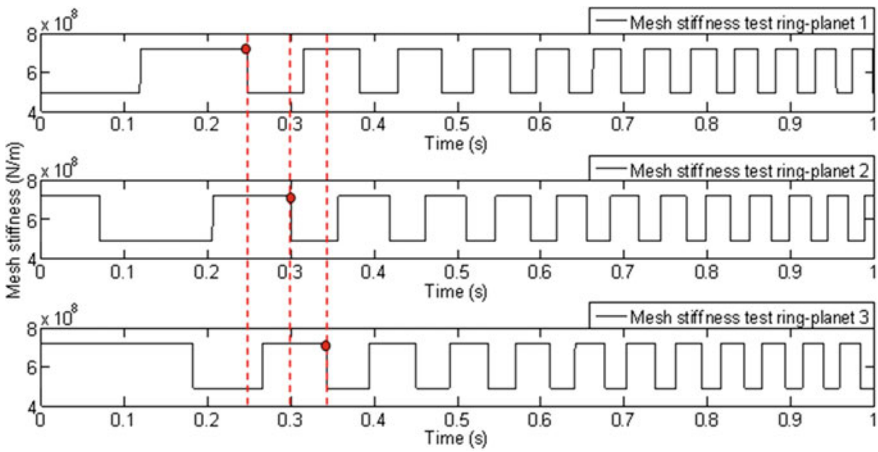

Fig. 4 Evolution of the mesh stiffness ring-planets during run-up

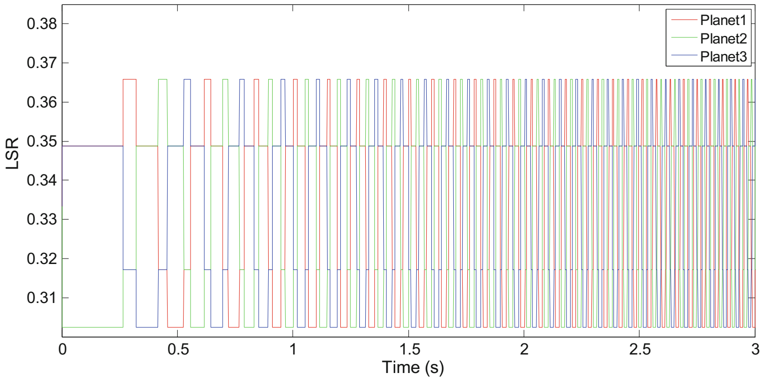

Fig. 5 Planet load sharing ratio for the nominal position of planets

are modelled as square functions. Figure 4 shows the evolution of mesh stiffness for ring-planets on the test gear set during run up taking into account mesh phasing.

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

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 with a phase shift of $2\pi/3$. This phase is induced by the fact that gear mesh sun-planets and ring-planets are sequentially phased. In addition, the period of fluctuation of LSR of each planet decrease with time which is explained by the evolution of the mesh stiffness ring-planets during run-up.

3.2 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 = 60 µm”, the planet 2 has an error “e_2 = −5 µm” and the planet 3 has an error “e_3 = −60 µm”. The LSR in this case is represented in Fig. 6.

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 very important in the LSR (Bodas and Kahraman 2004). In addition, planet load sharing ratio tends towards fair values in the run up regime which is explained by the fact that the transmitted load decrease in each planet as the speed increase.

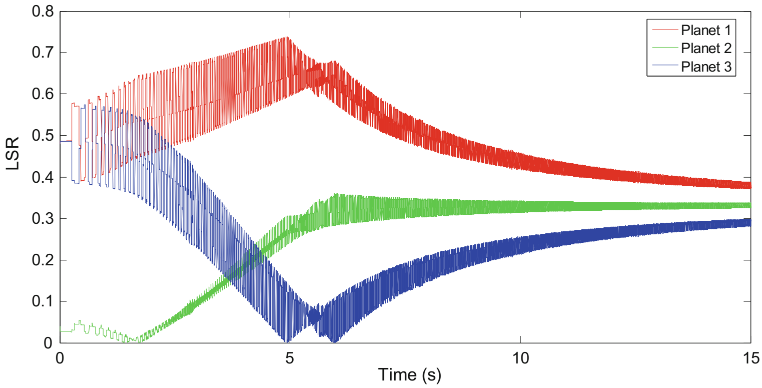

Fig. 6 Planet load sharing ratio with planets position errors

4 Correlation with Experimental Results

Strain-time histories for three planets system having errors "e_1 = 60 µm" and "e_2 = −5 µm" and "e_2 = −60 µm" are shown in Fig. 7. It is clear that the positioning error has an important effect in the strain of each pin hole of planet. Also, strains tend towards fair values as the speed increase.

The computational results of the load sharing ratio are compared to the measured LSR (Fig. 8). In general, the calculated load sharing agrees with the measured data. In fact, 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.

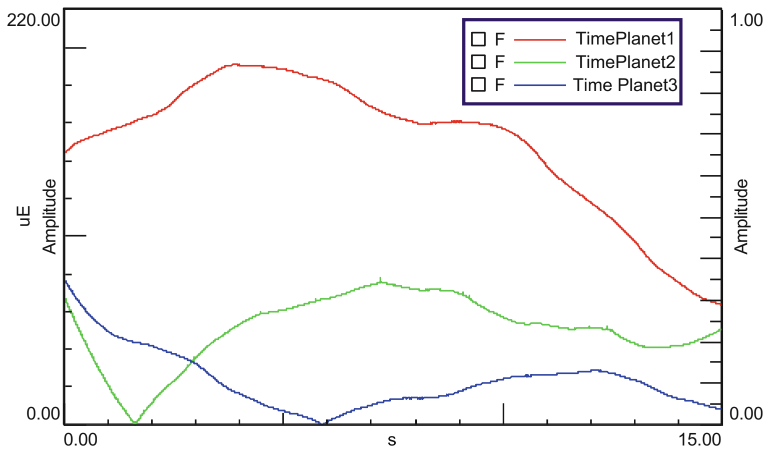

Fig. 7 Variation of the measured planets strains for the speed motor 165 rpm

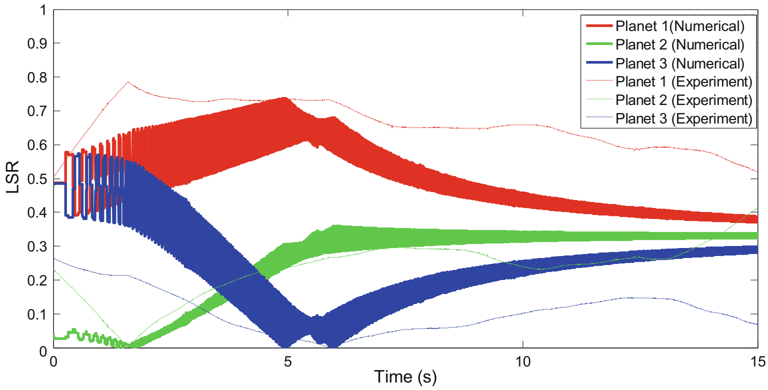

Fig. 8 Evolution of measured and calculated LSR

5 Conclusion

In this paper, the planets load sharing behaviour is studied during the run up regime 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 and the period of fluctuation of each planet decreases with time. The planets position errors have an important effect on the LSR of each planet which tends towards fair values in the run up regime. The final numerical results with the two effects agree with the measured strains on planets.

Acknowledgments This paper was financially supported by the Tunisian-Spanish Joint Project No. A1/037038/11.

The authors would like also to acknowledge project "Development of methodologies for the simulation and improvement of the dynamic behavior of planetary transmissions DPI2013-44860" funded by the Spanish Ministry of Science and Technology.

Acknowledgment to the University of Cantabria cooperation project for doctoral training of University of Sfax's students.

References

Bodas A, Kahraman A (2004) Influence of carrier and manufacturing errors on the static lad sharing behavior of planetary gear sets. Bull Jpn Soc Mech Eng 47(3):908–915

Guo Y., Keller J (2012) Combined effects of gravity, bending moment, bearing clearance, and input torque on wind turbine planetary gear load sharing. American Gear Manufacturers Association technical paper, 12FTM05

Hammami A, Fernández A, Viadero F, Chaari F, Haddar M (2014a) Modal analysis of back-to-back planetary gear: experiments and correlation against parameter model. J Theor Appl Mech 53(1):125–138

Hammami A, Fernández A, Viadero F, Chaari F, Haddar M (2014b) Dynamic behaviour of back-to-back planetary gear in run up and run down transient regimes. J Mech 31(4):481–491

Hammami A, Fernández A, Chaari F, Viadero F, Haddar M (2014c) Dynamic behaviour of two stages planetary gearbox in non-stationary operations. In: Mechatronic system: theory and application, pp 23–35

Iglesias M, Fernandez A, De-Juan A, Sancibrian R, Garcia P (2013) Planet position errors in planetary transmission: effect on load sharing and transmission error. Front Mech Eng 8:80–87

Kahraman A (1994) Load sharing characteristics of planetary transmissions. Mech Mach Theory 29:1151–1165

Kahraman A (1999) Static load sharing characteristics of transmission planetary gear sets: model and experiment. SAE Paper No. 1999–01–1050

Khabou MT, Bouchaala N, Chaari F, Fakhfakh T, Haddar M (2011) Study of a spur gear dynamic behavior in transient regime. Mech Syst Signal Process 25:3089–3101

Ligata H, Kahraman A, Singh A (2008) An experimental study of the influence of manufacturing errors on the planetary gear stresses and planet load sharing. J Mech Des 130

Ligata H, Kahraman A, Singh A (2009) A closed-form planet load sharing formulation for planetary gear sets using a translational analogy. J Mech Des 131:021007

Singh A (2005) Application of a system level model to study the planetary load sharing behavior. J Mech Des 127:469–476

Singh A (2010) Load sharing behavior in epicyclic gears: physical explanation and generalized formulation. Mech Mach Theory 45:511–530

Viadero F, Fernández A, Iglesias M, de-Juan A, Liaño E, Serna MA (2014) Non-stationary dynamic analysis of a wind turbine power drivetrain: offshore considerations. Appl Acoust 77:204–211