Modeling the Transmission Path Effect in a Planetary Gearbox

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Abstract. In such mechanical systems, as helicopters and self-propelled cranes, designers need to use gearboxes which have an important reduction ratio within compact space. Hence, planetary gearboxes are widely used. Consequently, its monitoring presents an important task for researchers and engineers either in healthy or damaged case. Many researchers are interested on the investigation of the modulation phenomenon in planetary gearbox. It is presented in a frequency representation as side-band activity near to the gear-mesh frequency component and its harmonics. In a healthy case, the origin of this phenomenon in a planetary gearbox (stationary ring) is that the transducer, which is mounted on the external housing of the ring gear, perceived signals from all components including sun-gear, ring-gear, carrier and planet-gears which can occupy different position in one carrier period rotation. Hence, when the planet comes closer to the sensor, the vibration signal increases and vice-versa. In this work, a two dimensional linear lumped parameter model is proposed to model vibration sources. A mathematical formulation of the transmission path is introduced in order to model only the amplitude modulation phenomenon due to the change of the planet-gear position since the speed of the sun is constant. A frequency representation of numerical results is presented and analyzed.

Keywords: Planetary gearbox · Transmission path · Modulation function

1 Introduction

Due to its importance, the amplitude modulation phenomenon occurring in a planetary gearbox is investigated by several researchers to clarify that this phenomenon is a major characteristic in healthy case and differs from a modulation due to a fault. In addition, this phenomenon will influence the overall vibration signal collected by a transducer mounted on the external housing of the gearbox.

Sondkar and Kahraman (2013) proposed a three dimensional lumped parameters model of a double helical planetary gear-set. Firstly, their work aimed at predicting the amplitude of the maximum dynamic mesh force; secondly, it aimed at evaluating the

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change of the mesh force under a radially floating sun gear. Inalpolat and Kahraman (2009) developed a mathematical model to report the origin of modulation side-band including in a healthy planetary gear-set. As investigated, the modulation side-band in a frequency representation comes from an epicyclic gearbox having either a stationary sun gear or a stationary ring gear. In a later work (2010), they proposed a nonlinear dynamic model to evaluate the modulation activity in an unhealthy planetary gear-set in the form of run out or eccentricity. Fluctuating mesh force are investigated also in the work of Guo and Parker (2010) and it was related to tooth wedging which causes bearing failures. A model was developed to combine bearing clearance, tooth separation and wedging and back-side contact. The modulation phenomenon either amplitude or frequency modulation in time domain which is called side-band activity in a frequency representation were investigated in the work of Feng and Zuo (2012), Liang et al. (2015) and Liu et al. (2016). In Feng and Zuo (2012), the authors simulate faulty gear damages for instance faulty planet gear and faulty sun gear after defining characteristic frequency of faulty gear in a planetary gearbox. In Liang et al. (2015), a lumped parameter model was developed to build vibration sources then all vibration was concluded in the sensor location by taking into account the transmission path effect due to the rotational motion of the carrier which holds planet gears. Two vibration properties were investigated: healthy case and cracked tooth case. In a later work Liu et al. (2016), they focused only on transmission path which is modeled as two parts: a first part inside the gearbox to the housing and a second part along the housing to the sensor location.

This paper is organized as follows: In Sect. 2, the origin of the modulation phenomenon is investigated and the transmission path is defined. In Sect. 3, the transmission path is formulated as function of geometric and physical parameters of the planetary gearbox. Finally, some numerical results are presented in Sect. 4 where the impact of planets on the resultant vibration is investigated and the vibration characteristics are revealed.

2 Origin of the Modulation Phenomenon

As mentioned in Sect. 1, one planet can occupy different positions in one carrier rotation period. Figure 1 presents three locations of one planet. The sensor is mounted on the external housing of the planetary gearbox. It can acquire signals due to the vibration coming from all components including sun-gear, ring-gear, carrier and planet-gear. All components have only a rotational motion with respect to its center except the planet-gear which has an additional motion with respect to the center of the gearbox. Due to this additional motion, the vibration signals are under modulation phenomenon either amplitude modulation in case of stationary speed or amplitude and frequency modulation in case of fluctuating speed.

Since the study is focused on the stationary conditions, we will investigate only the amplitude modulation phenomenon. As shown in Fig. 1, the transmission path can be divided into two parts: a first part inside the gearbox (blue one) and a second part along the casing. As the planet moves, the dimension of the blue path is still constant. On the

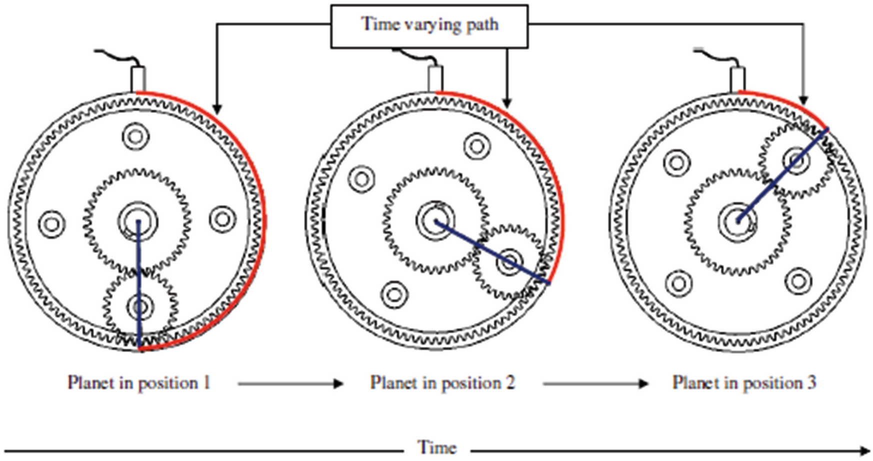

Fig. 1. Different position of one planet

other hand, the dimension of the red path decreases which creates the amplitude modulation function (AMF). Hence, two points have to be mentioned:

- the main cause of the amplitude modulation is the time varying transmission path which is represented by the arc of the circle.
- when the dimension of the path decreases, the vibration signal increases since the planet becomes closer to the transducer. Therefore, the AMF and the time varying path are inversely proportional.

3 Mathematical Formulation of the Transmission Path

In Sect. 2, it was mentioned that the time varying path (origin of modulation phenomenon) is an arc of the circle. Hence, a geometric construction presented in Fig. 2(a) was made in order to link the time varying arc with geometric parameters of the planetary gear-set.

Derived from the geometrical construction given in Fig. 2(a), the AMF can be expressed as:

$$AMF = \frac{\frac{1}{2 \times R_r \times \sin(Arc/R_r) + 1}}{\max\left(\frac{1}{2 \times R_r \times \sin(Arc/R_r) + 1}\right)} \tag{1}$$

An offset equal to one is taken into account to avoid the division by zero since the AMF and the time varying transmission path are inversely proportional. In addition, the AMF is divided by its max to consider only the percentage of the function.

Figure 2(b) turns out the shape of the AMF mentioned in Eq. 1.

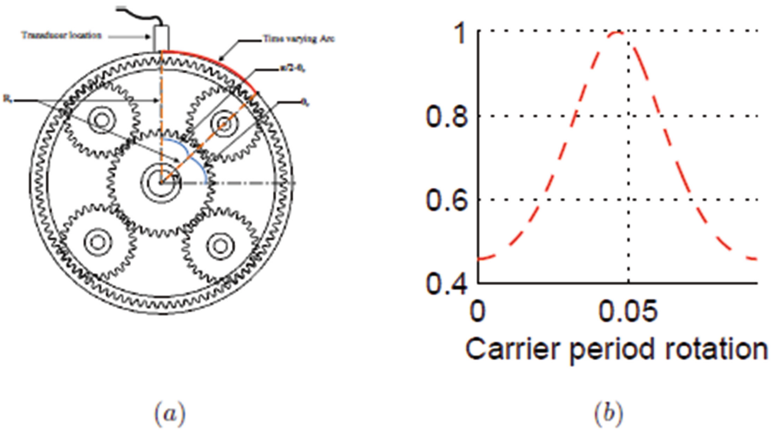

Fig. 2. (a) Geometric construction (b) Modulation function

4 Numerical Simulation

Table 1 resumes physical parameters of the planetary gear-set to simulate its dynamic behavior. The dynamic model used is shown in Fig. 3. Acceleration is measured with respect to the carrier.

Table 1. Physical parameters of a planetary gear set

Parameters	Sun gear	Planet gear	Ring gear	Carrier
Number	1	4	1	1
Number of teeth	39	27	93	–
Modulus	2	2	2	–
Pressure angle	20	20	20	–
Mass (Kg)	2.3	0.885	2.94	15
Base circle radius (m)	0.078	0.054	0.186	0.132
Bearing stiffness	$K_{sx} = K_{sy} = K_{px} = K_{py} = K_{rx} = K_{ry} = K_{cx} = K_{cy} = 10^8$			
	$K_{sw} = 0$	$K_{pw} = 0$	$K_{rw} = 10^{15}$	$K_{cw} = 0$
Input torque (Nm)	150	–	–	–
Input-speed (tr/mn)	2183.6	–	–	–

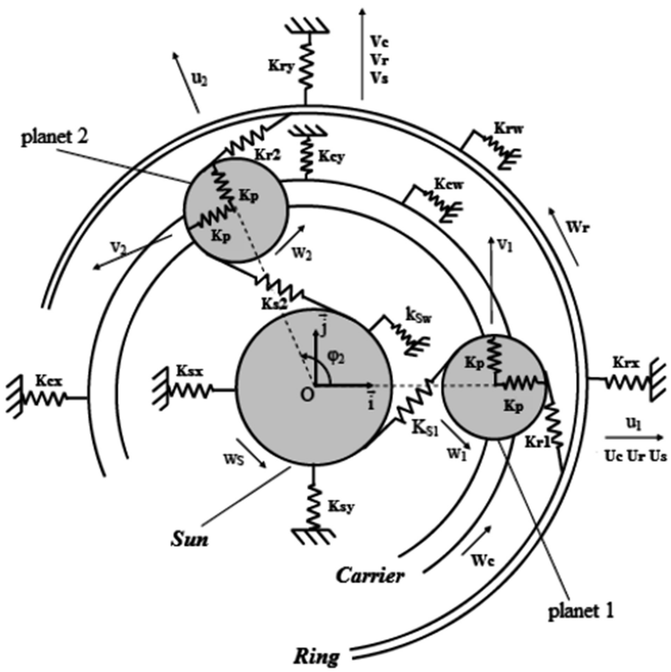

Fig. 3. Lumped parameters model

4.1 Impact of Each Planet on the Resultant Vibration

Figure 4 highlights the contribution of each planet alone on the overall resultant vibration. As shown, the consequence of the passage of each planet is presented by the modulation of the vibration collected by the transducer.

4.2 Analysis of Numerical Results

Figure 5 displays a zoom section between 2500 Hz and 4500 Hz of the frequency representation of the resultant vibration. As seen, there is a side-band activity near to two gear-mesh frequency harmonics (H3GMF = 3000 Hz and H4GMF = 4000 Hz). To identify the origin of side-band components, it is necessary to calculate the carrier frequency.

Based on Table 1 and on formulas presented below, the frequency of the carrier is obtained.

$$f_s = \frac{N_s}{60} = 36.39\,\text{Hz} : \textit{sun frequency};\ r = \frac{Z_s}{Z_s + Z_r} = 0.2955 :\ \textit{ratio (planetary)}$$
$$f_c = r \times f_s = 10.75\,\text{Hz} :\ \textit{carrier frequency}$$

Table 2 resumes the identified frequencies in Fig. 5 and its correspondences.

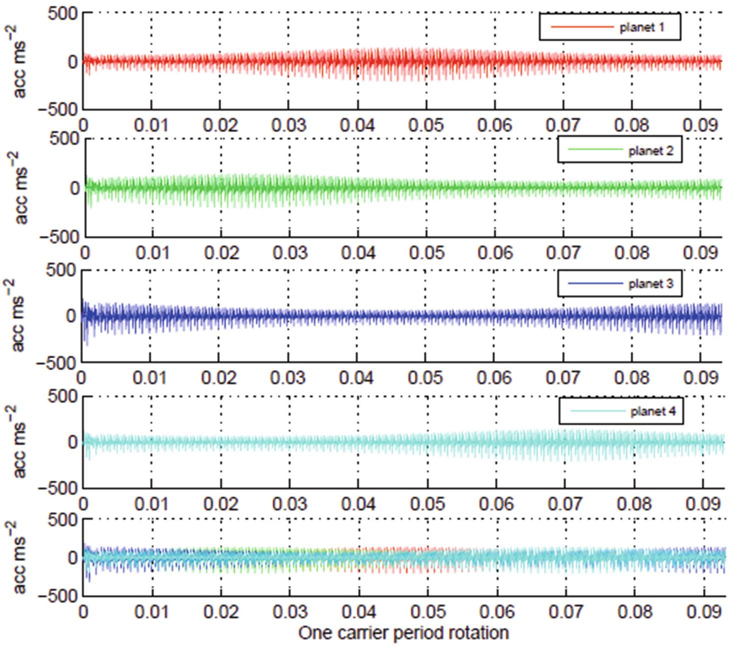

Fig. 4. Contribution of each planet on the resultant vibration

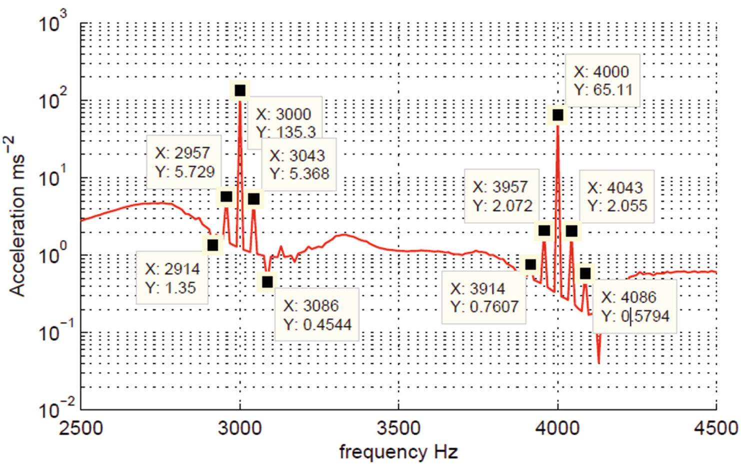

Fig. 5. Frequency representation of the resultant vibration

Table 2. Values of frequencies and its correspondences

Frequencies (Hz)	Correspondence
3000	$H3_{GMF}$
3043–2957	$H3_{GMF} \pm 4 \times f_c$
3086–2914	$H3_{GMF} \pm 8 \times f_c$
4000	$H4_{GMF}$
4043–3957	$H4_{GMF} \pm 4 \times f_c$
4086–3914	$H4_{GMF} \pm 8 \times f_c$

5 Conclusion

In this study, a vibration signal modeling method is proposed. A lumped parameter model is developed to simulate vibration signal issued from all components. A mathematical formulation based on geometric parameters of the planetary gearbox is presented in order to model the modulation phenomenon. Incorporating vibrations coming from all components and the transmission path effect, the resultant vibration is obtained at the sensor location as the sum of all vibration components influenced by the transmission path. The spectrum structure is analyzed and the side-band activity is predicted near to the gear-mesh frequency components and its harmonics.

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References

Sondkar, P., Kahraman, A.: A dynamic model of a double-helical planetary gear set. Mech. Mach. Theory **70**, 157–174 (2013)

Inalpolat, M., Kahraman, A.: A theoretical and experimental investigation of modulation sidebands of planetary gear sets. J. Sound Vib. **323**, 677–696 (2009)

Inalpolat, M., Kahraman, A.: A dynamic model to predict modulation sidebands of a planetary gear set having manufacturing errors. J. Sound Vib. **329**, 371–393 (2010)

Guo, Y., Parker, R.G.: Dynamic modeling and analysis of a spur planetary gear involving tooth wedging and bearing clearance nonlinearity. Eur. J. Mech. A/Solids **29**, 1022–1033 (2010)

Feng, Z., Zuo, M.J.: Vibration signal models for fault diagnosis of planetary gearboxes. J. Sound Vib. **331**, 4919–4939 (2012)

Liang, X., Zuo, M.J., Hoseini, M.R.: Vibration signal modeling of a planetary gear set for tooth crack detection. Eng. Fail. Anal. **48**, 185–200 (2015)

Liu, L., Liang, X., Zuo, M.J.: Vibration signal modeling of a planetary gear set with transmission path effect analysis. Measurement **85**, 20–31 (2016)