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Two methods for modeling vibrations of planetary gearboxes including faults: Comparison and validation

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ABSTRACT

Planetary gearboxes are important components of many industrial applications. Vibration analysis can increase their lifetime and prevent expensive repair and safety concerns. However, an effective analysis is only possible if the vibration features of planetary gearboxes are properly understood. In this paper, models are used to study the frequency content of planetary gearbox vibrations under non-fault and different fault conditions. Two different models are considered: phenomenological model, which is an analytical-mathematical formulation based on observation, and lumped-parameter model, which is based on the solution of the equations of motion of the system. Results of both models are not directly comparable, because the phenomenological model provides the vibration on a fixed radial direction, such as the measurements of the vibration sensor mounted on the outer part of the ring gear. On the other hand, the lumped-parameter model provides the vibrations on the basis of a rotating reference frame fixed to the carrier. To overcome this situation, a function to decompose the lumped-parameter model solutions to a fixed reference frame is presented. Finally, comparisons of results from both model perspectives and experimental measurements are presented.

1. Introduction

Planetary Gear sets (PG) are widely used because they are compact and have large torque-to-weight ratio. They are found in many applications such as helicopter transmissions, lifting cranes, wind turbines, and mining excavators. It is well known that vibration analysis has the potential to prevent expensive repair, downtimes and safety concerns of machines. However its application in PG is not straightforward due to the multiple movable meshing pairs that simultaneously take place inside the unit. These situations lead to a variable transmission path between the gear pairs and the transducer, which difficult the understanding of the vibration behavior of the PG. The vibrations of PG have been studied using two different models: First, there is the phenomenological model, where the vibration contributions resulting from the different meshing processes are directly modeled as periodic functions considering the system kinematics. That is, it is an analytical-mathematical model. Then, there is the lumped-parameter model, or dynamic model, which is based in the numeric resolution of the equations of motion of the system.

The study of phenomenological model started three decades ago with the work of McFadden and Smith [1], who contributed to the understanding of the difference between the dominant frequency and gear meshing frequency. They also used the model to explain the asymmetry of the spectrum measured by a transducer mounted on the outside of the ring gear

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(Fig. 1). Years after, McNames [2] used the Fourier series to complement the work of McFadden and Smith. Parker and Lin [3] studied the vibration phases of each gear pair inside a PG. Inalpolat [4] and Vicuña [5] generalized the previous work by expanding the analysis to different geometries of PG. Both works took the amplitude modulation effect (AM) caused by the carrier rotation into account, but did not consider any frequency modulation effect caused by meshing stiffness variation or gear damage. The latter was included by Feng in the analysis of his work [6]. More recently, Hong [7] used Fourier series analysis to explain the distinct sideband patterns in healthy and faulty PG. All studies mentioned propose models that bring solutions referred to the measurements that the sensor would take placed as in Fig. 1.

The first studies of the lumped-parameter model started as a method to determine the natural frequencies and vibration modes of PG. Kahraman [8] presented a torsional model for this purpose. Then Lin [9] worked in modal analysis on an equation of motion with multiple degrees of freedom. Chaari et al. [10] expanded the previous work by studying the influence of manufacturing errors. Additionally, there are works on other research topics like load sharing among planet gears [11,12], nonlinear dynamics and tooth faults [13–17]. Among these we highlight the work of Chaari et al. [18], where changes in gearmesh stiffness due to tooth spalling and breakage were studied, although not in PG.

Unlike the fixed transducer scheme of Fig. 1, generally all lumped-parameter model solutions are referred to a non-inertial reference frame, fixed to and rotating with the carrier. In the case of comparing the solutions with experimental measurements, it is desirable to know the vibration in the inertial basis as seen by a ground-based observer [19]. In brief, solutions of lumped-parameter model are not directly comparable with results from phenomenological model and real vibrations measured on the ring gear. Other works include the lumped-parameter model and present their solutions as representing the fixed transducer response, but no explanation of the method used to obtain the solutions are provided [7,20]. Other authors propose different methods to decompose the rotatory reference frame solutions into a fixed reference frame like the transducer measurements, but they make incorrect assumptions: Inalpolat and Kahraman [21] expressed the sensor measurements in function of the dynamic forces of the planets-sun and planets-ring without considering the difference between the direction of their lines of action. Torregrosa and Vicuña [22] proposed a different function, but missed the fact that the direction of the lines of action of the dynamic forces change with the rotation of the shafts. Liang et al. [16] propose that the sensor measurements are obtained by the summation of weighted vibration of each planet gear, which doesn't consider the vibrations of other PG components like ring, sun, and carrier. Finally, Karray et al. [23] include a transmission error function in the line of action, to explain the modulation sidebands pattern of the vibrations, thus incorrectly including an artificial modulation of the gearmesh forces.

This study examines the frequency content of an equally spaced planetary gear set with the use of the lumped-parameter model and phenomenological model, in both healthy and faulty condition. Faults considered are local faults on sun gear, planet gear and ring gear. To compare the lumped-parameter model results with the phenomenological model results and experimental measurements (to account for additional frequency components related to the local faults), we propose a method that provides a solution to the decomposition of rotatory frame to fixed reference frame vibrations.

2. Planetary gearbox vibration models and frame decomposition

In this section, vibration models of the PG used in this study are presented. The configuration and measurement arrangement considered is shown in Fig. 1. According to the classification suggested in [4], the PG pertains to group A, i.e., with $N = 3$

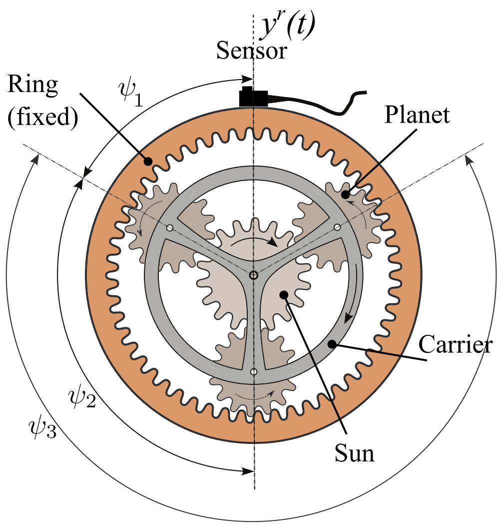

Fig. 1. Measurement arrangement.