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Gear meshing analysis of planetary gear sets with a floating sun gear

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ABSTRACT

The goal of this study is to propose an analytical approach for analysis of gear meshing in a planetary gear set with a floating sun gear. With focus on the basic geometrical relation, we derive a set of equations based on the exact involute gear geometry for calculation of the tooth clearances among engaged unmodified or modified flanks of gears having relevant errors. Two constraint conditions for the floating sun gear are established for determination of the movable area. Numerical examples are presented to explore the influences of the planet gear number, the backlashes, and the assembly/manufacturing errors on the tooth clearance, the moveable area and assemblability of the sun gear.

1. Introduction

Compact design, high power density and coaxial arrangement of the input and output shafts of planetary gear drives play a very important role in power transmission. As a consequence of the multiple planet gears, the interaction of the engaged teeth of the planetary gear set is more complicated than for the parallel spur or helical gear set. The analysis of tooth contact among multiple tooth pairs of various gears under loaded and no-loaded conditions is the fundamental for improving the performance of planetary gear drives. In general, two-dimensional geometric and static analysis of planetary gear drives is a basic, but efficient tool, which can be expanded either for three-dimensional static or dynamic analysis. Some important issues such as the mesh condition of each sun-planet-annulus gear pair, the un-loaded and loaded transmission error, and the load sharing with and without the profile modification should be included. These are mostly interwoven together. For example, the load sharing between the engaged teeth among multiple planets is influenced sensitively by the manufacturing and assembly errors, which also affect the mesh condition of the gears.

In the past few years, several valuable studies haven been carried out seeking to solve the load sharing problem in planetary gear trains. Bodas and Kahraman [1] used an FE-approach to analyze the influences of manufacturing errors of the gears and the carrier on the load sharing of planetary gear drives. Boguski, Kahraman et al [2] utilized two proximity probes to measure the trajectory of a sun gear in the radial direction during operation. Their study showed that the shape of the size of the sun gear orbit is related to assembly or manufacturing errors and planet mesh phasing condition of the planetary gear set. Especially the radial motion of the sun gear is restricted by the error applied. Singh [3] applied FEM to analyze the load sharing of planetary gear sets with 4, 5, or 6 planets, but under the same errors. He also gave a simple framework to explain and predict load sharing in planetary gear drives [4,5].

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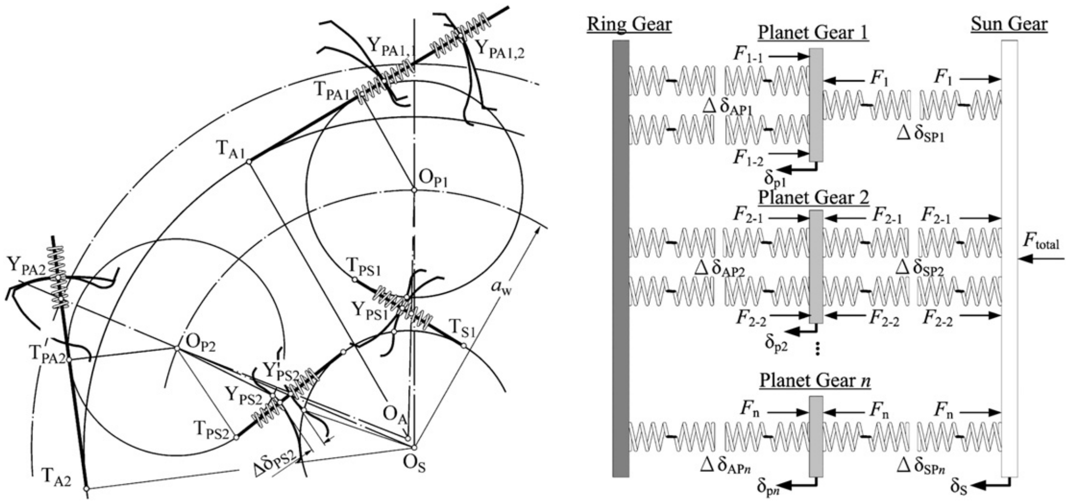

Fig. 1. Stiffness model of a planetary gear set.

However, none of the studies mentioned above offer clear information about the relation of shared loads and the mesh condition of the engaged gears. Tsai et al. [6] established an analytical approach using a stiffness model (shown in Fig. 1) to analyze load sharing among the planets. The mesh stiffness and the tooth clearances of the contact tooth pairs are considered in the model. The acting load between each contact tooth pair can thus be calculated based on the load-deformation relation, [6]. It is obvious from the model that the contact tooth pair with a larger tooth clearance $\Delta\delta$ and/or a smaller stiffness will share a smaller load. In other words, uneven load sharing among planets occurs, when there is a difference in mesh stiffness and/or different tooth clearance $\Delta\delta$ of the contact tooth pairs. This brings us to the design concept for the load balancing mechanisms for planetary gear drives: that the tooth clearances can be adjusted by using additional degrees of freedom for specified gears so as to obtain optimal load sharing. The most common type of load balancing mechanism is the floating sun gear design.

The mesh conditions of gears affect not only the load sharing, but also the assemblability of the planetary gear set having assembly and manufacturing errors. Because of the presence of such the errors, backlash is essential for assembly of the gears. However the backlash of the planetary gear set plays also an important role for precision motion transmission. The relation of the backlash and the assembly/manufacturing errors on the assemblability is valuable to analyze. On the other hand, the moveable area of a floating sun gear, which can be also a criterion for the evaluation of the eccentric positional error of the sun gear, is also dependent on the backlash. It is also essential to analyze the mesh condition of the floating sun gear while in designing the planetary gear set.

Some research studies have also focused on the mesh relation of the floating sun gear in the planetary gear set. For example, Yashino et al. [7] analyzed, theoretically and experimentally, the self-centering path of a floating sun gear with 3 planet gears under consideration of the effects of gravity. In order to determine the self-centering path of the sun gear, the clearance between the teeth of the sun gear and the planet gears, and the movable distance of the sun gear were obtained according to two constraint conditions. The results showed that the self-centering locus was inside a hexagonal area. They also conducted dynamic experiments related to the self-centering path and abnormal vibration of the orbit of the floating sun gear, with and without considering the effects of a frictional force acting on the contact teeth [8,9]. However, the analysis was only based on the assumption of the linear gear flanks. Hidaka [10] also carried out static analysis of the relation between the run-out error and the motion of the sun gear, both analytically and experimentally. Vecchiato [11] proposed a numerical method for calculating the trajectory of the sun gear in a planetary gear set with misalignment of the sun gear, the carrier and the planets using a tooth contact analysis (TCA) program based on Litvin's gearing theory.

Although the works mentioned above offer valuable results on load analysis, there has been little research on the mesh conditions of the engaged gears using analytical approach. Such a study would be useful not only for static analysis of the load sharing and assembly conditions of the complete planetary gear set, but also for the dynamic analysis, especially in the case of a high speed floating sun gear. The goal of this study is to establish an analytical approach for gear meshing analysis of planetary gear drives. A set of equations based on the *exact involute gear geometry* is at first derived for calculation of the tooth clearances among engaged unmodified or modified flanks of multiple gear pairs caused by manufacturing errors of the planet gears and the carrier [1], and also the deviation in position of the sun gear. The related equations are thus expended for calculation of the assemblability and the movable area of the sun gear under consideration of the backlash. Numerical examples are provided to illustrate the proposed approach. The influences of the number of planets, the backlash and the assembly/manufacturing errors on the movable area and allowable errors of the components are all discussed.