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Dynamic simulation of planetary gear set with flexible spur ring gear

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ABSTRACT

Ring gear is a key element for vibration transmission and noise radiation in the planetary gear system which has been widely employed in different areas, such as wind turbine transmissions. Its flexibility has a great influence on the mesh stiffness of internal gear pair and the dynamic response of the planetary gear system, especially for the thin ring cases. In this paper, the flexibility of the internal ring gear is considered based on the uniformly curved Timoshenko beam theory. The ring deformation is coupled into the mesh stiffness model, which enables the investigation on the effects of the ring flexibility on the mesh stiffness and the dynamic responses of the planetary gear. A method about how to synthesize the total mesh stiffness of the internal gear pairs in multi-tooth region together with the ring deformation and the tooth errors is proposed. Numerical results demonstrate that the ring thickness has a great impact on the shape and magnitude of the mesh stiffness of the internal gear pair. It is noted that the dynamic responses of the planetary gear set with equally spaced supports for the ring gear are modulated due to the cyclic variation of the mesh stiffness resulted from the presence of the supports, which adds more complexity in the frequency structure.

1. Introduction

In the past several decades, studies on planetary gear have attracted so much attention from numerous researchers and scholars due to its wide applications in industry, wind turbine, national defense and aerospace fields. This is because of its advantages, such as compactness, large torque-to-weight ratio, large transmission ratios, reduced noise and vibrations as well as high efficiency due to the relatively smaller and stiffer components. Most of the previous studies assumed that the internal gear ring is rigid [1–9]. This is a supportable assumption for the internal gear with thick rim whose deformation can be neglected. However, the internal gear ring is always designed to be as thin as possible for the weight reduction. In addition, a thin ring could improve the load sharing among planets by introducing more compliance [10–12]. It is demonstrated that inaccuracies resulted from the errors of the internal gear and the carrier can be reduced with smaller ring thickness [12]. Due to these advantages of thin internal gear ring, there have been many published literatures about the investigations on the internal ring gear performances.

As early as in 1970s, Hidaka et al. [13] tested experimentally the displacement away from the basic positions for the sun and the ring gear. And they [14] calculated the deformations of a ring gear by the finite element (FE) method and

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theoretical approach. An investigation on the root stress and the rim deformation of a thin-rimmed internal spur gear supported by pins was carried on by ODA et al. [15] using FEM. Wu and Parker [16] calculated the free vibration eigensolutions of a thin ring supported by a general elastic foundation with using perturbation and Galerkin methods, where they derived the closed-form expressions of the natural frequencies and vibration modes. And further they [17] employed perturbation analysis and a candidate mode method to investigate the distinctive modal properties of planetary gear sets having equally spaced planets and elastic ring gears, where the ring gear was modeled as an elastic body and the other components were assumed as rigid bodies. Additionally, the same authors [18] studied mathematically the vibration modes of planetary gear sets with unequally spaced planets and elastic internal gear rings. Rotational and translational modes were found in their studies. In most of the previous literatures, the authors always employed a smoothed ring to represent the real internal gear, saying the effect of the gear teeth on the deformation of the rim was neglected. In order to quantify the frequency deviations due to the application of the simpler smooth ring to represent the ring gear structures, Tanna and Lim [19] made comparisons on the modal frequencies of the ring gears and the idealized smoothed rings without gear teeth. Kahraman et al. [12] applied a deformable body dynamic model by combining the near-field semi-analytical technique and the far-field finite element method to investigate the dynamic effects of the gear rim thickness and the number of planets on the gear stresses. Abousleiman and Velex [20] proposed a hybrid 3D finite element/lumped parameter model for the analysis of quasi-static and dynamic analyses of planetary/epicyclic gear sets. Deformable ring-gears were taken into consideration by using either beam elements for simple structures, or 3D brick elements for complex geometries. And then they [21] added the planet carrier by a constraint mode substructuring technique. However, there were very few literatures considering the effect of the ring gear flexibility on the mesh stiffness of internal gear pair which is a critical excitation influencing the dynamic responses of the planetary gear system.

Fortunately, there are numerous works on static and dynamic performances of smoothed rings. For example, in Timoshenko's [22] early contributions, he extended the linear Euler–Bernoulli bending theory to curved beams. Lim et al. [23] analyzed the exact relationships of the deflections and the stress resultants between Timoshenko and Euler–Bernoulli curved beams, which made the conversion of the Euler–Bernoulli solutions to Timoshenko solutions come true. Gasmi et al. [24] obtained the closed-form solution of a shear deformable and extensional ring based on the Timoshenko curved beam theory and the principle of virtual work. Williams [25] derived the equations of motion for small and elastic displacements with warping effect by employing Hamilton's Theorem, where the results agreed well with that obtained by using momentum principles. Lang [26] employed the inextensional and extensional deformation theories to investigate the in-plane vibration of thin circular rings. Lin [27] derived the exact solutions for extensional circular curved Timoshenko beams with non-homogeneous elastic boundary conditions. Lin and Lee [28] derived the closed-form solutions for dynamic analysis of extensional circular Timoshenko beams with general elastic boundary conditions based on the Green function proposed by Lin [27]. Lin and Huang [29] proposed an analytical method to determine the general solutions of a 2D static curved beam with arbitrary curvature for an isotropic material without considering shear deformation. And later, they [30] considered the effect of the shear deformation to obtain the static closed form solutions for in-plane curved beams with variable curvatures. Then, this method was employed by Guedes and Alcides [31] to validate the three-point bend method for determination of hoop modulus and that of the maximum circumferential stresses at both extremes of the curved beam.

Consequently, there are some literatures about the studies on the effects of flexible ring deformation. The mesh process under the effect of the ring deformation could be automatically involved by using the numerical methods, such as FE method. While the analytical calculations of internal mesh stiffness were always carried on without ring flexible deformation in most previous literatures. So, few published papers concerning the total mesh stiffness of an internal gear pair with flexible ring gear rim which is a key excitation in the dynamic analysis of gear systems with ring gears. In the present paper, to derive a general equation for calculation of internal mesh stiffness with ring deformation and to investigate the effects of the ring flexibility on planetary gear dynamic properties are the main objective and contributions. The mesh stiffness of an internal single-tooth pair under the effect of ring flexibility can be obtained based on Refs. [24,32] with the uniformly curved Timoshenko beam theory. Based on which, the general method to calculate the total mesh stiffness of an internal gear pair is derived in this paper with considering the effect of gear ring deformation and the tooth errors resulted from manufacturing, assembly process, or intentional tooth profile modifications. And the influences of the ring gear rim thickness on the mesh stiffness and dynamic responses of the planetary gear set are studied.

This paper is organized as follows: reviews on the previous literatures concerning the research work with regard to the curved/circular beams and the ring gears are carried out in Section 1. Then, the calculation of the mesh stiffness of an internal gear pair under the effect of ring flexible deformation will be given out in Section 2. Based on the proposed method, a case study of an individual planetary gear set is going to be discussed in Section 3 and the conclusions will be drawn in Section 4.

2. Mesh stiffness of an internal gear pair with flexible ring gear

2.1. Review on mesh stiffness calculation of an internal single-tooth pair

A flexible beam always deforms under certain loads. The force and motion analysis of a uniformly curved Timoshenko beam under action of the distributed loads q_r and q_θ is shown in Fig. 1. By ignoring the dynamic effect when the operation speed is low, the static deformation of the curved beam, namely the transverse displacement (w), the circumferential