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Dynamic modeling and contact analysis of a cycloid-pin gear mechanism with a turning arm cylindrical roller bearing

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ABSTRACT

A method for analyzing the contact dynamics of the multi-tooth meshing in a cycloidal-pin gear transmission was proposed considering the influences of the turning-arm cylindrical roller bearing. The dynamic model of the cycloidal-pin gear transmission was established within the framework of the dynamic theory of multi-body system. As for the contact model of the multi-tooth meshing in the cycloidal-pin gear transmission, the tooth profile curve of the cycloid gear was dispersed as a series of points firstly. Then, by cyclically judging whether these points and each pin tooth meet the contact condition, the contact region, the maximum contact depth and the contact load were calculated in sequence. Additionally, the turning-arm cylindrical roller bearing with multi-point contact was modeled using a non-linear contact force system, with consideration of the influence of the bearing kinetic characteristics. The results show that the fluctuations in the kinematic response, the cycloidal-pin teeth contact forces and the bearing roller-raceway contact forces are mainly affected by the multi-tooth meshing characteristics of the cycloidal-pin wheel transmission system. The theoretical model and the analytical results were verified through numerical example and a virtual prototype simulation based on multi-body dynamics theory.

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1. Introduction

Cycloidal-pin wheel transmission, characterised by advantages including high transmission ratio, torsional rigidity, transmission precision, and transmission efficiency, has been widely used in industrial robot joints and precision machine tools. In ideal conditions, all teeth of the pin wheel are in contact with cycloid gear teeth, but half of them transfer the loads. However, due to factors such as machining error and the elastic deformation of the component parts, as a matter of fact, rarely do as many as half of the teeth on the pin wheel transfer the loads. The number of teeth actually transfer the loads significantly influences transmission precision, transmission efficiency, and the torsional rigidity of the cycloid gear. Considering this, establishing the contact dynamics model for the multi-tooth meshing of a cycloidal-pin wheel transmission system and clarifying the meshing characteristics and the distribution of contact load are of significance to the design and optimisation of the geometrical parameters of such a system.

Scholars have researched the design of the cycloidal tooth profile and novel cycloidal-pin wheel transmission structures. In the early stages, Blanche and Yang [1] developed an analytical model of cycloid drive with machining tolerances. The effect of machining tolerances on backlash and torque ripple was investigated. Later, the authors [2] presented a computer-aided analysis and

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synthesis of cycloid drives. The kinematic relationships among tolerance, drive parameters and performance indices were analysed in detail via a computer-aided procedure. Shung and Pennock [3] introduced a unified and compact equation describing the geometry and the geometric properties of the different types of trochoid. The characteristics and the relationships of the different types of trochoid and conjugate envelope were discussed. Dizioglu [4] discussed the problem of the continuous transition between singular points of cycloids. Yan and Lai [5] proposed a geometry design of an elementary planetary gear train with cylindrical tooth-profiles. Litvin and Feng [6] developed a computer program to design and analyse the geometrical profile of cycloidal gearings. With the help of computer analysis, profile and surface singularities can be avoided in design. Shin and Kwon [7] proposed a method for the lobe profile design of a cycloid gear by means of the principle of the instant velocity centre in the general contact mechanism and used a homogeneous coordinate transformation. Hwang and Hsieh [8–9] created a mathematical model of the internal cycloidal gear with tooth differences based on the theory of gearing. This approach can simulate not only gerotor pump but also cycloidal speed reducers. Chen et al. [10] presented a new design of cycloid drive with double contact lines between one tooth pair by applying double-enveloping gear theory. Theoretical and experimental analysis results both verified that double-enveloping theory can be applied for the design of cycloid drives. Gorla et al. [11] presented a theoretical and experimental investigation of an innovative cycloidal speed reducer. This reducer has an external ring gear and engages with the planet wheel by means of cylindrical rollers. Ivanović et al. [12] developed a comprehensive model of trochoidal gearing with clearances which can be applied for gerotor pumps and cyclo-reducers. With the help of this method, the influence of gear profile geometrical parameters on gearing process, clearance height change, and pulsation of drive moment can be analysed. Li et al. [13] introduced a double crank ring-plate-type cycloid drive which requires no output unit and places no limit on the size of the tumbler bearing. Blagojevic et al. [14] proposed a new design of a two-stage cycloidal speed reducer. Compared with the traditional two-stage cycloidal speed reducer, the newly designed two-stage cycloidal speed reducer has one cycloid disc for each stage. With the help of AutoCAD software and finite element analysis software, Li [15] investigated the geometric design of trochoidal gear reducers and analysed the loads and contact stresses distributed on trochoidal gear teeth. Lin et al. [16] presented a design for a new two-stage cycloidal speed reducer with tooth modifications. This cycloidal drive returned outstanding performance in its compact structure, high speed reduction ratio, and high-accuracy speed reduction. Sensinger [17] presented a unified set of equations to optimise the design of cycloid gears considering the effects of profile reduction, backlash, torque ripple, and maximum gear-ratio. Later, this author discussed the transmission efficiency of cycloid drives [18]. It was indicated that the efficiency can be substantially improved by the use of rolling contacts in cycloid drives. Hsieh [19] proposed a new transmission design for an eccentric speed reducer that used the internal gear as its fixed part: transmission between the external gear and output shaft occurs via pins connected to a drive plate. Subsequently, a non-pin design with multi-tooth difference was proposed by the same author [20]. It then showed that the proposed non-pin design can improve on the shortcomings of traditional designs by producing more regular stress fluctuations and eliminating stress peaks. In terms of cycloid-pin gear transmission dynamics research, Malhotra and Parameswaran [21] made an analysis of the forces on various elements of the cycloid speed reducer as well as the theoretical efficiency. Meng et al. [22] proposed a mathematical model of a 2K–H pin-cycloid planetary mechanism with one tooth difference. The output moment of the mechanism was calculated by computer program and justified by experimental data. Hsieh [23] investigated the dynamic contact and collision conditions of the transmission components in cycloid drives with pinwheel and non-pinwheel components. Thube and Bobak [24] investigated the load and stress distributions on a cycloid disc using 3-dimensional finite element analysis.

According to cycloidal-pin wheel transmission theory, it is known that the cycloid gear is revolved and rotated under the driving force from the input shaft (crankshaft), as does the turning-arm cylindrical roller bearing between the cycloid gear and the crankshaft. As a result, the change of load on the turning-arm bearing becomes extremely complex, which greatly reduces the service life of the bearing. In addition, engineering applications have proved that the actual service life of a cycloidal-pin wheel reducer is determined by that of the turning-arm bearing. However, the influences of the turning-arm bearing on the design of the geometrical structure parameters and the dynamic response performance of the cycloidal-pin wheel system are not considered in the aforementioned investigations. In recent years, regarding the dynamic modeling of cylindrical roller bearings, Shao et al. [25] proposed a dynamic analysis method to model a localised surface defect in a cylindrical roller bearing. Wang et al. [26] presented a multi-body dynamic model for investigating the vibration responses of a cylindrical roller bearing with dents in its raceways. Ye et al. [27] analysed the distribution of loads and contact stress in high-speed roller bearings considering the effects of tilted misalignment between inner and outer rings. Gao et al. [28] established an analytical model for calculating the radial and angular stiffnesses of a cylindrical roller bearing considering bearing housing deflections. The present author [29–30] has published a general method for dynamic modeling of a planar multi-body system with non-ideal rolling ball bearing joints, in which the radial clearance, contact deformation, and bearing kinematics are included. With the help of this approach, the dynamic load distribution characteristics of bearings under real mechanism movement conditions can be simulated. Later, the approach for modeling a rolling bearing with a waviness defect [31] and a localised defect [32] in a multi-body system is proposed. These studies have laid a foundation for the construction of dynamic models of cycloidal-pin wheel transmission systems which consider the turning-arm cylindrical roller bearing.

The authors attempted to build a contact dynamics model for the multi-tooth meshing of the cycloidal-pin wheel transmission system considering the influence of the turning-arm cylindrical roller bearing. Based on this model, the contact dynamic characteristics of multi-tooth meshing of the system were discussed, as well as the variation of the contact load on the bearing. The results provide a theoretical basis for analysing the precision, and evaluating the dynamic performance, of the cycloidal-pin wheel transmission as well as calculating the service life of the turning-arm bearing. The remainder of the paper is organised as follows: Section 2 introduces the approach used to model a cycloid-pin gear mechanism with a turning arm cylindrical roller bearing,

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