博士学位论文

（学术学位）

组合齿廓非圆齿轮设计方法及其应用研究

Research on design method and application of non-circular gear with composite tooth profile

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摘 要

取苗机构是自动移栽机实现自动移栽的关键核心部件，自动移栽机要实现高效作业，取苗机构的精准取苗和较大推苗角推苗是取苗过程的重要环节。非圆齿轮行星轮系传动可以实现自动移栽取苗机构的取苗和推苗动作，相比其它各种杆机构为主的取苗机构，行星轮系传动机构由于其采用的对称旋转式分布，机构工作平稳，旋转一周可以实现两次取苗和推苗动作，取苗效率高，因此行星轮系取苗机构具有各种杆结构的取苗机构无法媲美的取苗效率和工作平稳性优势。受小曲率半径和带尖点节曲线非圆齿轮设计约束、及机构传动引起取苗轨迹误差的限制，传统非圆齿轮设计方法及非圆轮系取苗机构无法实现精准取苗和较大推苗角的设计。

本文创新的提出了一种拥有较大推苗角的大重合度非圆齿轮行星轮系取苗机构。主要内容包括：以设计较大推苗角的取苗机构和精准取苗为目标，建立变渐开线-变摆线组合齿廓非圆齿轮设计方法，开发小曲率半径和带尖点节曲线非圆齿轮设计软件；提出大重合度非圆齿轮设计方法，揭示齿形齿向双重因素的非圆齿轮重合度变化规律；研制了一种具有较大推苗角（大于 80°）的取苗机构，构建取苗机构的运动学及取苗轨迹误差模型，面向齿侧间隙和中心距误差，基于误差和移动方差开展取苗轨迹的误差分析；最终开展取苗机构取苗试验。

（1）提出渐开线-摆线组合齿廓及变渐开线-变摆线组合齿廓非圆齿轮设计方法

针对小曲率半径节曲线非圆齿轮渐开线齿廓根切现象，采用渐开线和摆线组合齿廓对小曲率半径节曲线进行齿廓设计，推导了渐开线-摆线组合齿廓和变渐开线-变摆线组合齿廓数学模型并开展主动非圆齿轮设计，利用包络法开展从动非圆齿轮设计，基于齿廓连接点等压力角设计和左右偏导相等开展组合齿廓连接处光滑连续性研究，开发了小曲率半径节曲线组合齿廓非圆齿轮设计软件，对渐开线-摆线组合齿廓及变渐开线-变摆线组合齿廓进行压力角、重合度等啮合特性研究，并对其进行齿侧间隙和传动比测量试验。

（2）提出变渐开线-不完全变摆线组合齿廓设计方法

针对尖点节曲线非圆齿轮设计难题，提出变渐开线-不完全变摆线组合齿廓设计方法，首先构建变渐开线-不完全变摆线组合齿廓数学模型，并开展组合齿廓连接处光滑连续性研究，开发带尖点节曲线非圆齿轮设计软件，研究滚圆半径、椭

圆离心率及变幅系数对变渐开线-不完全变摆线组合齿廓形状、压力角及重合度的变化关系，开展带尖点节曲线非圆齿轮传动机构啮合特性及运动特性研究，并开展其齿侧间隙和传动比测量试验。

（3）提出齿形齿向双重因素的大重合度齿廓非圆齿轮设计方法

针对齿侧间隙引起的传动误差影响行星轮系取苗机构取苗轨迹精度，最终影响取苗机构的取苗成功率，提出通过增大齿高系数、负变位、减小节曲线压力角、大重合度组合齿廓的齿形因素进行大重合度齿廓非圆齿轮设计，通过非圆叠加齿轮的齿向因素进行大重合度非圆齿轮设计，研究椭圆离心率、滚圆半径、节曲线比例、负变位系数、节曲线压力角的齿形因素及螺旋角、滚圆半径的齿向因素对非圆齿轮重合度、压力角、滑动率特性的变化规律，并开展齿侧间隙测量试验。

（4）研制一种具有较大推苗角（大于 80°）的大重合度组合齿廓非圆齿轮行星轮系取苗机构，并开展取苗轨迹的误差分析和取苗试验

首先，基于傅里叶函数设计一种二次不等幅传动比曲线，分析傅里叶系数对取苗机构取苗特性和运动特性变化规律，基于专家经验设计了满足取苗要求且具有较大推苗角的取苗轨迹，并确定了传动比曲线和取苗机构的设计参数；其次，构建了取苗机构运动学模型及取苗轨迹误差模型和移动方差模型，对取苗机构进行运动学分析，基于齿侧间隙和中心距误差开展取苗轨迹的误差分析；最后，基于高速摄像技术开展取苗机构空转试验，测量取苗机构取苗角和推苗角，开展不同转速的取苗机构台架取苗试验研究。

本论文通过理论分析、传动试验、应用试验相结合的方法，对渐开线-摆线、变渐开线-变摆线、变渐开线-不完全变摆线组合齿廓、大重合度非圆齿轮进行设计方法研究及其试验验证，为小曲率半径节曲线非圆齿轮和带尖点节曲线非圆齿轮的设计及较大推苗角的精准取苗机构的设计应用奠定了一定的理论指导基础。

关键词：移栽机械；取苗机构；非圆齿轮；组合齿廓；重合度；误差分析

Abstract

The seedling picking mechanism is a key component of an automatic transplanting machine to achieve automatic transplanting. To achieve efficient operation, the precise seedling picking and large pushing angle of the seedling picking mechanism are important links in the seedling picking process of the seedling picking mechanism. The non circular gear planetary gear train transmission can achieve automatic seedling picking and pushing actions of the transplanting and seedling picking mechanism. Compared to other seedling picking mechanisms mainly composed of various rod mechanisms, the planetary gear train transmission mechanism, due to its symmetrical rotation distribution, operates smoothly. One rotation can achieve two seedling picking and pushing actions, resulting in high seedling picking efficiency, therefore, the planetary gear system seedling harvesting mechanism has advantages in seedling harvesting efficiency and work stability that cannot be compared to various rod structures of seedling harvesting mechanisms. Due to the constraints of small curvature radius and non-circular gear design with sharp point pitch curve, as well as the limitations of seedling trajectory error caused by mechanism transmission, traditional non circular gear design methods and non-circular gear system seedling picking mechanisms cannot achieve precise seedling picking and large seedling pushing angle design.

This article innovatively proposes a seedling picking mechanism for non-circular complete gear planetary gear trains with large contact angles. The main content includes: establishing a design method for non-circular gears with variable involute variable cycloid combination tooth profile, with the goal of designing a seedling picking mechanism with a large pushing angle and precise seedling picking, and developing software for designing non circular gears with small curvature radius and sharp pitch curve; revealing the variation law of non-circular gear contact ratio due to the dual factors of tooth shape and tooth direction, and proposing a design method for non-circular complete gears with high contact ratio. A seedling picking mechanism with a large pushing angle (greater than 80 °) was developed, and the kinematics of the seedling picking mechanism and the error model of the seedling picking track were constructed. Finally, a seedling harvesting experiment by the seedling harvesting mechanism was carried out.

(1) Propose a design method for non-circular gears with involute–cycloid composite tooth profile and Variable-Involute and Variable-Cycloid composite tooth profile.

Aiming at the phenomenon of involute tooth profile undercutting in non-circular gears with small curvature radius pitch curves, a composite tooth profiles of involute and cycloid was used to design non-circular gears with small curvature radius pitch curves. The mathematical models of involute–cycloid composite tooth profile and Variable-Involute and Variable-Cycloid composite tooth profile (VIVC-CTF) were derived, and active non-circular gears were designed. The envelope method was used to design driven non-circular gears. Based on the equal pressure angle design of the tooth profile connection point and the equal left and right partial derivatives, the smooth continuity of the joint of the composite tooth profile is studied, and the design software of the small curvature radius pitch curve composite tooth profile non-circular gear is developed. The meshing characteristics of the composite tooth profile such as pressure angle and contact ratio are studied, and the flank clearance and transmission ratio of the involute–cycloid composite tooth profile and VIVC-CTF non-circular gears are measured.

(2) Propose a design method for the composite of variable–involute and incomplete variable–cycloid composite tooth profiles.

Aiming at the design problem of non-circular gear with cusp pitch curve, the design method of variable involute and incomplete variable cycloid composite tooth profile is proposed (VIIVC−CTF). First, the mathematical model of VIIVC−CTF is constructed, and the research on the smoothness continuity of the joint of composite tooth profile was carried out. The design software of non-circular gear with cusp pitch curve was developed. The variation on the profile shape, pressure angle and contact ratio of the VIIVC−CTF was studied about the relationship between the radius of rolling, elliptical eccentricity and amplitude coefficient of. The research on the meshing characteristics and transmission characteristics of non-circular gear transmission mechanism with sharp pitch curve was carried out, and the measurement test of its backlash and transmission ratio was carried out.

(3) A design method for non-circular gears with high contact ratio tooth profile

based on dual factors of tooth profile and tooth direction.

In view of the transmission error caused by the tooth side clearance affecting the accuracy of the seedling picking track of the seedling picking mechanism, and ultimately affecting the success rate of the seedling picking mechanism, it is proposed to design the non-circular gear with high contact ratio profile by increasing the tooth height coefficient, negative displacement, reducing the pressure angle of the bar curve, and the tooth profile factors of the high contact ratio composite tooth profile. The non-circular gear with high contact ratio profile is designed by the tooth orientation factors of the non-circular superposition gear, and the elliptic eccentricity, radius of rounding the tooth profile factors of pitch curve proportion, negative modification coefficient and pitch curve pressure angle, as well as the tooth alignment factors of spiral angle and rolling radius on the change law of non-circular gear contact ratio, pressure angle and sliding rate characteristics, and the tooth side clearance measurement test was carried out.

(4) Develop a non-circular gear planetary gear train seedling picking mechanism with a high contact ratio composite tooth profile and a large seedling pushing angle (greater than 80 °), and conduct error analysis and seedling picking experiments on the seedling trajectory.

First, a quadratic unequal transmission ratio curve is designed based on Fourier function, and the variation law of Fourier function coefficient on the seedling picking characteristics and movement characteristics of the seedling picking mechanism is analyzed. Based on expert experience, seedling picking track that meets the seedling picking requirements and had a large seedling pushing angle was designed, and the transmission ratio curve and design parameters of the seedling picking mechanism were determined, and the kinematics model of the seedling picking mechanism; Second, the error model of the seedling picking track and the movement variance model were constructed. Kinematics for the seedling picking mechanism and error analysis of the seedling picking track based on the tooth side clearance and center distance error were carried out; Finally, the idle running test of the seedling picking mechanism based on the high-speed camera technology, measure the seedling picking angle and pushing angle of the seedling picking mechanism and seedling picking test research on the platform of the seedling picking mechanism with different sun gear input shaft speeds were carried out.

This dissertation combines theoretical analysis, transmission experiments, and application experiments to study the design method and experimental verification of involute–cycloid composite tooth profile, VIVC-CTF, VIIVC−CTF, and high contact ratio overlap non circular gears. This provides certain theoretical guidance for the design of small curvature half diameter pitch curve non circular gears and pointed pitch curve non circular gears, as well as the design of precise seedling picking mechanisms.

Key words: Transplanting machinery; Seedling picking mechanism; Non-circular gear; Composite tooth profile; Contact ratio; Error analysis