機　械　工　程　學　系

博　士　論　文

切線雙貝茲齒形之諧波齒輪設計與剛輪之動力刮削刀具設計

Design of Harmonic Drive of Tangential Double Bezier Tooth Profile and Design of Power Skiving Tool of Circular Spline

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摘要

論文名稱：切線雙貝茲齒形之諧波齒輪設計與剛輪之動力刮削刀具設計

本論文旨在進行創新切線雙貝茲齒形之諧波齒輪嚙合特性研究，以及其內齒剛輪之動力刮削刀具設計。現今，諧波齒輪主要運用於小空間、高精度且高減速比的場域，比如：半導體設備、機械手臂關節、醫療設備等機構內，且隨著近年全球智慧化機械的發展，使用於機器手臂之諧波齒輪逐年增加。

但目前國內缺乏諧波齒輪系統化設計方法與流程，因此本研究透過一連串的特性分析，嘗試導入各種齒形與結構設計以找尋具最佳嚙合特性的設計參數，此外也提供切製最佳剛輪齒形之新穎的動力刮削刀具設計方案。首先，基於齒輪原理與包絡法發展市面上常見之漸開線與切線雙圓弧諧波齒輪數學模式以及本論文創新之切線雙貝茲諧波齒輪數學模式，再以自行開發的自動化網格生成程式建立二維與三維有限元素模型，從而進行諧波齒輪有限元素分析，以獲得應力分布、扭轉剛性、嚙合齒數、遲滯損失與傳動誤差。以有限元素分析為基礎，依序進行二維齒形最佳化分析與三維結構最佳化分析，得到具有最佳剛性與嚙合齒數之諧波齒輪齒形設計參數與柔輪柔杯結構設計參數。

隨後，發展動力刮削刀具設計之通用數學模型，以推導切製最佳剛輪齒形之動力刮削刀具的無誤差設計刃口線，與磨削此刀具設計刃口線之圓盤狀磨輪設計，並根據 ISO 精度規範計算切齒精度，以探討動力刮削刀具重磨對於剛輪齒形誤差、最大絕對誤差與峰谷值的影響。最後，在加工過程加入機台補償角以降低因重磨前刀面造成之齒形誤差，從而延長刀具使用壽命，並且比較機台補償前、後之刀具有效重磨量。

關鍵字：諧波齒輪、柔輪、剛輪、有限元素分析、扭轉剛性、嚙合齒數、傳動誤差、遲滯損失、最佳化分析、動力刮削刀具、前刀面重磨、機台補償角、有效重磨量

Abstract

Title: Design of Harmonic Drive of Tangential Double Bezier Tooth Profile and Design of Power Skiving Tool of Circular Spline

The purpose of this thesis is to study the meshing characteristics of harmonic drive with a novel tangential double Bezier tooth profile as well as the cutter design of its inner toothed circular spline. Nowadays, harmonic drives are mainly used in fields with small space, high precision, and high reduction ratio, such as semiconductor equipment, robotic arm joints, medical equipment, and other institutions. With the development of global intelligent machinery in recent years, the number of harmonic drives used in the robotic arm increases year by year.

However, there is currently a lack of systematic design methods and processes for harmonic drives in the country. Therefore, through a series of characteristic analysis, this research tries to explore various tooth profiles and structural designs to find the design parameters with the best meshing characteristics. In addition, the innovation power skiving tool design for generating the optimum circular spline profile is provided. First of all, based on the theory of gearing and enveloping method, the mathematical models of involute and tangential double arc harmonic drives, those are common in the market, and of innovated tangential double Bezier harmonic drive in this paper are developed. Then, the self-developed automatic meshing generation program is used to establishe the two-dimensional and three-dimensional finite element models to conduct the finite element analysis of harmonic drives to obtain the stress distribution, torsional stiffness, number of engagted teeth, hysteresis loss, and transmission error. Based on the finite element analysis, the optimization analysis of two-dimensional tooth profile and that of three-dimensional structure are carried out sequentially, and the design parameters (including tooth profile and FS's cup structure) of the harmonic drive with the optimal torsional stiffness and number of engaged teeth are obtained.

Subsequently, a general mathematical model for the design of the power skiving tool was developed to derive the tool's error-free designed cutting edge (for cutting the tooth profile of the optimum circular spline) and the disk-shaped grinding wheel (for grinding the designed cutting edge of the tool). Moreover, the cutting accuracy of gear is calculated according to the ISO accuracy specification to discuss the influence of the resharpening of the power skiving tool on the tooth profile error, maximum absolute error and peak-to-valley value of the circular spline. Finally, the machine compensation angle is added in the machining process to reduce the tooth profile error, caused by regrinding the rake face, to prolong the tool life, and the effective resharpened amounts of the tool before and after the machine compensation are compared.

Keywords: Harmonic drive, flexspline, circular spline, finite element analysis, torsional stiffness, number of engaged teeth, transmission error, hysteresis loss, optimization analysis, power skiving tool, rake face regrinding, machine compensation angle, effective resharpened amount