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A Flexible Electronic Helical Guide Controller

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Abstract

In this paper, an Electronic Helical Guide Controller (EHGC) is proposed, for helical gear shaping processes. In most traditional gear shaper machines, the cutter's reciprocating movement is driven by a crank-connecting rod mechanism. Therefore, this study adopts this kind of gear shaper as the machine platform to establish an accurate mathematical model. The control algorithm is embedded in the interpolation module of the CNC system using electronic gearbox techniques to realize special multi-axis linkage control requirements. The crankshaft's angular position is measured and the rotational speed is calculated in each control cycle. The actual position and velocity of the cutter along the Z-axis can be calculated using the geometric relations of the crank-connecting mechanism, and motion in the other axes can be controlled by the electronic gearbox. A special G code with parameters (G83) is also designed and the EHGC control through NC programming is realized in an improvised gear shaping CNC machine. The proposed EHGC is low cost and easy to implement in practice since it does not need a linear grating ruler and a probe on the Z-axis. Furthermore, EHGC allows the flexibility to change a part's helix angle to compensate for distortions caused by heat treatment. Simulations and experiments are performed to verify the effectiveness of the proposed EHGC.

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Keywords: Gear shaping; Electronic gearbox (EGB); Generating process; Tracking error

1. Introduction

Gear shaping is a versatile and accurate means of manufacturing helical gears, herringbone gears, internal gears, spur gears and face gears [1-3]. Previous generations of CNC controlled gear shaping machines were not truly flexible, because their guides for helical gears had remained mechanical[4]. There were some inherent weaknesses in adopting mechanical helical guides, since use of mechanical helical guides imposed a limitation of using only one lead in a given setup and was restricted to a given minimum lead angle. To address these problems a totally new shaping head was developed by the Gleason Company featuring a backlash-free direct driven helical guide for the cutter spindle. The shaping head is controlled by the software which is developed based on the Siemens 840D CNC. With the appropriate software, additional generating cutter rotational motion required for helical gears can be superimposed electronically on the cutter spindle rotation. These functions are embodied in the "Electronic Helical Guide". All gear cutting, tooling and process data are entered via the dialog program. The CNC controller calculates all the necessary machine data/settings. However this kind gear shaping machine is very expensive, such as the GP200ES.

In view of the above analysis, the paper mainly focuses on an Electronic Helical Guide Controller (EHGC) design, performance evaluation and experimental study. The EHGC designed in this work is different from Gleason's in the aspect that it does not need extra data dispersed through preprocessing, as the control process is based on an accurate mathematical model. In addition, a special G codes with parameters (G83) is designed and the EHGC control through NC programming is realized in a laboratory-scale gear shaping CNC. The control law is embedded in the interpolation module of the CNC system in the form of an electronic gearbox[5,6] to satisfy special multi-axis linkage

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control requirements. Furthermore, EHGC offers the flexibility to change a part’s helix angle to compensate for heat treatment induced distortion. Typical “winding or unwinding” of the helix, resulting in helix angle slope errors can easily be addressed with simple changes in the part program by creating a compensating helix angle value.

The subsequent sections of this paper are arranged as follows: In Section 2, the theory model of EHGC is first introduced, the hardware platform of the laboratory-scale gear shaping CNC is given, and the implementation principle of EHGC is also introduced. Section 3 illustrates the tracking performance using the proposed EHGC through simulations. Experiments were then conducted based on a homemade four-axis CNC, and the results are analyzed in Section 4. Finally, our conclusions are given in Section 5.

2. Electronic helical guide controller design

In typical gear shaping processes, the cutter motion includes two stages [7, 8]: the cutting (down) stroke, where the work gear is generated and the return (back) stroke without material removal. The kinematics of gear shaping is depicted in Fig.1. When machining helical gears[9-11], the cutter (C2-axis) and workpiece (C1-axis) are rotating in parallel axes, in harmony with each set of the teeth. Meanwhile the cutter dose a reciprocating motion along the Z-axis to engage the workpiece. The constraint for the cutter rotational axis, workpiece rotational axis and reciprocating motion axis (Z-axis) is that the cutter rotational axis must move an additional round (ΔC_2), while the cutter moves a helical lead along the Z-axis, as shown in Fig.2. During the reciprocating motion of the cutter, the back-stroke features a lift-off maneuver from the workpiece to prevent damage of the face. The radial feed is along X-axis.

The relationship of C1-axis and C2-axis can be expressed as

$$n_{C2} = -\frac{Z_{C1}}{Z_{C2}} n_{C1} + \frac{\sin\beta}{\pi m_n Z_{C2}} v_Z \quad (1)$$

In Eq. (1), n_{C2} is the cutter-axis speed, n_{C1} is the workpiece-axis speed, v_Z is the feed rate on Z-axis caused by the reciprocating motion of the cutter, Z_{C1} is the number of gear teeth, Z_{C2} is the number of gear shaper cutter teeth, m_n is the gear normal module, and β is the gear helix angle.

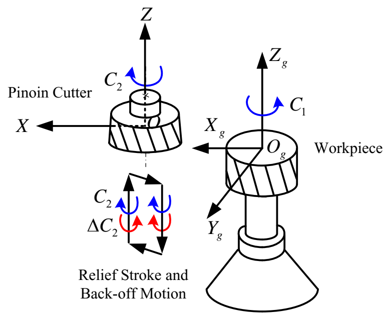


Fig. 1. The kinematics of gear shaping.

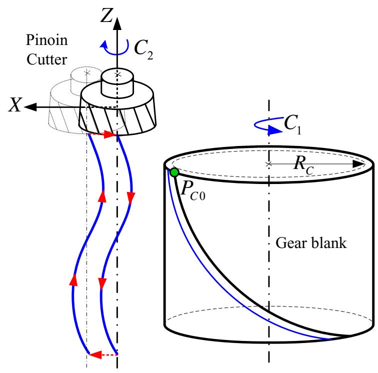


Fig. 2 The principle of EHGC.

The cutter reciprocating motion is driven by the crack-connecting rod mechanism in most gear shaper machines, as shown in Fig.3. The feed rate v_Z is caused by the rotational movement of crank drive. So we can calculate the cutter moving speed through converting the rotation position and the speed of A-axis to the moving position and the speed of Z-axis.

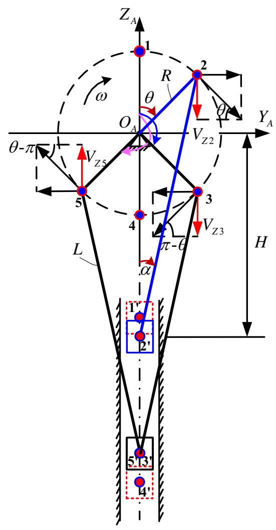


Fig. 3. The crack-connecting rod mechanism of gear shaper machine.

In Fig.3, Dot 1, 2, 3, 4 and 5 are the different positions of crack in a turning circle, while Dot 1’, 2’, 3’, 4’ and 5’ are the corresponding positions of connecting rod on the Z-axis. The crank radius is R, the length of the connecting rod is L, n_A is the rotational speed of crank (A-axis). θ is the angle of the crank turns from the starting point (Dot 1). Through the geometric relationships we have:

$$H = L\cos\alpha - R\cos\theta = R\left(\frac{L}{R}\cos\alpha - \cos\theta\right) \quad (2)$$

$$L\sin\alpha = R\sin\theta \quad . \quad (3)$$

Then we have

$$\cos\alpha = \sqrt{1 - \frac{R^2}{L^2}\sin^2\theta} = \sqrt{1 - \frac{R^2}{2L^2} + \frac{R^2}{2L^2}\cos 2\theta} \quad (4)$$

$$H = \sqrt{L^2 - \frac{R^2}{2} + \frac{R^2}{2}\cos 2\theta} - R\cos\theta . \quad (5)$$

When the cutter is at the highest point, it can be easily seen H=L-R, so the displacement of cutter can be expressed as

$$Z = -\sqrt{L^2 - \frac{R^2}{2} + \frac{R^2}{2}\cos 2\theta} + R\cos\theta + L - R \quad (6)$$

Thus the speed of the cutter can be derived as

$$v_z = Z' = \left(-\sqrt{L^2 - \frac{R^2}{2} + \frac{R^2}{2}\cos 2\theta}\right)' + \left(R\cos\theta\right)' \quad (7)$$

$$v_z = \frac{R\omega\sin 2\theta}{2\sqrt{\frac{L^2}{R^2} - \frac{1}{2} + \frac{1}{2}\cos 2\theta}} - R\omega\sin\theta \quad (8)$$

Substituting $\omega = 2\pi n_A$ and Eq. (8) into Eq. (1) yields

$$n_{C2} = -\frac{Z_{C1}}{Z_{C2}} n_{C1} + \frac{R\sin\beta}{m_n Z_{C2}} \left(\frac{\sin 2\theta}{\sqrt{\frac{L^2}{R^2} - \frac{1}{2} + \frac{1}{2}\cos 2\theta}} - 2\sin\theta \right) n_A \quad (9)$$

From Eq. (9) we know that the rotation speed of gear shaper cutter is determined by the rotation speed of workbench, the rotation speed of crank and the angle θ. So the cutter rotational axis (C2-axis), the workpiece rotational axis (C1-axis) and the reciprocating motion axis (Z-axis) can constitute a set of master-slave electronic gearbox (EGB), i.e. the software type electronic helical guide controller. The control principle is shown in Fig. 4, where the C1-axis and the A-axis are the master axes, and the C2-axis is the the slave axis. By the electronic helical guide controller (EHGC), we just need to know the number of the workpiece teeth (Z_{C1}), the number of the gear shaper cutter teeth (Z_{C2}), the normal module (m_n), the workpiece teeth helix angle (β), the workpiece-axis speed (n_{C1}), and the A-axis speed (n_A), then the rotational speed of gear shaper cutter (n_{C2}) can be calculated in every interpolation cycle of the CNC.

The derivative of Eq. (9) is the acceleration expression of C2-axis, as illustrated in Eq. (10). Considering of Eq. (10) is a continuous function, we know that there is no acceleration mutation in the rotational movement of gear shaper cutter axis.

$$\alpha_{C2} = \left(\frac{4\cos\theta * (\frac{L^2}{R^2} - \frac{1}{2} + \frac{1}{2}\cos 2\theta) + \sin^2 2\theta}{2(\frac{L^2}{R^2} - \frac{1}{2} + \frac{1}{2}\cos 2\theta)^{\frac{3}{2}}} - 2\cos\theta \right) \frac{R\sin\beta}{m_n Z_{C2}} \varphi_A \quad (10)$$

Where, φ_A is the angular speed of A-axis, thus $\varphi_A = 2\pi n_A$.

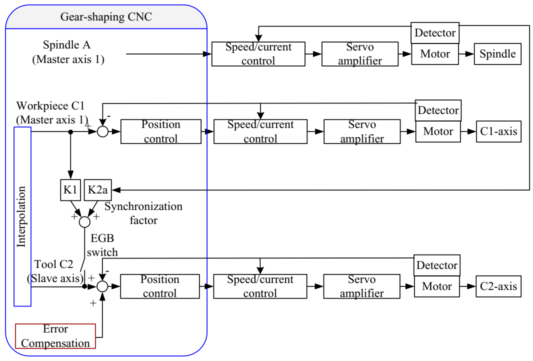


Fig. 4. The control principle of electronic helical guide.

3. Performance evaluation and discussion

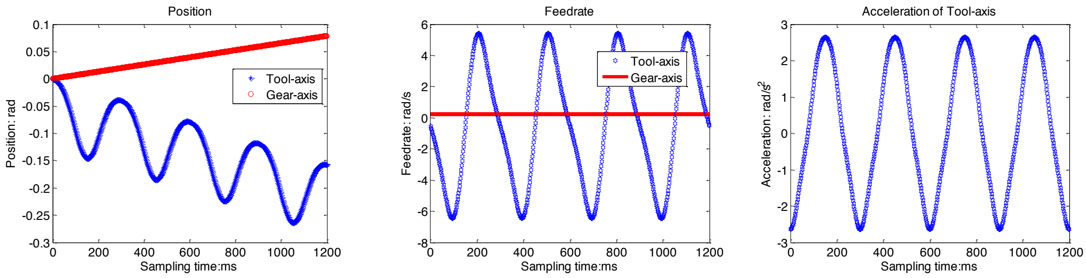
In this section, we discuss the application of the EHGC in the gear shaping control system. To investigate the performance of the proposed EHGC approach, simulation experiments were conducted using two different spindle speed. Here, the sampling period for both the simulation and the experiments was chosen to be 1ms. Parameters of the workpiece gear and gear shaper cutter are shown in Table 1.

The gear shaper cutter reciprocating motion speed in the first simulation experiment is 200str/min, as shown in Fig. 5. The gear shaper cutter reciprocating motion speed of the second simulation experiment is 300str/min, as shown in Fig. 6.

From the simulation analysis, we can see that the final displacement value of the tool axis and the gear axis in the two simulation experiments are consistent. The rotational directions of tool axis and gear axis are opposite. The speed of the gear axis is uniform, while the motion of the tool axis is the composition of the screw motion and the uniform motion. Therefore, the feed rate and the acceleration of the tool axis are variable, and they will be increase as the spindle speed increase.

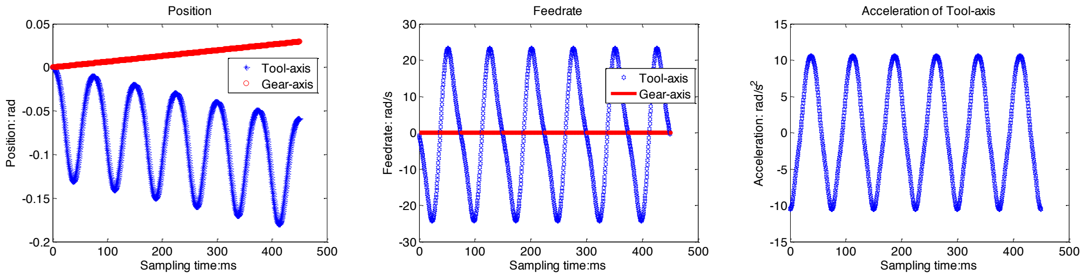
Table 1. Gear and gear shaper cutter parameters used in the simulation experiments.

Gear Parameters		Gear Shaper Cutter Parameters	
Pressure angle α (°)	20	Pressure angle α (°)	20
Number of teeth Z_C	42	Number of hob threads Z_B	21
Normal module m_n (mm)	2	Normal module m_n (mm)	2
Tooth width B (mm)	30	Spiral angle direction	Left hand
Gear spiral angle β (°)	25	Crank radius (mm)	25
Spiral angle direction	Left hand	Connecting rod length (mm)	50



a) b) c)

Fig. 5. Simulation results using 200str/min.



a) b) c)

Fig. 6. Simulation results using 300 str/min.

4. Experimental study

In this section, processing experiments were performed on an YKS5132B four-axis gear shaping machine, which is a semi-closed loop system. Position sensing is provided by 5000 counts/ revolution optical shaft encoders. The CNC system is a homemade four-axis open experimental gear shaping platform, which consists of EP9315 ARM9 and TMS320C6713 DSP. The EHGC were implemented in C language. The reference command and the feedback position of the table were sent and received by the DSP through the control card at a sampling rate of 1 kHz. The parameters of the workpiece and the tool are as shown in Table 1.

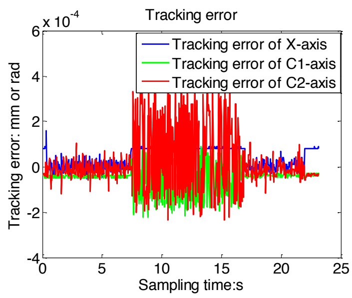


Fig. 7. Tracking error analyses by using 200str/min.

To consistent with the simulation experiments, we conducted two experiments with the same speeds as the simulations. In the first experiment the gear shaper cutter reciprocating motion speed is 200 str/min, the tracking error of the X-axis, the gear axis (C1-axs) and tool axis (C2-axis) throughout the gear shaping process is shown in Figure 7. The gear pitch error analysis is shown in Figure 8. The gear helix deviation analysis is shown in Figure 9. The maximum gear pitch error is 0.012 mm and the maximum gear helix deviation error is 0.004 mm.

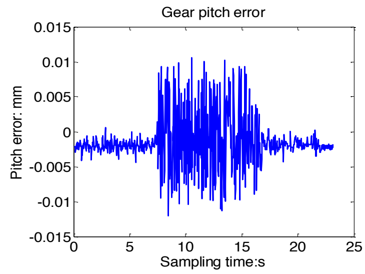


Fig. 8. Gear pitch error by using 200str/min.

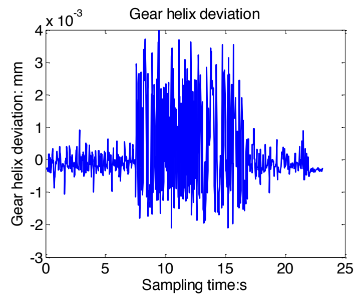


Fig. 9. Gear helix deviation by using 200str/min.

In the second experiment the gear shaper cutter reciprocating motion speed is 300str/min, the tracking error throughout the gear shaping process is shown in Figure 10. The gear pitch error and the gear helix deviation analysis are shown in Figure 11 and 12. The maximum gear pitch error is 0.014mm and the maximum gear helix deviation error is 0.0045mm.

The spindle speed range of this kind gear shaper (i.e. YK5132B) is 200~300str/min, so the EHGC will be suitable for the crack-connecting type gear shaper.

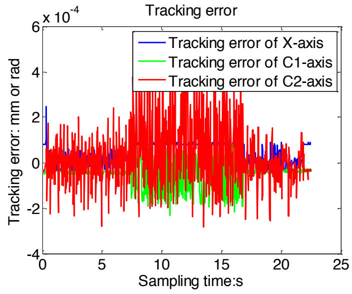


Fig. 10. The trajectory of the tool axis by using 300str/min.

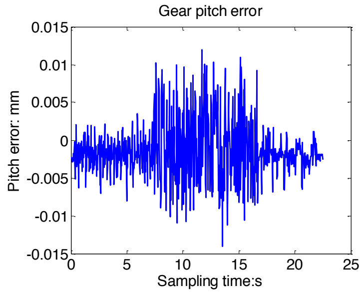


Fig. 11. Gear pitch error by using 300str/min.

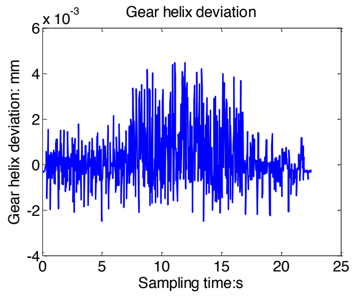


Fig. 12. Gear helix deviation by using 300str/min.

5. Conclusions

Gear shaping is the most common method to manufacture internal gears. In this paper, an Electronic Helical Guide Controller (EHGC) has been proposed for commonly used traditional gear shapers. The strict constraints among cutter rotational axis, workpiece rotational axis and reciprocating motion axis (Z-axis) were followed by the EHGC. The control model was embedded in the interpolation module of the CNC system in the form of an electronic gearbox to realize the special multi-axis linkage control requirements. Through theoretical studies, simulation analyses and final machining verification, we obtain the following conclusions: 1) the mathematical model could satisfy the requirements of the EHGC, and acceleration mutation phenomena were not observed; 2) the EHGC was easy to implement or to be called, because the function was integrated by the G code; 3) the EHGC is suitable for the crank-connecting type gear shapers; 4) the proposed EHGC is low cost since it does not need a linear grating ruler and a probe in the Z-axis. Besides, through the reprogramming of multi-axis relations, the proposed controller can easily be implemented in other similar motion systems.

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