Research on automatic correction method of spiral bevel gear error reversal based on single chip microcomputer

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Abstract. Because the traditional error correction of spiral bevel gears is based on the experience of technicians to manually adjust the parameters of production equipment and machine tools, the error range of gears in production is difficult to control, which affects the pass rate of gear production. Aiming at the above problems, the automatic correction method of spiral bevel gear error reversal based on single chip microcomputer is studied. On the basis of setting up the machining parameter model of spiral bevel gear, the gear data is measured and controlled by single chip microcomputer. After processing the measured gear data, the parameter error of the machine tool is reversed. The experimental results show that the error correction method based on single chip microcomputer can reduce the error and improve the pass rate of gear.

1. Introduction
Spiral bevel gears are the basic components used to realize the motion transmission of intersecting axes in mechanical transmission. They are widely used in aviation, precision machine tools, construction machinery and other industrial fields with advantages of bull coincidence degree, high bearing capacity, high transmission efficiency and low noise, etc[1]. The traditional automatic error correction method for spiral bevel gears is to adjust the parameters of the machine tool repeatedly, and it mainly relies on the experience of technicians in the paired rolling inspection of the rolling tester to manually correct the parameters of the machine tool. This error correction method of gear has a certain subjectivity, which makes it difficult to keep the error range of various parameters of gear within a stable range after the error correction of gear, and affects the service life of spiral bevel gear [2]. Therefore, on the basis of the above analysis, this paper studies the automatic correction method of spiral bevel gear error reversal based on single chip microcomputer.

2. Research on automatic correction method of spiral bevel gear error reversal based on single chip microcomputer

2.1. The machining parameter model of spiral bevel gear is established
According to the machining principle of spiral bevel gear machine tool, the center coordinate system of tool tool and machine tool bed is established[3-5]. Therefore, the relation between the diameter of the cutter and the tooth blank in the bull wheel convex surface machining is as follows:
In formula (1), \( r_0 \) is the nominal radius of the bull wheel cutter; \( W_2 \) is the top width of the grinding wheel in the convex processing of the bull wheel; \( r_{o2} \) is the diameter of the inner blade during the convex processing of the bull wheel, and it is equal to the diameter of the concave surface of the bull wheel and the diameter of the tip of the outer blade in numerical value. If the cutting surface of the grinding wheel is any point \( M \) in the bull wheel machining, \( \theta_2 \) is the phase angle of the bull wheel knife disc, \( M_0 \) is the apex of the grinding wheel cutting surface. Therefore, the vector diameter equation of a point \( M \) on the cutting surface is as follows:

\[
R_c^v = \begin{bmatrix}
(r_{o2} - s_2 \times \sin \alpha_2 \cos \theta_2) \\
(r_{o2} - s_2 \times \sin \alpha_2 \cos \theta_2) \\
-s_2 \times \cos \alpha_2 \\
1
\end{bmatrix}
\]

In formula (2), \( s_2 \) is the distance between point \( M \) and vertex \( M_0 \) on the grinding wheel cutting surface; \( R_c^v \) is the position vector of point \( M \) on the grinding wheel cutting surface. The cutter coordinate system is converted into the workpiece coordinate system by several coordinate transformations. Thus, the tooth surface equation of the bull gear of spiral bevel gear is established as follows:

\[
r(\theta_2, \varphi_2) = \begin{bmatrix}
r_x(\theta_2, \varphi_2) \\
r_y(\theta_2, \varphi_2) \\
r_z(\theta_2, \varphi_2)
\end{bmatrix}
\]

In formula (3), \( (\theta_2, \varphi_2) \) is the vector coordinate of the tooth blank of spiral bevel gear in the coordinate system of gear surface; \( r_x \) is the axial cutter position in the machining process of bull wheel; \( r_y \) is the radial cutter position in the bull-wheel machining process; \( r_z \) refers to the meshing quantity of the gear processed during the processing of the bull wheel.

In the same way, the coordinate system of the pinion machining is established. The single blade is used in the pinion machining, and the tooth angle and parameters of the concave and convex surface cutter of the pinion are different during the machining. The conical surface equation of the cutter disk of the pinion is as follows:

\[
r_{z_p} = \begin{bmatrix}
(r_x - s_p \times \sin \alpha_p \cos \theta_1) \\
(r_x - s_p \times \sin \alpha_p \cos \theta_1) \\
-s_p \times \cos \alpha_p \\
1
\end{bmatrix}
\]

In formula (4), \( r_c^v \) is the tip radius of the pinion during machining; \( \alpha_p \) is the profile angle of the cutter of the pinion machining cutter; When processing the concave surface of the pinion, the angle \( \alpha_p \) is positive; When machining the convex surface of the roller, the angle \( \alpha_p \) should be negative. \( s_p \) refers to the distance between the meshing point of the cutting tool blade and the wheel blank and the
knife tip during the processing of the pinion. After several coordinate system transformations, the following spiral bevel gear pinion model is established.

\[
\mathbf{r}_1(\theta_1, \varphi_1) = \begin{bmatrix}
r_x(\theta_1, \varphi_1) \\
r_y(\theta_1, \varphi_1) \\
r_z(\theta_1, \varphi_1)
\end{bmatrix}
\] (5)

In formula (5), \((\theta_1, \varphi_1)\) is the surface coordinate of the pinion in the gear coordinate system; \(r_x\) is the axial cutter position in the process of pinion machining; \(r_y\) is the radial cutter position in the process of pinion machining; \(r_z\) refers to the meshing quantity of the gear processed during the processing of the pinion. After setting up the machining parameter model of spiral bevel gear, the gear data is measured under the control of single chip microcomputer.

2.2. MCU controls and measures gear data

In this paper, STC12C5A single-chip microcomputer control measuring machine is selected to measure the tooth surface of spiral bevel gear[6]. The spiral bevel gear produced by the machine is installed on the measuring machine. The diagram of measuring spiral bevel gear is shown below.

![Diagram of tooth surface measurement](image)

As shown in the figure above, the gear axis is perpendicular to the datum of the installation position of the measuring instrument, and sampling points are set on the gear tooth surface. Within a certain range close to the detection point, the probe collects gear parameters at a constant rate under the control of the single chip microcomputer.

2.3. Implement error correction

In the established coordinate system for measuring gear parameters, the theoretical and practical position vectors of the probe center of the gear tooth surface detection probe are as follows:

\[
\begin{cases}
R_m = r_m(u,v) + \mu n_m(u,v) \\
R_m' = r_m(u,v) + \eta n_m(u,v)
\end{cases}
\] (6)
In formula (6), $R_m$ is the theoretical position vector of the probe center; $R'_m$ is the actual position vector of the probe center; $r_m$ is the position vector of the theoretical measurement point of tooth surface in the measuring coordinate system; $n_m$ is the unit normal vector of the theoretical measurement point of tooth surface in the measuring coordinate system; $\mu$ and $\eta$ are unit distance parameters; $(\mu-\eta)n_m$ is the distance between the probe center and the theoretical measurement point along the normal vector direction of the measurement point. Generally speaking, the gear tooth surface deviation mostly appears in the normal direction of the tooth surface, tangential upward error is small, can be ignored[7]. Then the error in the normal direction can replace the deviation between the actual value and the theoretical value of the tooth surface. After dividing the grid points of the tooth surface, the deviation value can be expressed as:

$$\Delta n_i = \Delta \left[ (R'_m - R_m) \cdot n_m \right]_{(\mu_i, \eta_i)} \quad (7)$$

In the coordinate system of the gear itself, the theoretical tooth surface expression is $r_o(u, v, d_j)$, in which $d_j$ is the adjustment parameter of the machine tool, $j$ is the number of adjustment parameters of the machine tool. After differential representation of the tooth surface, the differential expression of the actual tooth surface error can be obtained as follows:

$$q = \sum_{j=1}^{m} \frac{\partial r_o}{\partial d_j} \cdot n_i \delta d_j \quad (8)$$

In formula (8), $\delta d_j$ is the adjustment error correction value of the $j$th machine tool parameter; $n_i$ is the upward error of the point method of tooth surface measurement. By repeatedly measuring the actual tooth surface error for many times, calculating the error sum of squares and making the error sum of squares tend to the minimum, the correction quantity satisfying the error transcendental equations is the reverse adjustment quantity of the machine tool process parameters.

3. Method performance test

3.1. Experimental process

The single-chip microcomputer based automatic error correction method of spiral bevel gear studied above is denoted as the experimental group method, and the traditional error correction method of spiral bevel gear is denoted as the contrast group method. The experimental group and the comparison group were used to correct the errors of the gears produced. 5×9 detection points were selected as the marking points of the tooth surface error detection on the concave surface of the pinion and the convex surface of the bull wheel produced on the production line. The parameters of gears produced by the two methods were measured by high-precision measuring instruments, and the tooth surface errors of gears produced by different production lines were counted. Analyze the numerical value to get the experimental conclusion of this experiment.

3.2. Experimental results

The tooth surface parameters of the gear produced by the production equipment using the two modified methods were detected by the high-precision measuring instrument. By comparing the parameters with the design standard parameters, the detection errors of gears of different specifications in the experimental group and the comparison group were obtained respectively. Table 1 and Table 2 respectively show the detection errors of the bull wheel convex surface in the experimental group and the comparison group by using the detection instrument. Table 3 and Table 4 show the test errors of
the concave surface of the pinion in the experimental group and the comparison group, respectively.

Table 1 Test error of gear convex surface in experimental group /μm

| Tooth depth | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| direction  | 1.7 | 1.6 | 2.9 | 2.6 | 2.6 | 1.9 | 1.8 | 1.1 | -2.4|
| 2          | -0.9| 2   | -0.9| 1.6 | 2.3 | -2.3| 2.5 | -1.9| 2.0 | 0.9 |
| 3          | 2.7 | 1.4 | 1.2 | -1.3| 1.8 | 2.2 | 1.2 | -2.9| -2.9|
| 4          | -2.6| -2.6| -2.9| 1.1 | 2.9 | -1.8| 1.6 | 1.3 | 2.7 |
| 5          | 2.2 | 1.8 | 2.2 | 1.6 | -1.8| 1.7 | -1.0| 1.6 | -1.8|

Table 2 Detection error of gear convex in comparison group /μm

| Tooth depth | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| direction  | -5.7| 5.4 | 8.5 | 8.1 | 5.7 | 5.8 | 6.5 | 6.6 | -5.1|
| 2          | 6.2 | -7.9| 7.4 | -7.1| -7.9| 6.6 | -7.8| -5.8| 5.9 |
| 3          | -8.1| 5.9 | -6.1| 8.2 | 7.6 | -5.3| 6.1 | 5.0 | -7.1|
| 4          | 6.9 | -7.4| 5.3 | 7.9 | 7.6 | 7.2 | 5.4 | -8.1| 6.6 |
| 5          | -6.2| 6.5 | 7.2 | -6.2| -8.1| -5.7| -8.6| 7.3 | 7.4 |

Table 3 Test error of gear concave in experimental group /μm

| Tooth depth | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| direction  | 2.4 | 1.9 | 1.1 | 2.9 | 2.9 | 2.3 | 1.1 | 0.9 | 1.2 |
| 2          | 2.7 | 2.1 | 1.9 | 1.2 | 2.5 | 2.4 | 2.6 | 1.1 | 2.3 |
| 3          | 2.2 | 2.9 | 1.2 | 1.3 | 2.0 | 2.8 | 1.5 | 1.8 | 1.7 |
| 4          | 1.2 | 2.3 | 0.9 | 2.1 | 3.9 | 1.1 | 2.9 | 2.6 | 1.5 |
| 5          | 1.1 | 2.4 | 1.6 | 1.4 | 1.4 | 1.7 | 3.1 | 2.2 | 0.9 |

Table 4 Test error of gear concave in comparison group /μm

| Tooth depth | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| direction  | 5.6 | 6.1 | 5.1 | 5.0 | 6.2 | 5.8 | 5.6 | 5.1 | 5.5 |
| 2          | 5.9 | 5.6 | 5.3 | 5.2 | 5.3 | 6.5 | 6.7 | 5.8 | 6.1 |
| 3          | 6.1 | 6.8 | 5.7 | 5.7 | 5.6 | 5.9 | 6.5 | 5.9 | 5.7 |
| 4          | 6.7 | 5.9 | 6.4 | 6.1 | 6.8 | 5.7 | 5.2 | 5.3 | 6.4 |
| 5          | 6.3 | 5.4 | 6.3 | 6.6 | 6.0 | 6.1 | 6.6 | 5.3 | 6.7 |

The analysis of table 1 and table 2 shows that the error detection error of bull wheel gears produced with different error correction methods is stable within 2.9 μm in the experimental group, and fluctuates between -8.6 ~ 8.5 μm in the contrast group. The average detection error of gear convex surface corrected by the two groups is 1.91 μm for the experimental group and 6.78 μm for the comparison group. The average detection error of the experimental group was about 2/7 that of the comparison group. The maximum detection error of gear concave in the experimental group was 3.9 μm, far less than the maximum detection error of gear concave in the comparison group was 6.88 μm. The above data show that the error correction method of experimental group can effectively reduce the error of gears and improve the pass rate of gears in production.

4. Conclusion

The error correction of spiral bevel gear is very important to improve the accuracy of gear. Therefore, this paper studies the automatic error correction method of spiral bevel gear reverse adjustment based
on single chip microcomputer. The processing parameter model of spiral bevel gear is constructed, and the gear data is measured by single chip microcomputer. The gear data is processed to realize the inverse adjustment control of machine tool parameter error. The following conclusions are drawn through the experiment:

1. This method can effectively reduce the gear convex surface error. The average detection error of gear convex surface is only 1.91 μm, which is about 2/7 of the control group.
2. In this paper, the method can effectively reduce the gear convex surface error, the maximum gear concave detection error is only 3.9 μm, far less than the control group.

On the whole, the error correction method can effectively reduce the gear error and improve the qualified rate of gear production.

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