Research on Spiral Bevel Gear Detection Based on Environmental Tooth Surface Error Correction Method

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Abstract. This paper studies the influence of the machine tool adjustment parameter error on the tooth surface error of the spiral bevel gear wheel processed by the double helix method. Based on the gear meshing principle, MATLAB software was used to establish the error tooth surface equation, and the analytical formula of the discrete point error of the tooth surface containing the machine tool adjustment parameter errors was derived. The topological map of the concave and convex tooth surface errors corresponding to the machine tool adjustment parameter errors was obtained and analyzed. The mapping relationship between machine tool adjustment parameter errors and tooth surface errors is determined, and the adjustment parameters that have a greater influence on the tooth surface errors are determined. With the help of the approximate expression of the topological diagram of the tooth surface error by the second-order surface, the influence weight of the machine tool adjustment parameter error on the tooth surface error is obtained. Based on the tooth surface error and the two-tooth surface error sensitive matrices, a tooth surface error correction model was established. The least square method of the generalized inverse matrix was used to transcend the equations to obtain the correction amount of the machine tool adjustment parameters. Finally, an example is used to verify the correction effect of the error tooth surface. The results show that the error of the tooth surface on the concave and convex sides after the correction is greatly reduced.

Keywords: Error repair, spiral cone wheel, adjustment parameters, gear measuring instrument.

1. Introduction
Spiral bevel gear is one of the most extensive and important parts used in machinery industry and transportation industry. Since the actual tooth surface shape is one of the important factors that affect the dynamic performance of the gear, measuring and controlling the tooth surface shape and accuracy of the spiral bevel gear is an important means to ensure high-quality gears. Therefore, the measurement of the shape of the spiral cone tooth surface has attracted increasing attention from researchers and field technicians.

At present, in the processing of spiral bevel gears, the processing parameters of the machine tool are usually adjusted by correction (counter regulation) technology to improve the machining accuracy of the tooth surface. The method adopted by Glasson is to first calculate the characteristic parameters...
of the difference surface fitting equation between the theoretical tooth surface and the actual tooth surface, and then adjust the parameter correction amount according to the characteristic parameter computer bed, but this compensation method needs to consider each characteristic parameter. The comprehensive effect of the modification on the tooth surface shape; Literature proposes a method for tooth surface error compensation different from Gleason—the function method, which regards the point vector on the tooth surface as a machine tool. The function of adjusting parameters, error identification and compensation calculation are based on the differential expression of this vector function, but the least square method is used to solve, it is easy to make the solved machine adjustment parameters exceed the actual adjustment range of the machine. Based on this deficiency, the literature proposes to use the actual range of the machine tool adjustment parameters as the constraint condition and use the optimization method to solve it, which has achieved relatively good results. Therefore, the algorithm for seeking the tooth surface error correction model is the key to the high-precision tooth surface deviation correction technology [1].

For the double spiral machining of spiral bevel gears, this paper studies the mapping relationship between the adjustment parameter error and the two tooth surface errors, and conducts tooth surface correction research through theory and experiment to achieve simultaneous correction of both tooth surfaces and improve meshing performance.

2. Measurement standard of spiral bevel gear

2.1. Measurement area and measurement mode
In this paper, the hypoid gear measuring instrument is selected for testing. The gear measuring instrument adopts a two-dimensional measuring head and adopts a scanning method of higher speed scanning. Due to its high measuring speed and many sampling points, this measuring instrument has been used in the rear axle bevel gear companies of major automobile companies in Japan. Moreover, the repeatability of the measuring instrument can be guaranteed to be around 2 μm, but the evaluation of its absolute accuracy has never been solved [2].

In order to reasonably assess the accuracy of the gear measuring instrument, when actually measuring a standard prototype, not only the size of the measurement area must be properly defined, but also the measurement mode and the trajectory of the probe must conform to the mode when measuring the gear. The measuring principle of Osaka Precision Machinery's spiral bevel gear measuring instrument is mainly four-axis linkage. The probe can move in three directions of XYZ axis, and the main shaft of the gear can be rotated. At the same time, in the measurement work, always keep the probe moving in a plane parallel to the X-Z plane. This measurement area is shown in Figure 1. The four vertices are abcd, and their polar coordinates (u, v) are point a (45°, 35°), point b (75°, 35°), point c (45°, 2°), Point d (75°, 2°). There are eight measurement lines in this area. The sampling point of each measurement line is 113 data. The movement direction of the probe is shown by the pointed tip in the figure, and the diameter d of the probe is 2.0 mm.
2.2. Calculation method of benchmark data

The so-called reference data is the coordinate data provided to the movement of the probe to the target position, that is, the theoretical three-dimensional surface coordinate data. The Osaka Precision Mechanical Tooth Surface Measuring Instrument is composed of \( \theta, X, Y, Z, NX, NY, NZ \) at each measuring point, where \( \theta \) is the rotation angle of the main shaft, and \( X, Y, \) and \( Z \) are the coordinates of the measuring point, respectively [3]. \( NX, NY \) and \( NZ \) are the normal vectors of the measuring points. The calculation method of the benchmark data is introduced below. First, as shown in Figure 2, rotate the standard model instrument to move the center point of the field to be measured (assumed to be P point) to the \( Y=YH \) plane (the \( Y \) coordinate is a certain value \( YH \) plane). Assuming that the coordinate of point P before turning is \((XP, YP)\), the distance from point P to the origin of the coordinate is:

\[
R_p = \sqrt{X_{P0}^2 + Y_{P0}^2}
\]  

(1)

Rotation angle:

\[
\theta_p = \arctan\left(\frac{Y_{P0}}{X_{P0}}\right) - \arcsin\left(\frac{Y_P}{R_p}\right)
\]  

(2)

**Figure 1.** Measurement area and the trend of the probe
Figure 2. Schematic diagram of benchmark data calculation

Suppose the coordinate of any point A on the spherical surface before rotation is \((X_0,Y_0, Z_0)\), the normal vector is \((NX_0, NY_0, NZ_0)\), the coordinate after rotation is \((X,Y,Z)\), and the normal vector is \((NX,NY,NZ)\), then:

\[
\begin{align*}
X &= X_0 \cdot \cos \theta_p + Y_0 \cdot \sin \theta_p \\
Y &= -X_0 \cdot \sin \theta_p + Y_0 \cdot \cos \theta_p \\
Z &= Z_0
\end{align*}
\] (3)

\[
\begin{align*}
NX &= NX_0 \cdot \cos \theta_p + NY_0 \cdot \sin \theta_p \\
NY &= -NX_0 \cdot \sin \theta_p + NY_0 \cdot \cos \theta_p \\
NZ &= NZ_0
\end{align*}
\] (4)

Because the measuring method of this kind of measuring instrument is characterized in that the probe always moves on the \(Y = Y_H\) plane, therefore, during the measurement, each measuring point must be moved into this plane by the rotation of the main shaft. Assumming that the rotation angle is \(\theta\), after the measurement point P is turned to the \(Y = Y_H\) plane, the angle \(\theta\) of the point P is 0 at this time.

Secondly, it is necessary to determine the angle and direction of \(\theta\) when each measuring point rotates on the \(Y = Y_H\) surface. As shown in Figure 3, suppose point 1 on the sphere (distance to axis \(R_1 < \text{P distance from point to axis OP}\)), and point 2 (distance to axis \(R_2 > \text{P distance from point to axis OP}\)) as Examples. Let the 1 and 2 points be the position of 1 point and 2 point at the time of measurement.

At 1 o'clock:

\[
\theta_1 = \arctan \frac{Y_1}{X_1} - \arcsin \frac{Y_H}{\sqrt{X_1^2 + Y_1^2}}
\] (5)

At 2 o'clock:

\[
\theta_2 = \arctan \frac{Y_2}{X_2} - \arcsin \frac{Y_H}{\sqrt{X_2^2 + Y_2^2}}
\] (6)
As shown in Figure 3, the regulations $\theta_1 < 0 \Leftrightarrow \theta_2 > 0$.

Figure 3. Schematic diagram of coordinate transformation

Then the coordinate $(X'1, Y'1, Z'1), (X'2, Y'2, Z'2)$ and normal vector $(NX'1, NY'1, NZ'1), (NX'2, NY'2, NZ'2)$ can be calculated using equations (3) and (4). The reference value $(\theta, X, Y, Z, NX, NY, NZ)$ of all measuring points can be calculated by the same method.

3. Error correction

It is assumed that the gear cutting parameters (that is, the machine tool motion parameters) $Y_j (j=1,2,\ldots, m$ is the number of machine tool motion parameters, including the cutter head diameter $r$, tooth profile angle $\alpha$, radial tool position $S$, angular tool position $q$, (Installation angle $\gamma$, horizontal wheel position $X$, vertical wheel position $E$, machining bed position $B$ and hobbing ratio $R$, etc.) are known. After a series of coordinate transformation and derivation processes, the theoretical tooth surface $H$ in the measurement coordinate system is obtained the unit normal vector $n$. is used to compensate the probe radius to obtain the theoretical trajectory $H_e$ of the probe sphere center [4].

$$H_e(\theta, \phi, \Phi) = H(\theta, \phi, \Phi) + \rho n(\theta, \phi, \Phi)$$

(7)

Where $\theta$ and are the coordinates of the curved surface; $\rho$ is the probe radius. Due to the influence of error factors such as gear cutting and machine tool adjustment, the actual tooth surface $H^*$ often deviates from the theoretical tooth surface $H$, and the degree of deviation $\delta$ (that is, the tooth surface error) is usually at $H$ The unit normal vector is measured in the direction of $n$ [5].

$$\delta = (H^* - H) \circ n$$

(8)

4. Experimental design

According to the tooth surface error and the principle of proportional correction, the tooth surface error is mainly divided into three categories: tooth length error, tooth height error and diagonal error. Among them, the tooth length error is mainly reflected by the spiral angle error and the tooth surface curvature error; tooth the high error is mainly reflected in the pressure angle error and the tooth shape
curvature error; while the diagonal error is caused by the combination of the former two. In the actual gear manufacturing process, under normal circumstances, the tooth surface error is first-order error and second-order error. By reasonably selecting the machine tool adjustment parameters, the tooth surface error can be reduced to an ideal range. In order to verify the effectiveness of the tooth surface error correction algorithm in this paper, the amount of tooth surface error obtained by randomly changing the adjustment parameters of several machine tools is taken as the actual measured tooth surface error. Figure 4 is a diagram of the tooth surface error of the small wheel before correction [6]. The error correction amount of each adjustment parameter calculated by the concave and convex tooth error correction algorithm is shown in Table 1.

![Error diagram of small gear tooth surface before correction](image)

**Figure 4.** Error diagram of small gear tooth surface before correction

**Table 1.** Machine tool adjustment parameter correction amount

| status           | Sum of squared concave errors/μm² | Convex square error/μm² | Maximum concave surface maximum convex value/μm | Error value/μm |
|------------------|-----------------------------------|-------------------------|-----------------------------------------------|----------------|
| Before correction after fixing | 9518.84                           | 2,965.43                | 31.47                                         | 22.69          |
| Fine tuning      | 787.97                             | 344.43                  | 7.89                                          | 8.28           |
| Secondary fine-tuning | 506.29                           | 173.14                  | 6.36                                          | 4.6            |
|                  | 343.18                             | 193.17                  | 6.13                                          | 4.98           |

The correction amount of each adjustment parameter obtained is calculated again to obtain the error amount of the two tooth surfaces of the small wheel concave and convex as shown in FIG. 5.
5. Conclusion
Tooth surface error correction technology is the key technology of spiral bevel gear digital manufacturing. In this paper, the spiral bevel gear tooth surface error correction technology is studied from the perspective of digital manufacturing of spiral bevel gears. Through the establishment of the relationship between the various order tooth surface error sensitivity coefficients and the machine tool adjustment parameter changes, the essence of the tooth surface error correction is revealed.

References
[1] Kia, S. H. Henao, H. & Capolino, G. Gear tooth surface damage fault detection using induction machine stator current space vector analysis. IEEE Transactions on Industrial Electronics, 62(3) (2015) 1866-1878.
[2] Korta, J. A. & Mundo, D. Multi-objective micro-geometry optimization of gear tooth supported by response surface methodology. Mechanism & Machine Theory, 109(5) (2017) 278-295.
[3] Yasue, Y. Hiroshima, S., Hayashida, Y., & Matsumoto, S. Verification of micro pitting occurring process considering frictional force at the gear tooth mesh surface of power transmission gears. Transactions of the Japan Society of Mechanical Engineers, 81(828) (2015) 14-00687-14-00687.
[4] He, K. Du, Y., & Li, G. Analysis on tooth surface principle error of forming grinding lead modification helical gear. Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS, 24(6) (2018) 1401-1410.
[5] Liang, D. Chen, B. Peng, S. Hua, C. & Liao, R. Deviation calculation and analysis of tooth surfaces of conjugate-curve gear drive. International Journal of Precision Engineering & Manufacturing, 18(5) (2017) 689-696.
[6] Ming, X. Fang, S. & Wang, H. Tooth surface form error correction for face gear grinding. Zhongguo Jixie Gongcheng/China Mechanical Engineering, 29(17) (2018) 2031-2037.