Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 6633643, 9 pages
https://doi.org/10.1155/2021/6633643

Research Article

Gear Mapping Technology Based on Differential Envelope Principle

Yangpeng Liu,[1] Jingyang Guo,[1] Jianjun Ding ,[1,2] Duanzhi Duan,[1] Yuerong Jiang,[3] Changsheng Li,[1] Wei Zhao,[4] and Zhuangde Jiang[1]

[1]*The State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiao Tong University, Xi'an 710049, China*
[2]*Shaanxi Key Laboratory of Non-Traditional Machining, Xi'an Technological University, Xi'an 710021, China*
[3]*International Business Machines (China) Co., Ltd., Xi'an 710075, China*
[4]*Xi'an Qinchuan Siyuan Measuring Instrument Co., Ltd., Xi'an 710051, China*

Correspondence should be addressed to Jianjun Ding; dingjianjun@mail.xjtu.edu.cn

Received 3 November 2020; Revised 5 March 2021; Accepted 13 March 2021; Published 1 April 2021

Academic Editor: Ioannis Kostavelis

It is proposed that the complex molding process and the scanning process should be unified through the differential envelope principle. After scanning the surface of the part with the contact sensor, the contour coordinates of the measured surface are calculated by the trajectory of the center of the ball, and the contour data of the complex linear surface is extracted. Then, the intelligent analysis and calculation of precision generating surface parameters and quantitative adjustment are carried out, and the exact reverse method of the special line parts with characteristic parameters is studied. There is only micron scale difference between the reverse result and the nominal value. This technology is applied to the closed-loop manufacturing process of gear parts, which reduces the dependence on the artificial experience when the machining parameters of the cylindrical gear processing equipment is adjusted and provides an effective solution for the digital and intelligent manufacturing of the parts.

1. Introduction

The measuring link in the network collaborative closed loop manufacturing is no longer a simple error detection procedure, but the process of obtaining reverse of the machining parameters and the calculated quantitative inversion parameter [1, 2]. It includes three steps: linear surface data acquisition, data processing, and reconstruction [3]. At present, in addition to the contact scanning method, the common way of data acquisition also includes the non-contact optical scanning and the contact coordinate measurement by the trigger head [4–6]. Due to the measurement precision and efficiency of the last two methods, they are not suitable for application in the closed-loop manufacturing system of complex linear workpiece surface with high precision. The reconfiguration of the complex linear surface is generally achieved by a special reverse software developed for a certain part, or by a manual method, which makes the cost of reconstruction high or guarantee of accuracy difficult [7, 8]. It is the key to solve the above problems by studying a high-precision, simple and practical, and achievable integration of measurement results and processing parameters, and this is also a key part of closed-loop manufacturing technology.

According to the machining principle, the actual machined surface of the workpiece contains some information such as machine tool, cutter and the relative cutting motion of cutter, and workpiece [9]. Based on the detection results of the actual profile of the workpiece, the monitoring, and automatic intervention of the part processing process, achieving the application effect of intelligent closed-loop manufacturing can be completed by quantitative adjustment analysis of the machining process. As shown in Figure 1, the measurement link is transformed from the traditional passive detection assessment into active monitoring and feedback to realize the control of the quality of the product in the closed-loop manufacturing system [10]. At present, there are two kinds of feedback compensation methods from the

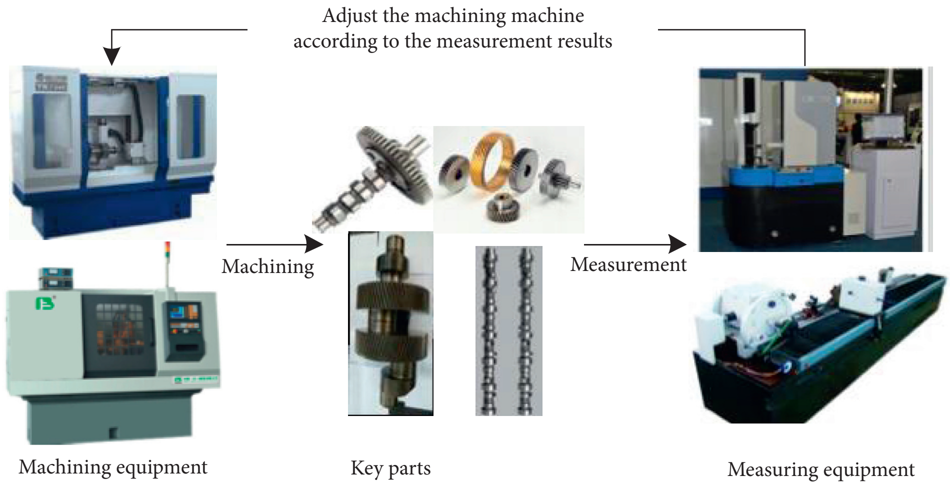

Figure 1: Schematic diagram of the closed-loop manufacturing system.

measurement link to the processing link. One is reserving the compensation parameters in the machining code of CNC machine tools. After the completeness of detection, the measurement results are converted to the recognizable compensation parameters by the numerical control system, and then the compensation parameters are fed back to the CNC machine tool through the network interface to realize the compensation processing [11]. The other is converting the measurement data into the feedback amount of the closed-loop control of the servo unit of the processing equipment and directly controlling the servo motor to realize error compensation [12]. This involves the integration of machining parameters and measurement results [13], which means that the test results and the input parameters of the machine tool need to be unified.

The processing input parameters of involute cylindrical gears such as number of teeth, modulus, pressure angle, helix angle, and the variation coefficient are characteristic. But the detection result is the shape error and circumferential distribution error of the profile, which needs to be analyzed and transformed according to the measurement results or directly output the result. That is to say, the characteristic parameters of the workpiece to be tested need to be mapped to obtain the quantitative inverse result that can be used to guide the machining. Wang Wenjing et al. proposed a method of calculating the normal modulus by the common normal line length, which is a new measurement method for determining the type of gear displacement by means of a three-coordinate measuring instrument to determine the helix angle and mutual interpolation by the helix angle and the tip circle diameter [14]. A large number of preprocessing studies on gear point cloud data to achieve a fast reverse of gear characteristic parameters were conducted by Wang and Fang [15]. A cooperative visual surface profiling system was proposed to achieve accurate measurement of the chamfered gear profile by Zhou et al. [16, 17]. A new method for calculating the basic parameters of a gear using the 3D digitizer was introduced to obtain the image data of the helical gear by Asgharifard [18]. A noncontact measurement method for gear parameters based on machine vision and laser sensors was proposed by Jun et al. [19, 20].

For the complex surface workpieces such as spiral bevel gears and nonlinear worm gears, the machining input parameters include not only the own characteristic parameters, but also the machine adjustment parameters and tool parameters. Therefore, the process of adjusting the machining equipment according to the measurement results is more complex. It is necessary to derive the mapping relationship between the parameters of the gear and the error of the tooth surface, although there are mature products abroad. China is still at the stage of theoretical research [21].

Gears are important parts of mechanical transmission, among which involute gear is an important part of modern high-efficiency transmission technology [22]. According to the conventional razor-pulling processing method for cylindrical gears, if the basic parameters such as the number of teeth, the modulus, the pressure angle, the helix angle, and the variation coefficient are determined, the processing of the involute cylindrical gear can be realized [23]. However, due to the adjustment error of the relevant parameters of the processing equipment (equipment error or human error), it is difficult to directly ensure the parameter requirements of the processed gear, which in turn affects the performance of the gear [24]. At present, the basic solution for enterprises is to use the gear meter to detect the gears and adjust the parameters according to the test report. It is difficult to obtain accurate and reliable adjustment parameters and the adjustment amount of the tooth surface. The accurate measurement and analysis system of cylindrical gear parameters can solve the above problems well and provide a method for the accurate reverse adjustment of tooth surface machining. At the same time, in the practical application of mechanical engineering, on the one hand, the gear mechanism often fails with the operation of the machine (such as the accidental overloading leading to the broken teeth, the tooth surface wear, the pitting and the gluing, etc.), which needs to be replaced in time. On the other hand, in the process of copying the machine or redesigning a new product, for some reasons (such as the absence of relevant design drawings in imported mechanical products), the original design parameters of the gear mechanism are not available. It undoubtedly brings difficulties to the replacement, imitation, and redesign of the gear mechanism. So how to extract the original design parameters of the unknown gear becomes the key to solve this problem [25].

Based on the theory of cylindrical gear machining, in this paper, the multiaxis linkage measurement center for complex linear surface is applied to study the cylindrical gear intelligent mapping method of actual tooth surface parameters. According to the actual surveying and mapping parameters, the quantitative correction of the gear processing parameters can be realized, thereby ensuring accurate processing of the product. Custom analysis technology for actual tooth profile is researched and implemented, which can further extract the modified tooth surface data, and a stable and reliable basis for the precise adjustment of the gear processing parameters and the accurate control of the tooth surface modification amount is provided.

2. Methodology

2.1. Reverse Mapping Based on Differential Envelope Technique. Most parts can be machined in a variety of equipment or methods. The mechanism and machine parameters of various machine tools are different. The principles and mechanisms of achieving tool tilting, tool turning, tool position, and deformation are also different, and many parameters are involved. On each type of machine tool, establishing a closed-loop feedback model between measurement and machining for a profiled surface part would be a huge project. In this paper, an analysis method based on the differential envelopment principle is proposed. It is not necessary to carry out complex geometric analysis on the theory model of linear profile. It is necessary to measure and analyse the actual motion trajectory, and then the extraction of the actual linear profile can be completed [26]. According to the conversion relationship between the probe and the tool (grinding wheel), the quantitative adjustment of the machining parameters is realized.

The machining process of the part can be regarded as the result of shaping the blank by a curved surface which moves with a certain law formed by the cutting edge of the tool. The final forming contour of a part is formed by the envelope of the curved surface and numerous tool edges [27]. In the process of scanning and measuring complex linear surface parts, the profile measurement data obtained by the probe scanning can be regarded as the movement of the probe surface along the surface of the part. The envelope of the probe surface forms a curve that is in contact with the part surface. Thereby, the processing process of the complicated linear surface and the measurement scanning process can be unified.

As shown in Figure 2, during the profile scanning process, the sphere of the probe S_2 is kept in contact with the measured surface S_1, and the two surfaces are tangent to the point P. S_2 is moving relative to S_1. In the workpiece coordinate system of S_1, at any two moments, $S_2(t)$ and $S_2(t+\Delta)$ should form two contact points with S_1, $P(t)$ and $P(t+\Delta)$, and have the following formula:

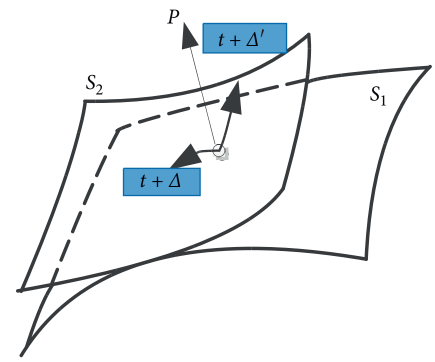

Figure 2: Scanning envelope analysis of actual machined profile.

$$\lim_{\Delta \longrightarrow 0} P(t+\Delta) = P(t), \quad (1)$$

when $\Delta \longrightarrow 0$,

$$S_2(t) \cap S_2(t+\Delta) \approx P(t) \in S_1. \quad (2)$$

Here, only the direction of the contour scanning motion trajectory is analyzed. Considering the characteristics of the part profile here, only the direction of trajectory is analyzed. Considering the characteristics of the part profile (the design line is generally scanning by a straight line or a spiral line), the same differential analysis can be performed in the other dimension direction of configuration. That is, at another moment, $S_2(t+\Delta')$ should form two contact points with S_1, another is $P(t+\Delta')$, and have the following formula:

$$\lim_{\Delta' \longrightarrow 0} P(t+\Delta') = P(t), \quad (3)$$

when $\Delta' \longrightarrow 0$,

$$S_2(t) \cap S_2(t+\Delta') \approx P(t) \in S_1. \quad (4)$$

So, when$\Delta \longrightarrow 0 \Delta' \longrightarrow 0$, P can be got by calculating $S_2(t) \cap S_2(t+\Delta) \cap S_2(t+\Delta')$ for time t. The calculation of the actual processing line lattice of the part is completed. After processing the lattice data, completing the reference matching and the nonlinear interpolation of the specified points, on the one hand, the machining error of the workpiece can be obtained through compared with the theoretical model of CAD. On the other hand, according to the mapping relationship of the profile line surface and the processing parameters, quantitative analysis of processing parameters can be realized.

The finishing process of complex linear profiles is generally realized by a precision grinding machine. In the complex linear closed-loop manufacturing based on processing method with the grinding machine, the process of integrating measurement and by differential enveloping technology can be explained by Figure 3. In Figure 3, the profile L is formed by grinding with a grinding wheel whose radius is$R1$. The obtained profile line is the envelope of the surface of the grinding wheel. The probe with radius $R2$ is used to detect the profile based on a way of measurement

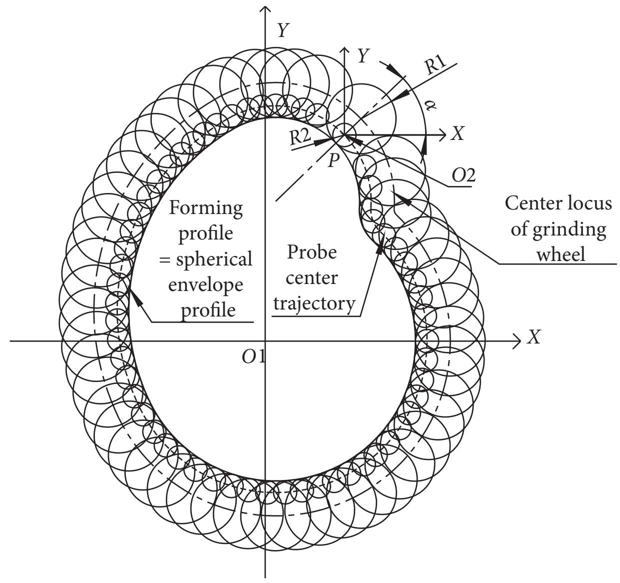

FIGURE 3: Integrated schematic diagram of processing and measurement through differential envelope.

which is fixed step size and constant force of measurement and automatic path planning. The envelope of the probe surface is the actual machining curve of the profile. Theoretically, the actual processing envelope is consistent with that of measurement. It is assumed that the coordinate of the ball center corresponding to the point P on the workpiece line $(x1, y1)$ at the workpiece coordinate system XO_1Y. The angle between normal direction of the P and the X-axis isα. Both the grinding wheel and the probe are tangent to the profile line at point P. So, it can be obtained in the probe coordinate system XO_2Y. The center coordinate of the grinding wheel corresponding to the P point is $((R1 - R2)\cos a, (R1 - R2)\sin a)$, and the coordinate of the center of the grinding wheel in the workpiece coordinate system XO_1Y is $(x_1 - (R1 - R2)\cos a, y_1 - (R1 - R2)\sin a)$. The normal angle of the P point is consistent with the normal angle of the probe ball trajectory. Therefore, the trajectory of the center of the grinding wheel during the machining process can be obtained from the probe ball trajectory which is obtained during the measurement process, thereby achieving uniformity of measurement and processing.

2.2. The Principle of Reverse Modulation of Cylindrical Gear. For involute helical gears, as long as the number of teeth Z, the end face modulus m_t, the pressure angle α, the helix angle β, the modification coefficient x(the undisplaced gear modification coefficient is 0), the tip circle radius r_a, and root radius r_f are calculated, the gear can be determined. Therefore, a workpiece having the same characteristics as a spur gear can be defined as a complex linear surface workpiece having characteristic parameters. The cylindrical gear mapping based on the differential enveloping technique is to extract the characteristic parameters through the measurement of the gear profile.

2.2.1. The Mapping of Base Circle Diameter. The process of measurement to get parameters (base circle diameter D_b, modulus m, and pressure angle α) is as follows: the number of teeth of the unknown parameter gear is counted, and the gear tip diameter and the root diameter are measured with a caliper. Enter the mapping software as basic parameters. The gear with unknown parameters is clamped on the measuring equipment, and the measuring head is moved to the root of the measured tooth space. The rotating shaft (C-axis) of the measuring equipment automatically rotates to drive the measured gear to rotate until there is some pressure between the probe and the measured gear. Then the software controls the rotary axis (C-axis) of the measuring equipment to rotate at a constant speed.

At this time, the amount of deformation of the probe will change slightly. The change is feedback to the motion control system in time, and the control system drives the linear axis motion, thereby offsetting the change of the probe. For spur gears, if the surface machining quality is good, the deformation of the 3D probe is in the X-direction. If the workpiece to be tested is a helical gear, it is required to calculate the combined effect of the three deformation directions of the probe. Three linear axes are required to realize. Closed-loop feedback is controlled according to the deformation amount of the probe. In short, during the process of measurement, under the premise of constant compression of the probe, the probe moved relative to the tooth profile of the measured gear, and the information of the position of the probe is collected during the moving process. So, the parameters of the measured gear are obtained by processing the collected information.

According to the principle of the involute, two different points are randomly selected on the involute of profile, and two extensions are made along the normal line of the tooth profile through two selected points. The two extension lines are the generating line of involute. Vertical line of the extension line is made by the center of the rotation, and the intersection point is on the base of the gear. According to the parameter expression of the involute, as (5), combined with the position information of two different points on the gear contour, assuming $A_i, B_i, i = 1, 2, 3, \ldots, n$, the base circle radius $r_{bi}, i = 1, 2, 3, \ldots, n$, is calculated. The average value $\overline{r}_{b1}$ is calculated by the measured spur gear according to formula (6). According to formula (7), if the result of r_{bi} minus $\overline{r}_{b1}$ exceeds a certain value$m$, then it is deleted as an error. So, the average value of rest r_{bi} is calculated, which is the theoretical base circle radius value r_b.

$$\begin{cases} r_k = \dfrac{r_b}{\cos\,\alpha_k}, \\ \theta_k = \tan\,\alpha_k - \alpha_k, \end{cases} \tag{5}$$

$$\begin{cases} r_{kAi} = \dfrac{r_b}{\cos\,\alpha_{kA}}, \\ \theta_{kAi} = \tan\,\alpha_{kAi} - \alpha_{kAi}, \\ r_{kBi} = \dfrac{r_b}{\cos\,\alpha_{kBi}}, \\ \theta_{kBi} = \tan\,\alpha_{kBi} - \alpha_{kBi} \\ \theta = \theta_{kAi} - \theta_{kBi}, \end{cases} \tag{6}$$

$$\overline{r}_{b1} = \frac{\sum_{i=1}^{i=n} r_{bi}}{n}. \tag{7}$$

In the formulae, r_{kAi} and r_{kBi} are path diameters of A_i and B_i, respectively. θ_{kAi} and θ_{kBi} are the angles of A_i and B_i, respectively. θ_{kAi} and θ_{kBi} are the pressure angles of A_i and B_i, respectively.

2.2.2. Check Preferred Sequence Table. In the design, manufacture and use of products, the performance parameters, and dimensions of various products need to be expressed by numerical values. For example, the size of the part, the diameter of the raw material, the tolerance value, the specifications of the product, etc., need to be expressed by numerical values. In order to meet the various requirements of users, the product will inevitably have different specifications. The same parameter of the same product needs to take different values from large to small, thus forming a series of products with different specifications. Whether this series is reasonable, it is directly related to how the values are divided and graded. Therefore, the priority number and a series of priority numbers are a scientific numerical standard, that is, simplifies, coordinates, and unifies for values of various technical parameters and the main content of standardization.

Table 1 shows a preferred series of modulus of the involute cylindrical gear. Generally, the preferred value of the pressure angle is 20°. For involute cylindrical gears, r_b, m, m_n z, α, and β are the base circle radius, the end face modulus, the normal modulus, the number of teeth, the normal pressure angle, and the helix angle. In the initial mapping process, if the helix angle β is 0°, according to the expression

Table 1: Modulus of preferred series of involute cylindrical gear (GB/T 1357-1987).

First series	0.1	0.12	0.15	0.2	0.25
	0.3	0.4	0.5	0.6	0.8
	1	1.25	1.5	2	2.5
	3	4	5	6	8
	10	12	16	20	25
	32	40	50		
Second series	0.35	0.7	0.9	0.75	2.25
	2.75	(3.25)	3.5	(3.75)	4.5
	5.5	(6.5)	7	9	(11)
	14	18	22	28	(30)
	36	45			

Note. (1) For involute cylindrical helical gears refers to the normal modulus. (2) The first series is preferred, and the modulus in parentheses is not used as much as possible. (3) The modulus code is m; the unit is mm.

(8) of the base circle radius, the modulus m_n and pressure angle $\alpha$of the measured gear can be determined by the pattern search in the preferred sequence table of modulus and the preferred sequence table of pressure angle. Of course, in the software, the search range of modulus and pressure angle can be customized, or one of them can be automatically calculated when another is determined.

$$\begin{aligned} r_b &= \frac{m \times z \times \cos(a\,\tan(\tan(\alpha)/\cos(\beta)))}{2}, \\ &= \frac{m_n \times z \times \cos(a\,\tan(\tan(\alpha)/\cos(\beta)))}{2 \times \cos(\beta)}. \end{aligned} \tag{8}$$

2.2.3. Mapping for Helix Angle. After the initial measurement of the modulus m, the pressure angle α is completed in accordance with steps (1) and (2), and the reverse mapping of the helix angle β can be started. The process of operation is as follows: moving the probe to position of the base circle radius $r_b$of the measured gear, the C-axis is manually controlled to drive the measured gear to rotate until the probe and the measured gear generate a certain amount of compression, and then the linkage between the C-axis and the Z-axis is controlled by software. Under the premise of keeping a certain amount of compression, the probe moves downward along the Z-axis for a distance of Lz. During the process, the distance of the probe relative to the gear is Lx in the X-direction, and the expression of the helix angle β of the cylindrical helical gear is as shown in the following equation:

$$\tan\,\beta = \frac{L_x}{L_z} \cdot \cos\,\alpha. \tag{9}$$

The differential enveloping principle is adopted in the surveying and mapping process, and the coordinate point of the measuring profile is obtained by center of probe whose radius compensation is carried out if the helix angle of the mapping is not 0, the modulus m and the pressure angle α of the initial mapping need to be corrected; that is, the influence of the helix angle is considered in the process of the radius compensation of the probe, and m and α should be recalculated.

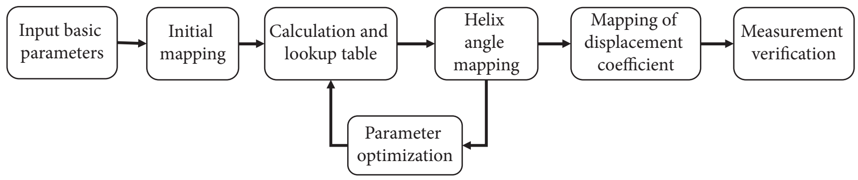

Figure 4: The software's operation procedure of the cylindrical gear to reverse and mapping.

2.2.4. Mapping of Modification Coefficient. According to the data collected by the probe at the root and the top of the tooth during the movement, the circle is fitted to obtain the actual root radius r_f, tip radius r_a.

According to the definition of the involute cylindrical gear, the expression of the reference radius and the angle of the cogging can be expressed as follows:

$$r_p = \frac{m \times z}{2}, \tag{10}$$

$$\theta = \frac{0.5 \cdot \pi - 2 \cdot x \cdot \tan \alpha \cdot \cos \beta}{z}. \tag{11}$$

The reference radius r_p of the measured tooth is calculated according to formula (10) (Z is the number of teeth) and the probe moves to the position of reference radius r_p of the measured gear. Then, the C-axis rotates to drive the measured gear for rotating until the amount of compression generated by the probe. The measured tooth surface reaches a threshold value and then rotates the measured gear in the opposite direction to make probe contact the other surface of tooth space. Compression amount reaches the threshold value, and the angle θ corresponding to the cogging on the reference circle is obtained. The modification coefficient x can be calculated according to the expression (11), which can be further optimized by the paired gear and the center distance parameter. In the actual machining process, according to the results of parameter mapping of the processed gear and the initial setting parameters of the machine tool, the intelligent reverse adjustment of the gear processing can be realized.

2.3. Software for Reverse Mapping of Cylindrical Gear. The software for procedure of operation of the spur gear to realize reverse mapping is shown in Figure 4. Firstly, you need to input the basic parameters of the workpiece, that is, the number of teeth of the gear, the actual diameter of top circle, the diameter of the root circle, and the width of tooth, and determine the diameter of the probe used for the measurement. The second step is mainly to detect the tooth shape in the initial step to calculate the actual diameter of base circle. The third step is to find the corresponding modulus and pressure angle in the preferred sequence. The fourth step is measuring the helix angle, then probing the obtainment a certain amount of compression on the lower end surface of the tooth profile, and performing a follow-up scan from bottom to top to complete the mapping of lead. The fifth step is to obtain the modification coefficient by the pitch detection and obtain the basic parameters through the front measurement. Based on those basic parameters, the profile and pitch of the gear can be measured to obtain the average value of the profile and the cogging angle, the modification coefficient and coefficient of the top/root tooth height are calculated. Finally, all parameters are obtained. In the fifth step, the measurement is verified. The second and third steps in the above are particularly important, and the detailed process is shown in Figure 5.

When the tooth profile is mapped, the starting position is determined as follows: the probe is moved into the space of gear and the coordinate of X-axis is a positive number, and the direction of tooth height is at the highest of the involute, as shown in Figure 6. The probe can be manually moved to the tooth surface, then the Y-axis is moved left and right, and the highest position is determined by the change in the compression amount of the probe.

In the gear design manual, there is the optimal sequence table of modulus and pressure angle. Select a set of modulus and pressure angle in the table. The diameter of the base circle and pitch are calculated. Compared with other choices in the table, when the difference between the calculated value and the measured value is the smallest, the selected modulus and pressure angle are the best choices. The final determination of the modulus and pressure angle is as follows:

(1) The results meet the requirements by table look-up
(2) Keep the standard modulus obtained by table look-up and modify the pressure angle
(3) Keep the standard pressure angle obtained by looking up the table and modify the modulus
(4) Know the actual modulus and modify the pressure angle
(5) Know the actual pressure angle and modify the modulus

3. Application

On the complex profile line measurement center equipped with Renishaw's 3D scanning probe SP80H, constant displacement, constant force tracking scanning measurement control method is applied to the parameter mapping of a standard involute cylindrical gear. The measured data are processed by differential envelope algorithm. The result of tooth profile data is shown in Figure 7.

During this measurement, the deformation amount of X-direction fluctuation range of the probe is $\leq \pm 0.5\,\mu$m. As shown in Figure 8, 11 points are interpolated in these sampled data in the above (all data can be processed in the actual software).

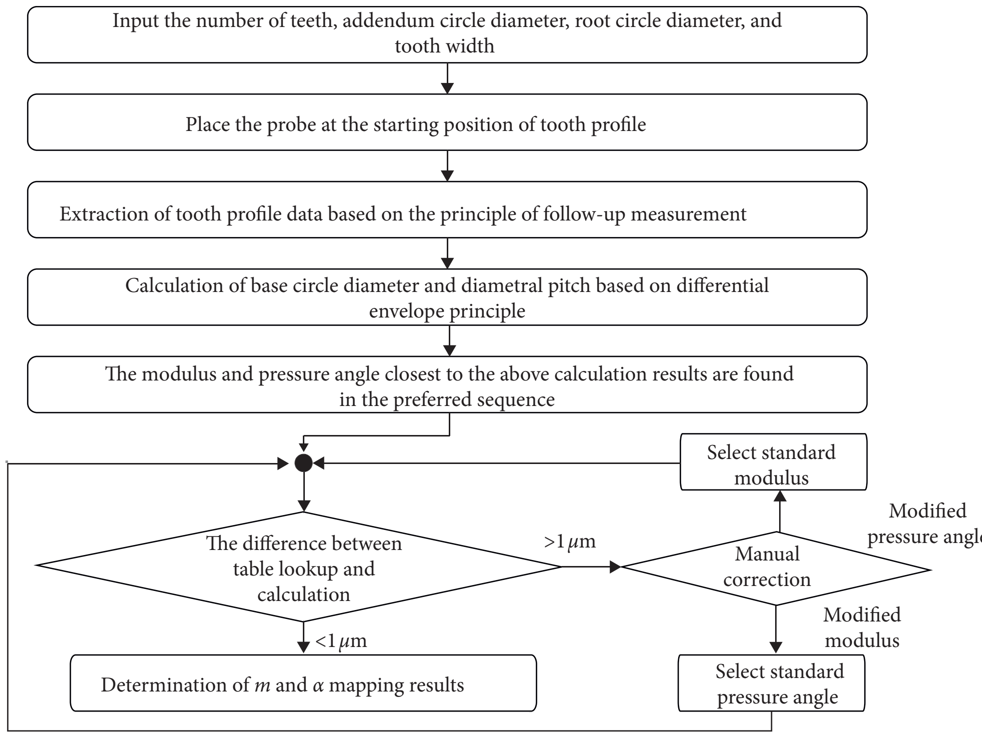

Figure 5: Flowchart of modulus and pressure angle to surveying and mapping.

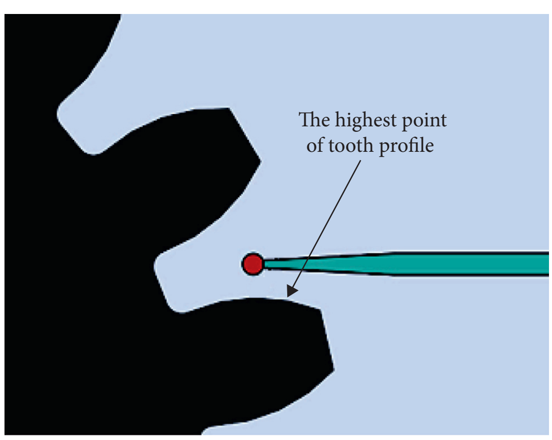

Figure 6: The starting position of the mapping for profile—the highest point of the profile.

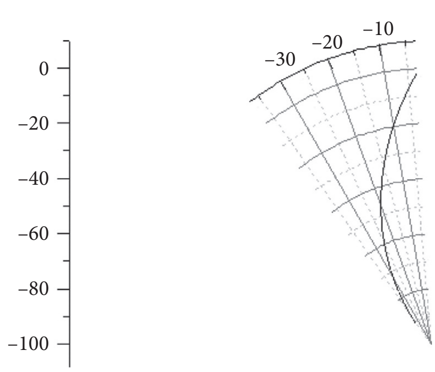

Figure 7: The measurement data is plotted according to the involute trajectory.

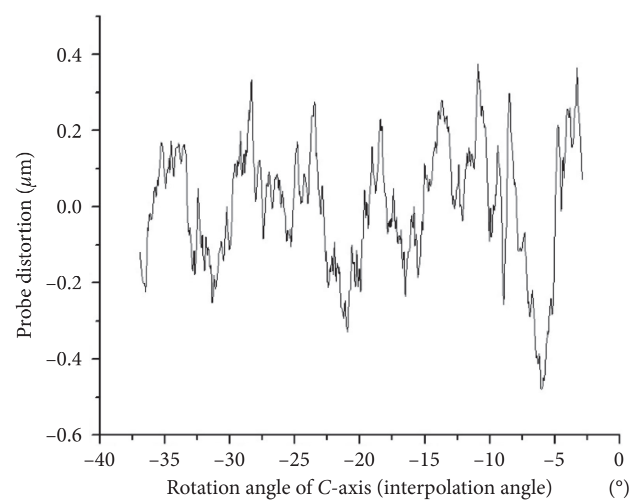

Figure 8: Deformation fluctuation of the X-direction of the probe during measurement.

Table 2 shows the interpolation angle and the extension value. These points are substituted into equation (6) for demonstration of processing process of the measurement data. That is, all points are combined in pairs to calculate the corresponding base circle radius, and the average is obtained after removing the coarse error. More accurate base circle diameter can be calculated.

Using the above principle to complete the parameter mapping of spur gear and helical gears, the results are completely consistent with the actual parameters. Table 3 shows the mapping results of the gear.

Table 2: The table for algorithm instance point data.

Order	Rotation angle of C-axis (interpolation angle) (°)	x-coordinate (extension) (mm)
1	−6	−8.8469
2	−9	−16.7037
3	−12	−24.5615
4	−15	−32.4205
5	−18	−40.2774
6	−21	−48.1342
7	−24	−55.9930
8	−27	−63.8436
9	−30	−71.7083
10	−33	−79.5636
11	−36	−87.4201

Table 3: Gear parameters.

Item	Nominal parameter	Parameters obtained by reverse calculation
Tooth number	31	31
Modulus	4 mm	4 mm
Base diameter	116.5219 mm	116.5199 mm
Pressure angle	20°	20°
Helix angle	0°	0°
Modification coefficient	0	0.54

Table 3 shows there is a slight difference in the diameter of the base circle and the coefficient of displacement. The diameter of the base circle differs by 0.002 mm, and the coefficient of displacement differs by 0.0054 mm.

4. Conclusions

In this paper, the method of differential envelope principle is used to unify the measurement and molding process of the workpiece surface, and the research of application of complex linear profile measurement in closed-loop manufacturing is carried out. This method equates the probe with the cutter, completes the envelope of the actual measured surface, and then calculates the deviation of the actual measured profile from the theoretical profile. According to the forming principle of theoretical profile, the quantitative optimized calculation of the machining adjustment parameters related to the surface to be tested is completed, and the closed-loop manufacturing process of the complex linear surface is realized. This method provides a good solution for the intelligent manufacturing to machine complex workpiece surfaces. In this paper, the effectiveness and feasibility of the proposed method are verified by the application of manufacture and reverse in camshaft profile and gear characteristic parameters.

Data Availability

The data were obtained by experiment. The original data can be obtained by using the general measurement center equipment. The data can be processed according to the method in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2018YFB2001400).

References

[1] P. Shandong, D. Han, and T. Jinyuan, “Corrected calculation of machine settings for spiral bevel and gears using an improved 6σ method,” *Journal of Xi’an Jiaotong University*, vol. 53, no. 6, pp. 35–43, 2019.

[2] C. Zhang and J. Pan, “Research on reverse design and five Axis machining technology of special - shaped surface,” *Machine Design and Research*, vol. 36, no. 2, pp. 87–90, 2020.

[3] R. J. Marzoog, R. J. Marzoog, A. A. Alduroobi et al., “Surface segmentation and reconstruction in reverse engineering,” *Conference Series: Materials Science and Engineering*, vol. 881, no. 1, pp. 012–082, 2020.

[4] G. Wang, Y. Yao, Z. Chen, and P. Hu, “Thermodynamic and optical analyses of a hybrid solar CPV/T system with high solar concentrating uniformity based on spectral beam splitting technology,” *Energy*, vol. 166, pp. 256–266, 2019.

[5] Z. Jianming, L. Songbao, P. Changtao et al., “Research and development trends of on-machine measurement technology on modern machine tools,” *Aeronautical Manufacturing Technology*, no. 9, pp. 43–49, 2016.

[6] Z. Chunwei, P. Shanfei, and L. Xiaofeng, “Research on Shape&Position detection method of high-speed RailParts-BasedonVisualInspection,” *Computer Measurement and Control*, vol. 28, no. 9, pp. 106–109+115, 2020.

[7] Novedge, Description of quicksurface free form edition, https://novedge.com/products/quicksurface-free-form-edition.

[8] S. Yingying, H. Lianjuan, and W. Jianan, “Quantum-behaved RS-PSO-LSSVM method for quality prediction in parts production processes,” *Concurrency and Computation-Practice & Experience*, p. e5522, 2019.

[9] Z. He, J. Duan, and Y. Li, “Simulation of double circular arc profile spiral bevel gear form grinding machining based on

VERICUT," *Mechanical Drive*, vol. 44, no. 4, pp. 125–131, 2020.

[10] "On the advantage of automatic production line in gear processing," *Mechanical Management Development*, vol. 35, no. 3, pp. 53–57, 2020.

[11] Z. Lv, L. Qiao, Q. Wang, and F. Piccialli, "Advanced machine-learning methods for brain-computer interfacing," *IEEE/ACM Transactions on Computational Biology and Bioinformatics*, 2020.

[12] G. M. Martinov and R. A. Nezhmetdinov, "Modular design of specialized numerical control systems for inclined machining centers," *Russian Engineering Research*, vol. 35, no. 5, pp. 389–393, 2015.

[13] G. Jian, P. Huang, W. Zhang et al., "Residual error compensation of in-situ inspection system for precision machining of complex components," *Journal of Mechanical Engineering*, vol. 52, no. 15, pp. 139–146, 2016.

[14] W. Wang and C. Feng, "Measurement and program realization for single-adapted helical cylindrical gear," *Manufacturing Technology & Machine Tool*, vol. 4, pp. 95-96, 2014.

[15] C. Wang and G. Fang, "Mapping of involute cylindrical gear based on point-cloud model," *Tool Engineering*, vol. 49, no. 12, pp. 66–70, 2015.

[16] C. Zhou, Z. Xu, C. Cai et al., "A high precision collaborative vision measurement of gear chamfering profile," in *Proceedings of the International Conference on Advances in Mechanical Engineering and Industrial Informatics*, Zhengzhou, China, April 2015.

[17] N. Krishnaraj, M. Elhoseny, E. L. Lydia, K. Shankar, and O. ALDabbas, "An efficient radix trie-based semantic visual indexing model for large-scale image retrieval in cloud environment," *Software Practice and Experience*, vol. 2021, no. 51, pp. 489–502, 2021, In press.

[18] P. Asgharifard-Sharabiani, A. Hannaneh, and M. Nikkhah-Bahrami, "Calculation of helical gear's basic parameters using COP-data acquired by optical 3D digitizer," *ARCHIVE Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science 1989–1996 (vols 203–210)*, vol. 225, no. 12, pp. 2953–2962, 2011.

[19] S. Jun, "Study on gear chamfering method based on vision measurement," in *Proceedings of the 2015 Conference on Informatization in Education, Management and Business*, Guangzhou, China, September 2015.

[20] Y. Z. Wang, Z. P. Chen, and W. Tang, "A non-contact measuring method for the parameter of standard cylindrical gear," *Modular Machine Tool & Automatic Manufacturing Technique*, no. 10, pp. 37–41, 2017.

[21] J. Han, Q. Yang, K. Zhang et al., "Compensation for cutter errors of spiral bevel gear CNC machining," *China Mechanical Engineering*, vol. 27, no. 5, pp. 569–576, 2016.

[22] Y. Ibaraki S , Ota, "A machining test to evaluate geometric erors of five-axis machine tools with its application to thermal deformation test," *Procedia CIRP*, vol. 14, pp. 323–328, 2014.

[23] K. D. Bouzakis, E. Lili, N. Michailidis et al., "Manufacturing of cylindrical gears by generating cutting processes: a critical synthesis of analysis methods," *CIRP Annals—Manufacturing Technology*, vol. 57, no. 2, pp. 676–696, 2008.

[24] Z. Lv, A. Halawani, S. Feng, Shafiq Ur Réhman, and H. Li, "Touch-less interactive augmented reality game on vision-based wearable device," *Personal and Ubiquitous Computing*, vol. 19, no. 3-4, pp. 551–567, 2015.

[25] C. Wang and G. Fang, "The research directions of cylindrical gear's surveying and mapping," *Shanxi Science & Technology*, vol. 4, pp. 53–55, 2015.

[26] H. Zhang, S. Qu, H. Li, J. Luo, and W. Xu, "A moving shadow elimination method based on fusion of multi-feature," *IEEE Access*, vol. 8, pp. 63971–63982, 2020.

[27] Z. Lv and L. Qiao, "Optimization of collaborative resource allocation for mobile edge computing," *Computer Communications*, vol. 161, pp. 19–27, 2020.