Development of Two-axis Linkage PLC Control System for Electrochemical Machining Helical Gear

YANG Si-guo, CHEN Yuan-long, YANG Wei-guo, ZHANG Quan-xi
Chuzhou Vocational and Technical College, No. 2188, Feng Le South Road, Chuzhou City, Anhui Prov., China 239000
School of Mechanical and Automotive Engineering, Hefei University of Technology No.193, Tunxi Road, Hefei City, Anhui Prov., China 230009
2849865748@qq.com, chenyuanlong@sina.com, 404259082@qq.com, zhangquanxi2013@126.com

Abstract. Without the effect of cutting force and cutting heat, electrochemical machining helical gear has the advantage of high production efficiency, good processing quality and tool cathode lossless. But the machine that based on small PLC control system does not have the function of helix interpolation, limiting the research and application of electrochemical machining helical gear. According to the principle of electrochemical machining of cylindrical helical gear, using pulse output instruction and powerful ability of floating point arithmetic of PLC, a helical gear two-axis linkage control algorithm is developed. This paper introduces the basic principle and presents a detailed derivation of algorithm formula. According to the principle and the algorithm formula, the control program is developed and the electrochemical machining of internal helical cylindrical gear is realized. Experiments show that the two-axis linkage control algorithm is stable, reliable and meet the needs of the helical gear electrochemical machining.

1. Introduction
Micro-segment helical internal gear is a new type and high-performance gear. Its tooth profile curve which consists of micro-segments is like the curve of grading arc tooth profile. As its tooth profile is complex and very difficult to machine, no mature manufacturing method has been found yet [1]. In order to solve this problem, institute of Non-traditional machining in Hefei university of technology put forward a method of electrochemical machining. Electrochemical machining is one of non-conventional machining technology. It shapes the workpiece using the machining method that based on the principles of electrochemical machining. Compared with the mechanical machining, electrochemical machining has no cutting force and cutting heat. What is more, electrochemical machining has the advantages of high production efficiency, good processing quality and tool cathode lossless [2].

Because of a series of advantages, such as strong universality, high reliability, easy programming, programmable controller (PLC) is widely used in industrial automation control. The working environment of electrochemical machining is moist, and there is corrosive gas generating during processing. That PLC control system is applied in electrochemical machining can foster strengths and circumvent weaknesses, improve the reliability, stability and adaptability [3]. However, many of the small PLC that are applied in the electrochemical machining tool such as OMRON CQM1H series and
SIEMENS S7-200 series, have no helix interpolation instruction, which limits the research and application of electrochemical machining helical gears. However, those small PLC have independent pulse output function and can complete floating point arithmetic instructions. Therefore, they can be used to develop linkage control algorithm in order to realize the helical gear machining.

DJK3150 vertical electrochemical machining tool is developed by the institute of Non-traditional machining in Hefei university of technology. In this paper, on the basis of the PLC control system, a two-axes linkage control algorithm is developed and successfully used in the micro-segment helical internal gear processing.

As shown in Figure 1, in the manufacturing process, the shaped cathode piece does a rotary motion while feeding vertically downward to the workpiece anode. It can form the tooth profile of helical gear by one-time processing.

![Figure 1. The motion diagram of electrochemical machining internal helical gear.](image_url)

1- Machine tool spindle; 2- NC rotary table; 3- Gear shaped cathode; 4- Workpiece; 5- Workbench;

2. The derivation of two-axes linkage control algorithm
The motion of electrochemical machining internal helical gears includes z-axis vertical feed movement and NC rotary table (C-axis) horizontal rotating movement. In order to ensure forming precision of the helical gear tooth surface, Z-axis and C-axis must be able to move simultaneously, in other words, two axes must have coordinate motion to fit a helical gear helix. A good control algorithm can implement high-precision linkage control. So the two axes linkage control algorithm is the key of control system.

The interpolation algorithm of the cylindrical helical gear helix is relatively mature, most of the current CNC systems have the helix interpolation function [4]. PLC, which is good at switch quantity control, cannot be compared with the special numerical control system in such aspects as floating-point data operation and position output, so the cylindrical helix interpolation algorithm cannot be directly applied in the PLC. Based on comprehensive analysis of helix interpolation of CNC system, and in combination with the motion characteristics, the craft parameter request of electrochemical machining helical gear and the existing performance of PLC control system, we decide to build two-axes linkage control platform based on PLC with the idea of data sampling interpolation. The helix track that is formed in the process of electrochemical machining internal helical gears is shown in figure 2.
Figure 2. Schematic diagram of helical gear helix fitting formation.

The starting point of the two axis movement is \( P_0 (x_0, y_0, z_0) \) and the end is \( P_e (x_e, y_e, z_e) \). After uniform feeding time \( T \), two axis with corresponding speed arrives at the point \( P_i (x_i, y_i, z_i) \). According to the cylindrical helix equation, \( P_i \) point coordinates can be expressed as:

\[
\begin{align*}
x_i & = R \cos \alpha_i \\
y_i & = R \sin \alpha_i \\
z_i & = R q \cot \beta
\end{align*}
\]  
(Eq. 1)

Where: \( \beta \) – The helix angle of micro-segment helical internal gear; 
\( R \) – The standard pitch circle radius of micro-segment helical internal gear; 
\( \alpha_i \) – After two axial feeding time \( T \), the rotation angle of C-axis relative to the starting point for \( P_0 \) in XY plane.

The formula (1) shows that in the XY plane, for every point \( (x_i, y_i) \) of circular arc line, there is a certain C-axis rotation Angle \( \alpha_i \) which correspond point \( (x_i, y_i) \). Thus, \( P_i (x_i, y_i, z_i) \) can also be expressed as \( P_i (\alpha_i, z_i) \). After the completion of processing, if the helical gear helix project to the XY plane, the corresponding NC turntable turned the arc length is \( S_{xy} \). Assuming that the helical gear tooth thickness is \( H \), the prolate helix is shown in figure 3.

Figure 3. The schematic diagram of helical gear line.

The relevant relationship is as follows:

\[
\begin{align*}
H & = S_{xy} \\
P_z & = \frac{P_{2}}{2\pi R} \\
S_{xy} & = R \alpha \\
P_{z} & = \frac{\pi d}{\tan \beta}
\end{align*}
\]  
(Eq. 2)

Where: \( \alpha \)—C-axis rotation angle (radian value);  
\( P_z \)—The helical pitch of micro-segment helical internal gear;  
\( D \) —Standard pitch diameter of micro-segment helical internal gear.

Assuming that the linear \( P_0 P_e \) in the first quadrant is machining path, as shown in figure 3, starting point coordinates is \( P_0 (\alpha_0, z_0) \), the end point coordinates is \( P_e (\alpha_e, z_e) \), \( P_i \) is the fixed point in the machining process [5]. In a feeding cycle of actual processing, the Z-axis feeding increments \( \Delta z \) is approximately equal to 2μm, and the rotation angle of C-axis is about 0.001° (described in third
section algorithm verification). Therefore, the rotation arc length $\Delta S_{xy}$ of C-axis in the XY plane can be approximated as a piece of string $^6,^7$. Spiral fitting step L can also be myopia as a line segment $\Delta L$:

$$\Delta z = \frac{\nu T}{60}$$  \hspace{1cm} (Eq. 5)
$$\Delta L = \frac{\Delta z}{\cos \beta}$$  \hspace{1cm} (Eq. 6)

Where: $\Delta z$—Within the period T, feeding increments of Z-axis;
$\nu$—The feed rate of Z-axis (mm/min).

The projection of $\Delta L$ on the XY plane is corresponded to the arc length $\Delta S_{xy}$, according to the proportional relationship, the following relations can be calculated out:

$$\frac{\Delta z}{\Delta S_{xy}} = \frac{H}{R \alpha}$$  \hspace{1cm} (Eq. 7)
$$\Delta S_{xy} = R \Delta \alpha$$  \hspace{1cm} (Eq. 8)

When the feeding speed $\nu$ of Z-axis and the feeding cycle $T$ is determined, two axis feed increment $\Delta z$, $\Delta \alpha$ can be determined according to the process parameters of helical gears, using formula (2) to (8). PLC control two motors feed $\Delta z$, $\Delta \alpha$ at the same time, so the synthesis trajectory of two axis is the hypotenuse of a right triangle whose side length is $\Delta z$ and $\Delta S_{xy}$ (shown in figure 3). And helical gear helix is composed of several such hypotenuses $\Delta L$. After the completion of a feeding cycle, the coordinates of next feed point $P_{i+1}$ is expressed as:

$$\begin{align*}
    z_{i+1} &= z_i + \Delta z \\
    \alpha_{i+1} &= \alpha_i + \Delta \alpha
\end{align*}$$  \hspace{1cm} (Eq. 9)

3. The implementation of the algorithm based on PLC

PLC control system platform: The control system adopts OMRON CQM1H PLC and pulse I/O board CQM1H - PLB21 as control core $^8$. CQM1H - PLB21 has two-way pulse input and output functions which are respectively used for the Z-axis and C-axis pulse control. At the same time, a half closed loop control is constituted by the encoder feedback. The feedback to port 1 and 2 of the high speed pulse signal is counted. Then the PLC can do interrupt handling according to the current value of the counter $^9$. Control system for the pulse input and output diagram is shown in figure 4.

Figure 4. The schematic diagram of control system of pulse input and output.

Implementation of PLC linkage algorithm: According to the data sampling interpolation theory, a time interval $t$ is determined. In time interval $t$, PLC control that the Z-axis feeding increments is $\Delta z$ and rotation angle increments of C-axis is $\Delta \alpha$. For the time interval $t$, there is an important constraints that $t$ must be more than PLC scan cycle. If $t$ is less than one scan cycle, the PLC corresponding pulse output point will have no time to refresh $^{10}$, resulting in being unable to feed. The formula (5) - (8)
show that when feeding period $T$ is determined, displacement increment $\Delta z$ can be determined according to the speed $v$ of Z-axis and $\Delta \alpha$ can also be calculated. But restricted by the size of the encoder feedback pulse equivalent, $\Delta z$ and $\Delta \alpha$ can not be less than the corresponding feedback pulse equivalent. Thus feeding time, displacement increment and feed speed should be considered synthetically. A two-axis linkage feed requires PLC output pulse number and encoder feedback number respectively is $N_1, N_2$:

$$N_z = \frac{\Delta z}{P_{mz}} \quad \text{(Eq. 10)}$$

$$N_c = \frac{\Delta \alpha}{P_{mc}} \quad \text{(Eq. 11)}$$

In the above formula, $P_{mz}, P_{mc}$ are the output pulse equivalents of Z and C-axis.

Two stepper motor operating frequency $f_z$ and $f_c$ can be determined:

$$f_z = \frac{N_z}{t} \quad \text{(Eq. 12)}$$

$$f_c = \frac{N_c}{t} \quad \text{(Eq. 13)}$$

The encoder feedback pulse number $N'_z, N'_c$:

$$N'_z = \frac{\Delta z}{P_{mz}'} \quad \text{(Eq. 14)}$$

$$N'_c = \frac{\Delta \alpha}{P_{mc}'} \quad \text{(Eq. 15)}$$

In the above formula, $P_{mz}', P_{mc}'$ are the Feedback pulse equivalent of Z and C-axis.

When a linkage feed starts, PLC first calculates the feedback pulse number which corresponds to displacement increment $\Delta z, \Delta \alpha$, then stores pulse number in the two register comparison table (CTBL instruction). And then the pulse I/O board output pulse whose frequency are $f_z, f_c$ to drive two step motor run, at the same time two comparison table are logged in. When the PLC high-speed counter 1 or 2 received feedback pulse number is equal to the number of pulses which is stored in the corresponding table, the PLC interrupt handle stop pulse output and exit the comparison table. It shows that $\Delta z$ or $\Delta \alpha$ have fed in place.

However, motor running frequency $f_z$ or $f_c$ may not be integer. PLC can round $f_z, f_c$ and give integer as a practical pulse output frequency in the processing. This will lead to two axis cannot feed strictly in place at the same time (there is a small time difference). So, in a linkage feed, two axis adopt the method of "first come, first stop". In the other words, when an axis feed in place at first, it will stop movement, waiting for the other axis feed in place. After completion of a linkage feed, PLC first calculate the next feeding point $P_{i+1}(\alpha_{i+1}, z_{i+1})$ which correspond to high counter values and store them in the register comparison table, and then start a new linkage feed.

Feedback pulse number $N'_z, N'_c$ may also not be integer, but comparison table register only store the integer parts of BCD code. So the decimal parts need to be scrapped. This leads to that the actual displacement increment may deviate from the theoretical value $\Delta z, \Delta \alpha$, thus appear the trajectory error. So in the feeding process, PLC should be able to accumulate and compare the deviation. When the cumulative deviation value is bigger than the corresponding pulse feedback, before the start of the next step, PLC add 1 to the number of feedback pulse that $\Delta z$ or $\Delta \alpha$ correspond to. Then PLC store pulse number in registers comparison table to eliminate cumulative error.

After the completion of a linkage feed, PLC judge that whether it has arrived the end. The discrimination use end point coordinates criterion. If it has arrived the end point, the feed processing will be end, otherwise return to feed again. Linkage feed flow diagram is shown in figure 5.
4. Algorithm validation

The parameters of micro-segment helical internal gear that need to be processed are: the helix angle $\beta = 25^\circ$, the gear teeth $z = 85$, the Module of gear $m = 1.15$, the thickness of the ring gear $H = 17$ mm. According to the technological requirements of electrochemical machining micro-segment helical internal gear, the feed speed of Z-axis is 0.5 mm/min and the feed time $T$ is 240 ms (Generally, $T$ is integer times of PLC maximum scan cycle). According to the formula (2) to (8), the feed equivalent of two axis $\Delta z$ and $\Delta \alpha$ are about:

\[
\begin{align*}
\Delta z &= 2 \mu m \\
\Delta \alpha &= 0.001^\circ
\end{align*}
\]

In fact, if the C-axis feed equivalent $\Delta \alpha = 0.001^\circ$, then the theoretical value of Z-axis feed equivalent $\Delta z' \approx 2.018 \mu m$, $\Delta z'$ is not equal to $\Delta z$. As the feedback pulse equivalent of the Z-axis encoder is 0.5 $\mu$m, the decimal parts must be discarded. And in fact $z = 2$ $\mu$m. When the processing complete, the angular displacement $\alpha$ that C-axis turned in the XY plane should be:

\[
\alpha = \frac{360^\circ H \sin \beta}{m z \pi}
\]

(Eq. 16)

According to the formula (16): $\alpha \approx 8.422^\circ$. The feed equivalent of C-axis is $\Delta \alpha = 0.001$, so the C-axis should feed 8422 steps. In the direction of Z-axis, processing depth is 17 mm and the feed equivalent of Z-axis is $\Delta z = 2 \mu m$, so the Z-axis feed is about 8500 steps. As a result of that Z-axis feed equivalent exist error, the total step number of Z and C-axis are not equal to each other. And with the development of linkage feeding, the error will be gradually accumulated. Therefore, after a linkage feeding, PLC compares the error and modifies the Z-axis or C-axis to ensure the machining precision of helical gear. For example, in one test process, the accumulated error $|\Delta z|$ of Z-axis is approximately equal to 0.498 $\mu$m after 27 linkage feedings, it is approximately equal to a feedback pulse equivalent of Z-axis. So, when the PLC calculates the feedback pulse number of the next point $P_{i+1}(\alpha_{i+1}, z_{i+1})$
corresponding to the Z-axis, the number will be added 1. And as a new interrupt value it will be stored in a comparison register table. In the next feeding cycle, Z-axis feeds more about 0.5μm.

Due to the limitation of hardware conditions, the feeding equivalent \( \Delta z \) and \( \Delta \alpha \) of two axes are hard to be the integer times of encoder feedback pulse equivalent at the same time. So in the manufacturing process, at least one axis need to correct its position. When the accumulation error is approximately equal to the corresponding axis feedback pulse equivalent, control system can automatically compensate in the next cycle. Therefore, in actual machining process, the maximum cumulative error of workpiece \( |\Delta z| \) in the Z-axis direction is approximately equal to the Z-axis feed equivalent \( \Delta z \). The largest deviation of C-axis \( |\Delta \alpha| \) is approximately equal to the C-axis feed equivalent \( \Delta \alpha \).

After completion of processing, micro-segment helical internal gear was measured. The results show that all of the helical gear parameters can meet the design requirements, such as root diameter, tip diameter, helix angle, machining surface roughness and so on. It proved that helical gear helix control algorithm that based on PLC is feasible and can meet the needs of the electrochemical machining helical gear. In addition, during the linkage machining, due to the influence of the PLC operating mode, there will be a pause between two feed. Theoretically, the pause time is approximately equal to a maximum scan cycle. In the test of the processing, the touch screen can monitor the PLC scan cycle, the maximum scanning process cycle is about 60 ms. As the electrochemical machining is a kind of corrosion processing, it has different degrees of corrosion to the metal material near the cathode, thereby reducing effect of the pause time. Although the pause reduces the average feed speed, the speed is constant during the linkage feeding process, and it is still the feeding speed of technical requirements. So the pause hardly has influence on machining precision of helical gear. The micro-segment helical internal gear is shown in figure 6.

![Figure 6. The internal micro-segment gear by electrochemical machining.](image)

5. Conclusion

During electrochemical machining test, the two-axis control algorithm is stable and reliable, it can meet the need of electrochemical machining micro-segment helical internal gear. Due to many factors, on the premise of ensuring accuracy, control system cannot yet reach higher feed rate. At present, small PLC that are commonly used generally have complete floating-point calculation instructions, input interrupt and high speed counter interrupt functions. Those functions are far more than the sequential control using range. What is more, they also have the characteristics such as low cost, convenient programming. Therefore, based on fully tapping the potential of PLC, we can develop economical and applicable CNC system. This method has important application value for the improvement of numerical control system of small or medium-sized manufacturing enterprises traditional machine tool.

Acknowledgments

This study has been funded by the national natural science foundation of China: mechanism and technical study of selective electrochemical etching of large scale refractory metal single crystal (Grant no. 51775161), hereby gratefully acknowledged.
References

[1] HUANG Kang, ZHAO Han, TIAN Jie. Experimental Research on Temperature Rise Comparison between Micro-segment Gear and Involute Gear[J].China Mechanical Engineering, 2006(18):80-83.

[2] ZHU Shu-min, CHEN Yuan-long. Electrochemical machining technology[M]. Bei-jing: Chemical Industry Press, 2006.9:3-58.

[3] CHEN Yuan-long, JIA Zhi-hua, HUANG Zhen-dong, WAN Sheng-mei. Development and Realization of ECM Machine Tool Control System Based on PLC[J]. Modular Machine Tool & Automatic Manufacturing Technique, 2008(7):77-80.

[4] LIAO Xiao-guo, LIU You-wu. Numeric Control Technology[M].Wuhan: Hubei science and Technology Press, 2000.

[5] ZHANG Chun-liang. Conical Helix Interpolation Algorithm Based On Time Division Method[J]. Manufacturing Technology & Machine Tool,2005 (5):52-53.

[6] REN Xi-yan.Study on Methods of PLC Linear Interpolation[J].Machine Tool & Hydraulics,2012(8):56-58.

[7] CUI Guo-dong, ZHAO Dong-biao. The Research for a Practical Spiral line Interpolation Algorithm[J]. Machinery & Electronics, 2008(12):14-16.

[8] CHEN Yuan-long, WANG Tian-ji, WAN Sheng-mei. Development of ECM Machine Tool Based on PLC and Touch Screen[J]. Electromachining & Mould, 2005(3):56-58.

[9] WANG Dong-qing. The principle and Application of OMRON CP1 series PLC[M]. Beijing: Publishing House of Electronics Industry, 2011.

[10] REN Xi-yan, TAN Xiao-dong, BAI Jie. Development and research of arc interpolation for PLC[J]. Manufacturing Automation, 2009(11):83-86.