Research on automatic detection system of encoder accuracy based on PID algorithm

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Abstract: After the encoder completes the installation and adjustment work, its accuracy needs to be checked again to confirm whether it meets the acceptance conditions. This process is usually manually operated by inspectors, and the inspection efficiency is low and there are certain manual errors. In order to improve this situation, an encoder automatic precision inspection system based on PID algorithm is designed. In this article, the working principle and structure of the detection platform are introduced in the first part, and then designs the corresponding detection software and operation interface according to its working characteristics. Finally, the platform was tested in combination with the actual detection products, and the encoder signal acquisition results were given, which further verified the accuracy and reliability of the detection device. The results showed that the accuracy detection platform can accurately and conveniently realize the error detection of the encoder’s function, and to a certain extent overcome the detection error caused by the drift of the photoelectric autocollimator during the detection process.

1. Introduction
Due to the advantages of high measurement accuracy, reliable use, and easy maintenance, photoelectric encoders are widely used in many angle measurement and control fields such as radar and CNC machine tools. In the actual production process, after the encoder has completed the assembly and adjustment work, it still needs manual operation to test its own accuracy again. Through the linkage device, the high-level reference encoder data is compared with the encoder data to be tested and the error is obtained. After the inspectors manually record the data, they use the host computer to summarize and calculate the mean square error of the encoder. This increases the cost of the detection process to a certain extent and greatly improves the error rate [1]. Starting from actual production, this paper designs an automatic detection system for encoder accuracy based on PID algorithm. By setting the detection angle interval and detection rate, the system can automatically perform detection, and the detection results and detection status will be displayed on the software interface in real time.
2. Hardware platform construction

The encoder detection platform is mainly composed of a mechanical platform and a measurement and control chassis. The platform system is a vertical shaft sleeve structure, divided into two internal and external shaft systems, which are independent of each other for movement and locking. The inner shaft system of the detection platform is composed of a high-precision precision angular contact ball bearing with a preloaded load, a drive motor, a standard encoder, an inner spindle, and an internal table. There is a conductive slip ring inside the shaft system for collecting signal transmission; The outer shaft system includes bidirectional thrust angular contact ball bearings, motors, encoders to be tested and an external table. In the outer shaft system, there are also conductive slip rings installed on the outer circular surface of the outer ring shaft. The motion range of the inner and outer shafts is continuous and unlimited, an internal shaft system, a base and a light pipe assembly. The overall system of the turntable is supported by precision mechanical bearings, a permanent magnet DC torque motor is selected as the drive device, and a built-in high-level encoder is used as an angle measurement comparison device and feedback element. High-power PWM drivers with more mature technology are used for power components. In order to meet the time response requirements of the control system, the RTX real-time expansion module developed by Ardence was selected in the design desk. RTX is currently the only pure software real-time extended subsystem in the Windows system[2]. Through this design, the control servo cycle can be controlled within 1ms, and the digital position loop PID controller algorithm and speed loop PID controller algorithm, human-computer interaction, Transition monitoring and other functions.

3. Control system

The measurement and control system is an important part of the encoder accuracy detection platform to realize the motion control function and meet the technical performance requirements. The hardware part is composed of a centralized control computer and a measurement and control chassis. It is divided into angle measurement system module, digital control system module, upper computer input/output system, motor drive control system, external communication interface system and other modules according to functional modules.

Figure 1. Physical map of measurement and control chassis

In the actual measurement, a closed-loop control system is composed of a driver, a grating, an autocollimator, and a motor to achieve precise control of the operating position of the turntable. The drive control system communicates with the host computer through the RS232 serial port.

In this design, a DC motor is used as the driving device of the turntable. The detection platform system adopts a dual closed-loop subordinate structure control method composed of a current loop and a position control loop[3]. The motor is driven by the grating angle measurement input signal connected to the motor driver to realize the motor Control, that is, there is a current inner frame plus a position
loop for position control. The mechanical stage of the detection platform feeds the turntable position signal from the angle measuring module to the driver through the circular grating, and then uses the PID algorithm to control the turntable to form a closed loop of the position of the entire system. In the detection platform system, the position loop is the main feedback loop of the system to ensure system accuracy. Another key part of the system is the current loop. The current loop is implemented inside the system driver, which can constitute the negative feedback of the armature current, which can effectively control the influence of the system power supply voltage fluctuations, improve the linearity of the control torque, and prevent the power conversion circuit and the motor overcurrent.

![Figure 2. Principle of measurement and control system](image)

4. PID algorithm adjustment

The digital PID adjustment algorithm is used in the control of the encoder accuracy detection system. The PID (proportional-integral-derivative) adjustment algorithm is widely used in the field of system control. It is characterized by the formation of a typical data feedback structure [4]. The application makes parameter setting and adjustment more convenient, and the system structure is flexible and adaptable.

The mathematical model of PID regulator is

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}$$  \hspace{1cm} (1)

Where $K_p, K_i, K_d$ are the proportional, integral and differential coefficients respectively.

The position loop algorithm is used in the system control algorithm, $e(t)$ is replaced by the value of the sampling point, integration and differentiation are realized by numerical integration and difference algorithms, using backward rectangular integral and backward difference, the obtained position expression is:

$$u(k) = K_p e(k) + K_i \sum_{j=1}^{k} e(j) + K_d \left[ e(k) - e(k-1) \right]$$  \hspace{1cm} (2)

Where:

$$K_i = \begin{cases} 
1, & |e(j)| \leq A \\
0, & |e(j)| > A 
\end{cases}$$  \hspace{1cm} (3)

A is the threshold. When there is a deviation, the integral term does not work. When the deviation is within the threshold, the integration algorithm is introduced, which can reduce the overshoot and make the integral control achieve the desired effect. Since the inertia and motor parameters of each axis of the turntable are different, the PID parameters of each axis are also different.
This design uses a position PID controller, through the differential gain to provide the damping and integral gain needed for system stability to eliminate the steady-state error, the integral gain can also select the effective area (effective for the whole process or when controlling the speed), and the speed feedforward gain is used To reduce the following error introduced by damping (the error is proportional to the speed), acceleration feedforward is used to reduce the following error caused by the inertia of the system and broaden the bandwidth of the system.

The position loop composed of the digital PID controller, the motor drive current and the PWM drive controller form the current loop, the high-precision angular position sensor signal and the PWM drive controller together form the multi-loop structure of the servo system, and the loop has a steady-state response. The characteristics of high precision and good dynamic characteristics can better meet the dynamic and static requirements of this type of turntable.

In the system, the main function of the speed loop is to reduce the motor time lag. Through the closed-loop structure, the disturbance error of the torque is reduced, and the gain and bandwidth of the system are increased. However, the bandwidth of the speed loop is limited by the system resonance frequency and the encoder sampling frequency. The correction parameters of the equivalent PID speed control loop selected based on the internal model control principle are selected as:

\[ G_{VC} = \frac{1}{\lambda} \times (15.636 + \frac{9.091}{s}) \quad (4) \]

The encoder position differential speed feedback sampling frequency of the speed loop is selected as 500Hz, the speed loop correction data update frequency is 500Hz, and the PWM update frequency is also 500Hz.

The encoder detection points collected by the system are often regarded as non-uniform sampling points. The Fourier transform processing of the collected signals is required for analysis and calculation. This requires preprocessing such as reconstruction of the collected signal points\(^5\), assuming the standard The signal generated by the encoder is fitted to \( y = s(t) \), the discrete sampling data point of the signal is \( (x_i, y_i) \), and the reconstruction error between the reconstruction function \( z = g(x_i) \) and \( y \) is \( \delta_i = g(x_i) - s(t)(i = 0,1,2...) \).

\[ \|\delta\|^2 = \sum_{i=0}^{n} \delta_i^2 = \sum_{i=0}^{n} [g(x_i) - s(t)]^2 \quad (5) \]

Assume that there is a family of linearly uncorrelated functions \( \varphi_i \) that makes \( \|\delta\|^2 \) take the
minimum value. Use the least square method to reconstruct the sampling point curve of the fitted curve:

$$\|\hat{\phi}\|^2 = \sum_{i=0}^{n} \omega_i [g(x_i) - s(t)]^2, \omega_i \geq 0 \tag{6}$$

$$g(x_i) = a_0 \phi_0(x) + a_i \phi_i(x) + \cdots + a_m \phi_m(x) \tag{7}$$

Because $\phi_i$ is a linearly independent array, when $a_i$ gets the minimum value, $\|\hat{\phi}\|^2$ can get the minimum value:

$$\frac{\partial \|\hat{\phi}\|^2}{\partial a_i} = 2 \sum_{i=0}^{n} \omega_i [a_i \phi_i(x) - s(t)] = 0 \tag{8}$$

Solve the partial derivative function to get the reconstructed coefficient and error. When the non-uniform sampling frequency meets the Nyquist frequency requirement, the non-uniform sampling can be predicted, and the sampling point curve can be analyzed through discrete Fourier transform. The reconstructed sampling point curve is composed of linear signal fundamental wave and multiple harmonics. Based on the discrete Fourier transform characteristic, the Fourier transform of the acquired signal of the encoder can be obtained by linear aliasing of a single signal curve.

5. Software operating platform

The system software design uses the RTX real-time expansion module developed by the American Ardence company. RTX is currently the only pure software real-time extension subsystem on the Windows platform. RTX does not encapsulate or modify the Windows system in any way. It implements priority-based preemptive real-time task management and scheduling by adding real-time HAL extensions to the HAL layer. RTX and Windows coexist in the same machine, without the need for traditional upper and lower computers. RTX runs on the system kernel layer. The RTSS thread of the real-time subsystem takes precedence over all Windows threads, providing precise and direct control of IRQ, I/O, and memory. Through the high-speed IPC communication and synchronization mechanism, RTX conveniently realizes high-speed real-time data exchange with Windows.

The structure of the turntable control software consists of two parts: the upper human-computer interaction interface and the bottom real-time control part. The upper layer is developed using Borland C++ Builder, and the bottom layer is developed using Microsoft Visual C++ 2005. The upper layer and the bottom layer are two relatively independent processes. They communicate by triggering "events" and exchange data through "shared memory", which can avoid mutual interference between processes and improve system reliability.
6. Experiment and analysis

In order to complete the online detection of the encoder, a detection test is designed according to the principles and methods described above. The detection system includes an encoder detection platform, a 23-bit encoder fixture, a 23-bit absolute photoelectric encoder to be tested, a measurement and control chassis and an upper computer control system. The test device is shown in the figure.

![Figure 5. Physical image of encoder detection platform](image)

Encoder automatic detection device design and selection: The angle measurement system uses HEIDENHAIN absolute angle encoder ECA4412 as the angle sensor. The measurement standard of this type of encoder is the periodic line-grating, and the grating is carved on glass or steel. The absolute position value comes from a grating code disc composed of a series of absolute codes. The position value can be obtained immediately when the encoder is powered on, without the need to rotate the shaft system to perform the reference point return operation. The photoelectric autocollimator is ULTRA-3050HR made by Tianjin Automel Optoelectronics Technology Co., Ltd., with a resolution of 0.01" and an accuracy of ±0.2" in the range.

The encoder automatic detection device needs to correct the platform itself when it is used for the first time. The prism tower error is corrected through the standard 23-sided prism and optical autocollimator to reduce the spindle rotation error during the debugging process[6]. In this process, the accuracy error value of the standard high-level encoder can be obtained through the measurement of the difference between the normal angle of the center of the adjacent working face of the 23-face prism by the photoelectric autocollimator.

After the turntable is debugged, the encoder to be tested can be fixed on the multi-size installation plane on the top of the inspection platform by screws, and the upper computer software is controlled to compensate for the internal shafting coordination error of the turntable again and start testing. After data collection is completed, through database query and comparison, the accuracy error of the encoder to be inspected can be analyzed. Compared with manual inspection, the inspection efficiency and accuracy are greatly improved.

| Num | standard value/° | Measurements/° | Difference/° | Num | standard value/° | Measurements/° | Difference/° |
|-----|------------------|----------------|--------------|-----|------------------|----------------|--------------|
| 0   | 0.00             | 359.9986       | -0.0014      | 18  | 180.00           | 179.9986       | -0.0014      |
| 1   | 10.00            | 9.9975         | -0.0025      | 19  | 190.00           | 190.0003       | 0.0003       |
| 2   | 20.00            | 19.9964        | -0.0036      | 20  | 200.00           | 199.9992       | -0.0008      |
| 3   | 30.00            | 29.9981        | -0.0019      | 21  | 210.00           | 210.0009       | 0.0009       |
| 4   | 40.00            | 39.9943        | -0.0057(mix) | 22  | 220.00           | 220.0012       | 0.0012       |
| 5   | 50.00            | 49.9960        | -0.0040      | 23  | 230.00           | 230.0029       | 0.0029(max)  |
| 6   | 60.00            | 59.9949        | -0.0051      | 24  | 240.00           | 240.0018       | 0.0018       |
| 7   | 70.00            | 69.9952        | -0.0048      | 25  | 250.00           | 250.0021       | 0.0021       |
| 8   | 80.00            | 79.9955        | -0.0045      | 26  | 260.00           | 260.0024       | 0.0024       |
|    |     |        |          |    |     |          |        |
|----|-----|--------|----------|----|-----|----------|--------|
| 9  | 90.00 | 89.9945 | -0.0055 (mix) | 27 | 270.00 | 270.0013 | 0.0013 |
| 10 | 100.00 | 99.9961 | -0.0039 | 28 | 280.00 | 280.0016 | 0.0016 |
| 11 | 110.00 | 109.9964 | -0.0036 | 29 | 290.00 | 290.0006 | 0.0006 |
| 12 | 120.00 | 119.9968 | -0.0032 | 30 | 300.00 | 300.0022 | 0.0022 |
| 13 | 130.00 | 129.9971 | -0.0029 | 31 | 310.00 | 309.9998 | -0.0002 |
| 14 | 140.00 | 139.9974 | -0.0026 | 32 | 320.00 | 320.0001 | 0.0001 |
| 15 | 150.00 | 149.9977 | -0.0023 | 33 | 330.00 | 329.9991 | -0.0009 |
| 16 | 160.00 | 159.9980 | -0.0020 | 34 | 340.00 | 339.9994 | -0.0006 |

7. Conclusion
Through the above analysis, our team confirmed that the detection system can meet the real-time and accuracy requirements of the photoelectric encoder factory inspection, and can be put into production after further system optimization and structural upgrade. In the software system algorithm, the detection platform should be further optimized and upgraded to solve the result interference caused by the fluctuation of some detection quantity values. In the structural system, it is necessary to further optimize the interference caused by the ambient temperature and noise. Therefore, there are still many difficulties to be solved for the research of the encoder detection platform system.

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