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A novel rotation speed uniformity evaluation method for the rotary laser scanning measurement system

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Abstract

For rotary laser scanning measurement systems, the rotation speed uniformity of the measurement part directly affects the system's measurement accuracy. To monitor the details of the rotation speed changes within a cycle, this paper proposes a rotation speed uniformity evaluation method for rotary laser scanning measurement systems, which can both detect the rotation speed change within a cycle and obtain the speed change with the angular position. This method is expounded in detail, including the calibration of the rotary encoder gratings, the acquisition of the real-time rotation speed change sequence, and the post-processing of the rotation speed change sequence. The feasibility of the novel processing method is verified by comparison experiments: the novel method is compared with a speed signal processing method based on measuring of rotational periodicity to verify the feasibility. The measurement accuracy of the novel method was analyzed based on the theory of uncertainty propagation. Based on the verification results, the novel method was utilized to evaluate the speed uniformity of the transmitter at different speeds and analyzes the influence of rotation speed uniformity on the angular accuracy of the system, and the experimental results reveal that the novel method is able to detect the fluctuation of the rotation speed within a circle at different speeds, and for the transmitter, the higher working speeds has less relative speed changes and less angle measurement errors.

Keywords: speed uniformity, measurement accuracy, uncertainty propagation, signal processing

(Some figures may appear in colour only in the online journal)

1. Introduction

As an indispensable part of the modern industry, precision measurement technology has been widely used in various manufacturing industries. Laser measurement technologies play a very important role in the improvement of manufacturing accuracy and efficiency [1, 2]. For rotary laser scanning measurement systems, such as the workshop measurement positioning system (wMPS) [3] and indoor GPS [4], the rotation speed uniformity of the measurement part directly affects the system's measurement accuracy. Due to the scalability of measurement range and parallel measurement ability, the wMPS has been widely promoted in the manufacturing industry [5–8]. As shown in figure 1(a), the wMPS consists of multiple transmitters, receivers, signal processors and terminal computers, which is a kind of distributed measurement system based on the principle of angle intersection. The scanning angle measurement performance of the single transmitter directly affects the system measurement accuracy. Based on the scanning angle measurement principle that is shown in figure 1(b), the rotation speed change within a cycle of the transmitter is the key factor for the scanning angle measurement.

Series of research efforts have been conducted on evaluating or improving the scanning angle measurement accuracy of this system. Limited by the existing speed signal processing methods, the evaluation methods of the rotation speed uniformity are lacking. The existing signal processing methods cannot pay attention to the fluctuation of the rotation speed within a cycle, which also limits the accuracy improvement of other rotary laser scanning measurement systems. Muelaner *et al* investigated the uncertainty of angle measurement for a rotary-laser automatic theodolite and the study provided a basis for the theoretical analysis of the angle verification [9]. Schmitt *et al* researched the performance evaluation of iGPS for industrial applications [10]. Zhao *et al* set up an integrated verification platform for verifying the angular measurement accuracy of the rotary-laser system [11]. The above methods were unable to evaluate the rotation speed change within a cycle of the transmitter. A rotation speed uniformity evaluation method is required to monitor the details of the rotation speed changes within a cycle.

This paper proposes a rotation speed uniformity evaluation method for the rotary laser scanning measurement systems, which can both detect the rotation speed change within a cycle and obtain the speed change with the angular position. The novel method comprises three steps. The first step is to calibrate the encoder gratings based on mathematical statistics. If the encoder output time interval signals are directly converted into the rotation speed signals, the scale errors and eccentricity errors will affect the evaluation of the rotation speed uniformity. With the calibration of the encoder gratings, a benchmark for evaluating speed change within a cycle is obtained. Secondly, the difference algorithm is utilized to acquire a real-time time difference sequence, which is calculated by subtracting the acquired benchmark from the real-time encoder output time signal sequence, and then a real-time rotation speed change sequence can be calculated through a series of operations. The third step is to process the rotation speed change sequence utilizing interpolation and filtering. The continuous fluctuation of the rotation speed within a cycle can be obtained, which can reflect the real-time rotation speed change with the angular position within a circle. This paper is organized as follows: section 2 introduces the specific steps of the novel method and the mathematical solution process. The experimental platform is set up and verification experiments are prepared in section 3 to verify the feasibility of the method. Section 4 utilizes the novel designed method to evaluate the speed uniformity of the transmitter at different speeds and analyzes the influence of rotation speed uniformity on the angular accuracy of the system. Finally, we present concluding remarks and potential future improvements in section 5.

2. Methods

The novel method includes the calibration of the encoder gratings, the acquisition of real-time rotation speed change sequence, and the post-processing of the rotation speed change sequence.

2.1. The calibration of the encoder gratings

For an ideal code disk, the interval of each grating is the same. As shown in figure 2, due to the eccentricity errors and scale errors, the grating distribution of the conventional encoder is uneven. The obtained time signal sequence of the encoder is also uneven while the encoder rotates at a constant speed for a cycle, which can represent the grating distribution. If this time signal sequence is directly converted into the real-time rotation speed signal sequence, the manufacturing errors of the encoder and the eccentricity errors will be introduced, which will affect the evaluation of the rotation speed change. Therefore, the calibration of the encoder gratings needs to be performed first.

The output time signal sequence representing the grating distribution can be obtained by averaging multiple measurements. With the transmitter working normally for a while, an output time signal sequence can be acquired. Suppose that the transmitter rotates $\boldsymbol{m}$ cycles and the code disk has $\boldsymbol{k}$ gratings, then the output time signal sequence can be written as

$$C(n) : \{t_{11} \quad t_{12} \quad \cdots \quad t_{1k} \quad t_{21} \quad \cdots \quad t_{m(k-1)} \quad t_{mk}\},\\ 1 \leq n \leq mk,\ n \in N^{*}.$$

Utilizing the average method, a time interval sequence $G(n)$ representing the grating distribution can be obtained, which can be utilized as a benchmark for evaluating the rotation speed changes within a cycle. The related formulas are written as:

$$\bar{t}_j = \frac{1}{m} \cdot \sum_{i=1}^{m} t_{ij}, 1 \leq j \leq k \tag{1}$$

where $\boldsymbol{j}$ represents the grating number and $\boldsymbol{i}$ represents the measuring cycles. The time interval sequence can be written as

$$G(n) = \bar{t}_n, 1 \leq n \leq k, n \in N^{*}. \tag{2}$$

$\bar{t}_n$ represents the reference time interval of the nth grating, and in the next process, the time interval sequence $G(n)$ needs to be treated as a periodic sequence so that this finite sequence can evaluate the real-time encoder output time signal sequence which can be treated as an infinite sequence.

2.2. The acquisition of the real-time rotation speed change sequence

After the calibration of the encoder gratings, the time interval sequence representing the encoder grating distribution can be acquired, which can be utilized as a benchmark for evaluating the rotation speed. During the evaluation process, a real-time encoder output time signal sequence can be obtained as the

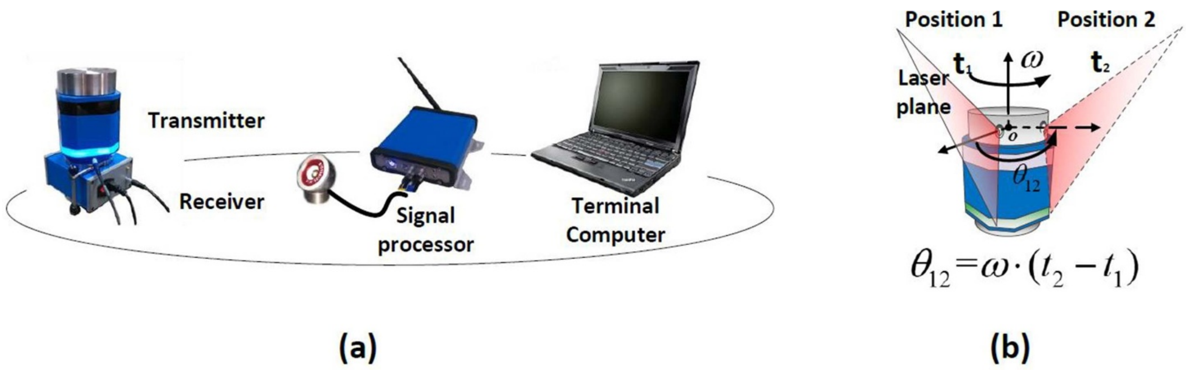

Figure 1. (a) The compositions of the workshop measurement positioning system (wMPS), (b) the angle measurement principle of the transmitter.

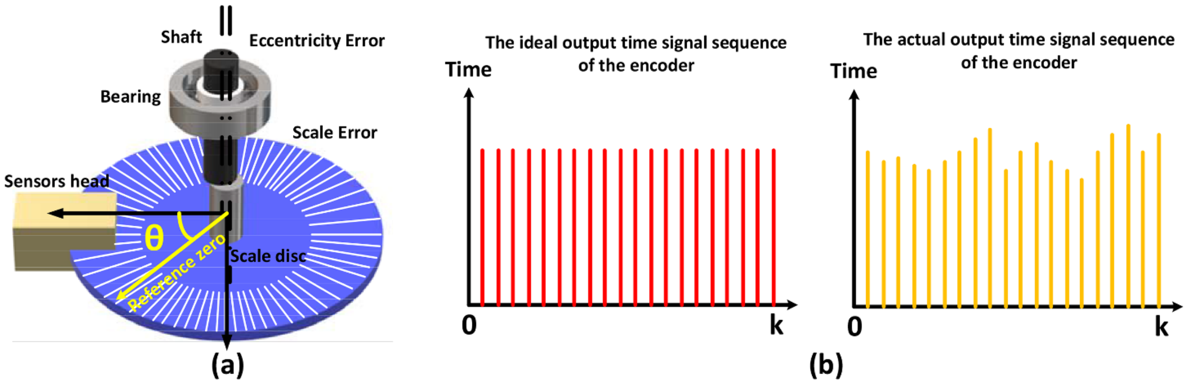

Figure 2. (a) The eccentricity errors and scale errors of the rotary encoder, (b) the effects on the output time signal sequence of the encoder due to the eccentricity errors and scale errors.

transmitter works normally. As illustrated in figure 3, utilizing the difference algorithm, a real-time time difference sequence can be calculated by subtracting the acquired benchmark from the real-time encoder output time signal sequence, and then a real-time rotation speed change sequence can be calculated through a series of operations, which can reflect the real-time rotation speed change and the correspondence between the speed change and angular position within a cycle.

The calibration process can obtain a time interval sequence representing the grating distribution, which can be written as

$$G(n)=\bar{t}_b, b=n \mod k, n\in N^*. \tag{3}$$

$\boldsymbol{k}$ represents the total number of gratings and $\bar{t}_n$ represents the reference time interval of the $\boldsymbol{n}$**th** grating. During the evaluation process, each cycle of the rotary encoder rotates, there will be $\boldsymbol{k}$ time signals and a real-time encoder output time signal sequence can be obtained, which can be expressed as $T(n)$. Utilizing the difference algorithm, the real-time encoder output time signal sequence $T(n)$ subtracts the benchmark $G(n)$ and a sequence of time difference $D(n)$ can be acquired. This method can detect the speed change with the angular position within a cycle. Take a real-time finite output time signal sequence $T_f(n)$ of the encoder within a cycle as an example. The related formulas are written as

$$\begin{cases} T_f(n):\{t_1 \quad t_2 \quad \cdots \quad t_n \quad \cdots \quad t_k\}, 1\le n\le k \\ G(n)=\bar{t}_n, 1\le n\le k \\ D(n)=d_n=t_n-\bar{t}_n, 1\le n\le k \end{cases}. \tag{4}$$

t_n represents the real-time time interval of the nth grating. and d_n represents the real-time time difference of the $\boldsymbol{n}$**th** grating, which can reflect the rotation speed change of the angular position $\frac{2\pi}{k}\cdot n$. Then, utilizing the real-time time difference sequence, a real-time rotation speed change sequence within a cycle can be obtained by a series of operations, and the related formulas are as follows:

$$\begin{aligned}\Delta\omega_n &= \omega_n-\bar{\omega}_n=\frac{1}{t_n}-\frac{1}{\bar{t}_n} \\ &= \frac{\bar{t}_n-t_n}{t_n\cdot\bar{t}_n}=\frac{-d_n}{\frac{1}{4}\cdot(t_n+\bar{t}_n)^2-\frac{1}{4}(t_n-\bar{t}_n)^2}.\end{aligned} \tag{5}$$

Due to $(t_n+\bar{t}_n)^2 \gg (t_n-\bar{t}_n)^2$, we have

$$\Delta\omega_n=\frac{-4d_n}{(t_n+\bar{t}_n)^2}. \tag{6}$$

$\Delta\omega_n$ can represent the real-time rotation speed change at the angular position $\frac{2\pi}{k}\cdot n$. Utilizing this algorithm, with the

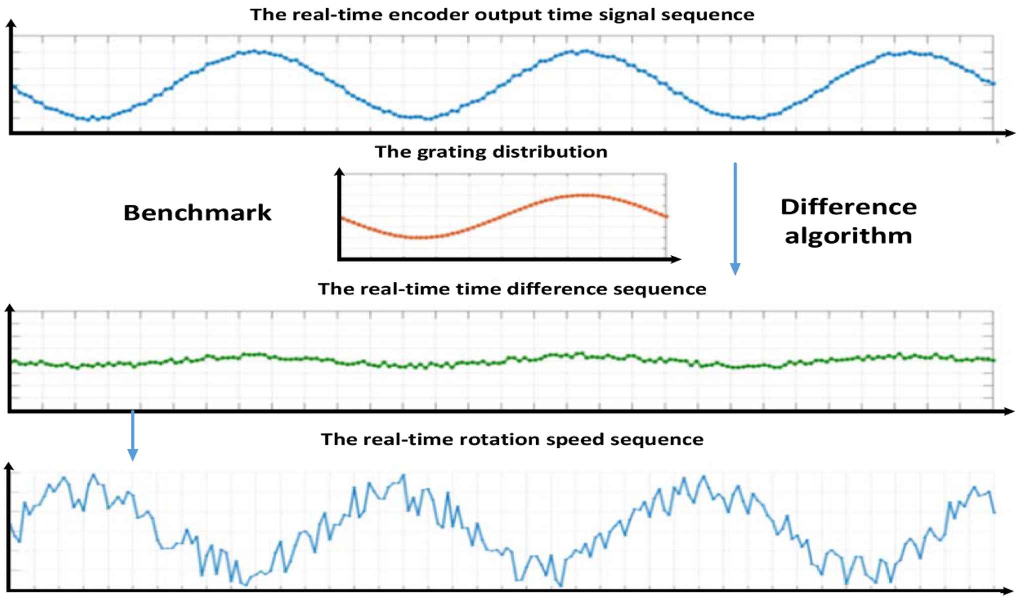

Figure 3. The schematic of the rotation speed change evaluation based on the difference algorithm.

transmitter rotating a cycle, a real-time rotation speed change sequence $\{\Delta\omega_n\}$ can be obtained, which can reflect the real-time rotation speed change and the correspondence between the speed change and angular position within a cycle.

2.3. The post-processing of the rotation speed change sequence

The real-time rotation speed change sequence acquired above is discrete. To reflect the continuous change of the rotation speed within one cycle, we utilize the linear interpolation and wavelet filtering to make it a continuous function for the rotation speed change. In the calibration process of the encoder, the distribution of the encoder gratings is obtained utilizing multiple average measurements, but the obtained encoder grating distribution still has a certain deviation from the real encoder grating distribution, which can affect the rotation speed evaluation and belongs to the periodic errors. Besides, such random errors due to the repeatability error of the reading-head and the sampling error caused by the insufficient sampling resolution of the collector also can inflect the obtained rotation speed signal. Therefore, the real-time rotation speed change sequence obtained in the detection process includes the encoder grating distribution errors and the reading errors, which can be written as

$$\begin{cases}\omega(n)=\Delta\omega_n, 1\leq n\leq k\\ \omega(n)=\omega'(n)+\sigma(n)+\varepsilon(n)\end{cases}. \tag{7}$$

$\omega'(n)$ represents the actual rotation speed change sequence, $\sigma(n)$ represents the encoder grating distribution errors and $\varepsilon(n)$ represents the reading errors of the reading-head. Utilizing wavelet filtering, the interference factors such as $\sigma(n)$ and $\varepsilon(n)$ can both be filtered out so that the actual rotation speed change sequence $\omega'(n)$ can be acquired. Then, with the linear interpolation, the sequence $\omega'(n)$ can be transformed into a continuous function $\omega'(\theta)$ of the angular position for the rotation speed change. The rotation speed change function of the angular position $\omega'(\theta)$ can evaluate the rotation speed uniformity of the rotary laser scanning measurement systems, which could both detect the rotation speed change within a cycle and obtain the speed change with the angular position.

3. Results

To verify the viability and effectiveness of the novel method, a series of comparison experiments were designed between the conventional speed signal processing method and the novel processing method. The conventional signal processing method evaluates the speed change by measuring rotational periodicity and calculating the rotation speed, which cannot reflect the correspondence between the rotation speed change and angular position within a cycle. Both the novel method and the conventional method were utilized to process the same output signal sequence of the transmitter's encoder and the results of the two methods were compared to verify the effectiveness and feasibility of the novel method. With a 1GHz sampling rate oscilloscope, the output signal sequence of the transmitter's encoder can be acquired and then be processed by a high-performance calculator with the two algorithms. For the same output signal sequence, if the detection results of the two methods are close, then verify the effectiveness and feasibility of the novel method.

The preset value of the rotation speed to be measured is 600 rpm min^{-1}. As shown in figure 4, the rotation speed change curve detected by the novel method is very close to the curve detected by the period measurement method. The novel method can reflect the speed change within a single cycle but the period measurement method cannot. The two curves are the attenuation oscillation curves with a low attenuation coefficient. Utilizing the method of periodic measurement, the

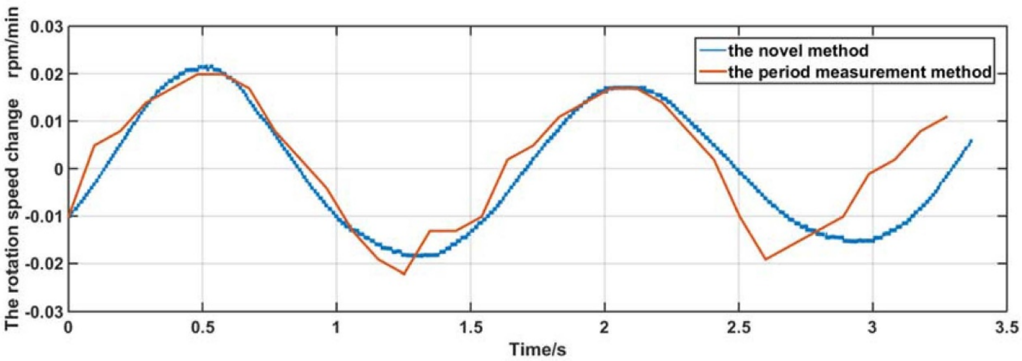

Figure 4. The detection results of the rotation speed change by the two methods.

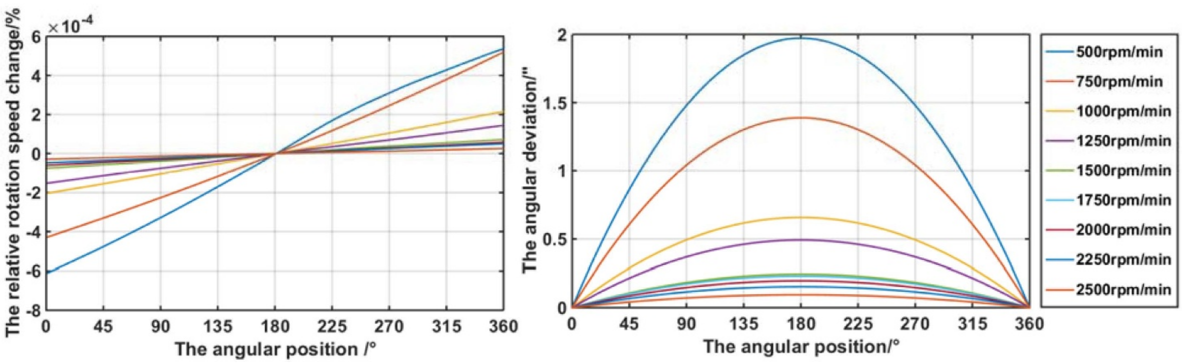

Figure 5. The evaluation results of the transmitter rotation speed change at different speeds.

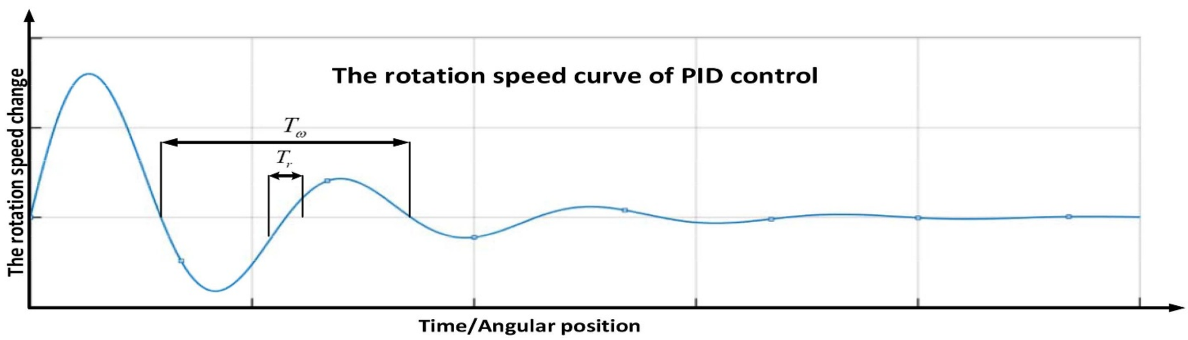

Figure 6. The rotation speed curve of PID control.

obtained speed changes are discrete and cannot reflect the speed change within a single cycle. The results of the novel method are smoother and continuous, which is consistent with the speed change trend of continuous motion. These detection results of the transmitter conform to the PID control theory. The oscillation periods of the two curves are 1.76 s, which can prove that the fluctuation in the curve is not caused by the eccentricity errors and distortion errors of the encoder. If the curve fluctuation is caused by these two types of errors, the oscillation periods of the curves will be consistent with the rotation period of the transmitter. The oscillation periods of the detection results in these two methods are much larger than the rotation period of the transmitter. So the curve fluctuation is caused by the slight change of the rotation speed. And the consistent detection results of the two methods also verified the effectiveness of the novel method.

4. Discussion

For the rotary laser scanning measurement systems, the rotation speed uniformity of the measurement part directly affects the system measurement accuracy. The novel method can both detect the rotation speed change within a cycle and obtain the speed change with the angular position. After the feasibility verification and uncertainty analysis of the novel method, a series of experiments were designed with a single transmitter, a 64-line high-precision code disk, and a high sampling rate

(1 GHz) oscilloscope. The novel method was utilized to evaluate the speed uniformity of the transmitter at different speeds, and then we analyzed the influence of rotation speed uniformity on the angular accuracy of the system. For the transmitter, the normal working speed range is from 500 rpm $\min^{-1}$ to 2500 rpm $\min^{-1}$, and the selected speeds to be evaluated included 500, 750, 1000, 1250, 1500, 1750, 2000, 2250 and 2500 rpm $\min^{-1}$. The experimental results of different rotation speeds are shown in figure 5.

As shown in figure 5, for the transmitter, the rotation speed change curves in a cycle under different speeds were all close to linear. As the rotation speed increases, the rotation speed change in a single cycle decreases. Within the working speed range of the transmitter, the higher speeds are more stable in a cycle, whose speed changes are less, and the angle measurement errors caused by the speed change in a cycle will be less. The motor of the transmitter utilizes PID control the speed, and its control curve is shown in figure 6. The relative rotation speed change is the attenuation oscillation curve. Where T_ω is the oscillation period, which is related to the damping coefficient and the electromechanical coefficient of the transmitter. T_r is the rotation period of the transmitter. With the increase of rotation speed, the rotation period decreases and $\frac{T_\omega}{T_r}$ also decreases, so the relative rotation speed change within a rotation period decreases.

Based on the angle measurement principle of the transmitter, we have

$$\theta = \omega \cdot (t_2 - t_1), \tag{8}$$

where the rotation speed is considered constant. With the novel rotation speed evaluation method, the rotation speed change within a cycle can be acquired, so that the angle error caused by the speed change can be obtained, the related formulas are as follows:

$$\varepsilon = \left|\frac{\theta' - \theta}{\theta}\right| = \left|\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} \frac{\Delta\omega}{\omega} dt\right|. \tag{9}$$

ε represents the relative angle measurement error of the transmitter and $\frac{\Delta\omega}{\omega}$ represents the relative rotation speed change. There is still a problem to be solved here, namely the rotation speed change $\Delta\omega_n$ is actually not the real-time rotation speed change at time t_n and it represents the rotation speed change near time t_n. As defined in equations (5) and (6), ω_n is the average speed for the entire time interval t_n and approximately equal to the instantaneous speed at time $t_{n/2}$ where $t_{n/2}$ represents the midpoint of the time interval t_n. It is necessary to change the time t_1 to t_2 into the time t_1' to t_2', where t_1' represents the midpoint of time interval t_1 and t_2' represents the midpoint of time interval t_2. So equation (12) should be corrected to the following equation which can be written as

$$\varepsilon = \left|\frac{\theta' - \theta}{\theta}\right| = \left|\frac{1}{t'_2 - t'_1} \cdot \int_{t'_1}^{t'_2} \frac{\Delta\omega}{\omega} dt\right|. \tag{10}$$

Based on the angle measurement principle of the transmitter, utilizing simulation calculations, the angle measurement error distribution within a cycle caused by speed fluctuations at different speeds are obtained. As shown in figure 5, the higher the working speed for the transmitter, the less the relative speed change and the less relative the angle measurement error. In the actual measurement process, the transmitter at a higher speed usually has a smaller measurement error than the one at a lower speed, which can verify the simulation results. At the rotation speed of 500 rpm $\min^{-1}$, the angle measurement error due to the rotation speed fluctuation is the largest when the angular position is 180 degrees, which is 1.97". For the other speeds, the largest angle measurement error also appears at 180 degrees. However, the method to improve the angle measurement accuracy based on the measurement of the rotation speed fluctuation is still being explored because in the actual measurement process of the transmitter, the accuracy of a single measurement can reach 9", which includes many factors such as errors caused by speed fluctuations and receiver timing errors, so it is still necessary to continue to explore new methods.

For the transmitter, a higher rotation speed can not only improve the uniformity of the rotation speed in a cycle but also increase the accuracy of the system's dynamic measurement. However, as the working speed of the transmitter increases, the mechanical structure requirements of the transmitter also increase. The novel method can both detect the rotation speed change within a cycle and obtain the speed change with the angular position. With this method, we can evaluate the rotation speed uniformity of the transmitter, which is the measurement unit of the rotary laser scanning measurement system. Under low speeds, the rotation speed changes were greater and the angle measurement errors were greater. The high rotation speeds had less relative speed changes and less angle measurement errors, which were more suitable for the angle measurement of the transmitter.

5. Conclusion

To monitor the details of the rotation speed changes within a cycle, this paper proposed a rotation speed uniformity evaluation method for rotary laser scanning measurement systems, which could both detect the rotation speed change within a cycle and obtain the speed change with the angular position. The proposed method comprises the calibration of the rotary encoder gratings, the acquisition of the real-time rotation speed change sequence, and the post-processing of the rotation speed change sequence. The experimental platforms were set up and verification experiments were designed to verify the feasibility of the proposed method. With the theory of uncertainty propagation, the speed fluctuation evaluation uncertainty of this method was acquired. The proposed method was utilized to evaluate the speed uniformity of the transmitter at different speeds, and experimental results revealed the proposed method was able to detect the fluctuation of the rotation speed within a circle at different speeds, and for the transmitter, the higher working speeds had less relative speed changes and less angle measurement errors. For the rotary laser scanning measurement systems, the fluctuation of the rotation speed within a cycle has a great influence on the angle measurement accuracy. How to improve the measurement accuracy of rotary laser scanning measurement systems based on the detection results of this method still needs to be explored.

However, for the proposed method, there are still some issues that need to be improved. In the calibration of the rotary encoder gratings, the distortion of the code disc cannot be eliminated, and due to the sampling rate of the selected data collector, the higher the speed, the less line encoder that can be used, and the fewer details of the rotation speed that can be reflected. It is necessary to propose novel evaluation methods that are suitable for the high rotation speed and can monitor more details of the speed change at high speed.

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