Roll angle measurement with a large range based on the photoelectronic autocollimator*

LI Wen-jie (李文杰)[1,2], **MU Quan-quan** (穆全全)[1], **WANG Shao-xin** (王少鑫)[1]**, **WANG Hai-ping** (王海萍)[1], **YANG Cheng-liang** (杨程亮)[1], **CAO Zhao-liang** (曹召良)[1], **and XUAN Li** (宣丽)[1]

1. State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

2. University of Chinese Academy of Science, Beijing 100039, China

(Received 25 October 2015)

In this paper, we propose a roll angle measurement method with a large range based on the photoelectronic autocollimator. According to the corresponding relationship between the rotation position of the measured shaft and the spot position on the circular trajectory, the roll angle is calculated quickly and conveniently using a simple algorithm. Only a mirror, a coupler and a fine shaft are contained in the measurement system besides the photoelectronic autocollimator. Aiming at the terrible measurement error induced by the axis wobbly error, two measurement schemes are proposed, which are linking the fine precision shaft to the measured shaft for reducing the axis wobbly error and using the segment measurement to enlarge the radius of the circular trajectory. The experimental results show that the measurement error is decreased by ±0.38°. The roll angle error of the mechanism is ±0.14°, and the measurement precision is about ±2′. The proposed method can be widely used in the engineering fields.

Document code: A **Article ID:** 1673-1905(2016)01-0074-3

DOI 10.1007/s11801-016-5213-4

There are many methods to measure the roll angle, mainly including the mechanical methods, electromagnetic methods, optical methods and photoelectronic methods[1-6]. As the development of the charge coupled devices (CCD) and the computer technology, the photoelectronic methods become more and more popular. Yafeng Li et al[7] used a single CCD and collimated beams to measure the roll angle conveniently. However, its measurement precision is limited by the area of the CCD panel and the calculation precision of the spot centroid. Although Yong Lv et al[8] used two CCDs to enlarge the distance between the spots and improve the measurement precision, the measurement errors induced by the pitch and yaw angles should not be ignored in the measurement process. Wenxia Hao et al[9] compensented the measurement error induced by the pitch and yaw angles using three CCDs to measure the roll angle, but its optical layout is complicated, and the measurement precision also depends on the calculation precision of the spot centroid.

Photoelectronic autocollimtor is the eqiupment containing the CCD and collimated beams. It can calculate the spot centroid precisely and mesure the angle change conviniently based on the spot position. The advantages of fine accuracy, simple sructure and high adaption to the environment make it popular in many engineering fields[10-12]. However, using two-dimentional autocollimator is only good at measuring the pitch and yaw angles, but is difficult to measure the roll angle. In this paper, we propose a roll angle measurement method with a large range based on the photoelectronic autocollimator. The theoretical analyses of the proposed method are introduced, and the demonstration experiment is performed.

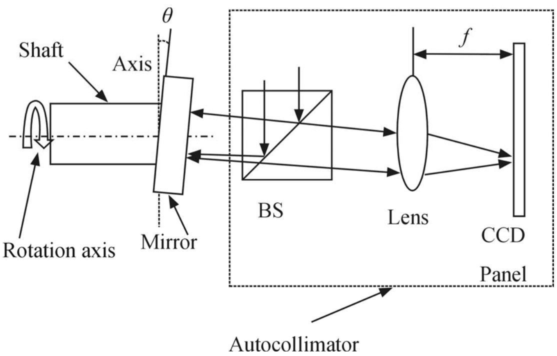
Fig.1 illustrates the measurement principle of the large range roll angle based on the photoelectronic autocollimator. As shown in Fig.1(a), the photoelectronic autocollimator is composed of CCD, convergent lens, beam splitter (BS) and parallel light source. A mirror is fixed on the end of the shaft and tilts an angle θ to the rotation axis, which ensures the beam emitted by the photoelectronic autocollimator is deflected to its optical axis and received again by the photoelectronic autocollimator. When the mirror rotates with the shaft, the reflected beam of the mirror rotates around the rotation axis. The whole process is similar with that the light emitted by spot source is converged by the lens after passing a block, which will form a circular trajectory on the reticle, as shown in Fig.1(b). According to the corresponding relationship between the rotation position of the shaft and the spot position on the CCD panel of the photoelectronic autocollimator, the roll angle is calculated quickly and conveniently. Supposing a and b are the spot positions on the circular trajectory and o is the centre, the roll angle of

* This work has been supported by the National Natural Science Foundation of China (Nos.11174274, 11174279, 61205021 and 11204299).

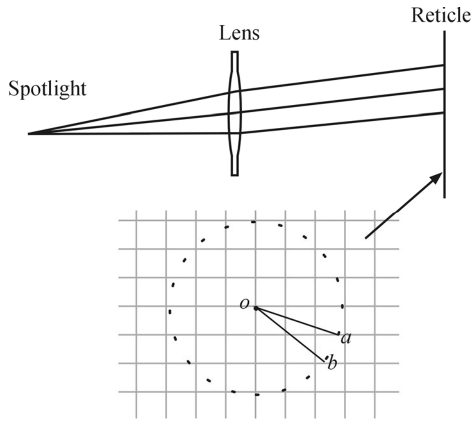
** E-mail: wangshaoxin@ciomp.ac.cn

the shaft can be given as

$$\delta_i = \cos^{-1} < \overrightarrow{oa}, \overrightarrow{ob} >= \cos^{-1} \left(\frac{\overrightarrow{oa} \cdot \overrightarrow{ob}}{\left| \overrightarrow{oa} \right| \left| \overrightarrow{ob} \right|} \right) . \quad (1)$$



(a) Inner structure of the photoelectronic autocollimator



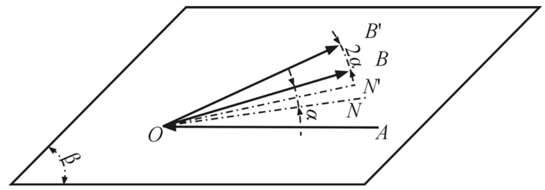
(b) The circular trajectory of the spot movement

Fig.1 Roll angle measurement principle

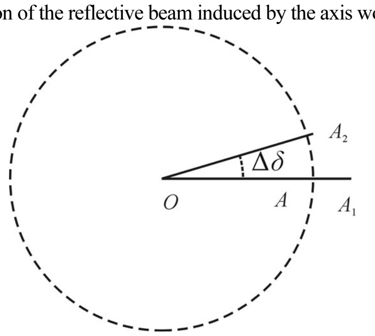
However, suffered from the machining error of the parts, installation error of the mechanism and clearance of the bearing, the rotation axis is wobbly when the shaft rotates, which leads to the spot deviation and results in the measurement error in the end. As shown in Fig.2(a), the plane β is composed of the incident light *AO* and the mirror normal *ON*. *OB* is the reflective light without the effect of the axis wobbly error. If the component of the axis wobbly error in the plane β is α, it will make the mirror normal deviating from *ON* to *ON*' with angle α, which results in the deviation of the reflective beam with angle 2α, deviating from *OB* to *OB*'. In this case, the spot on the CCD panel will deviate from A to A_1 radially with angular distance 2α, as shown in Fig.2(b). Similarly, the component of the axis wobbly error in the plane perpendicular to the plane β will make the spot deviates from A to A_2 tangentially. Obviously, the spot tangential deviation affects the measurement precision of the proposed method. The measurement error induced by the wobbly error can be given as

$$\Delta\delta = \frac{D_{\mathrm{T}}}{R} \times \frac{180}{\pi} \quad , \quad (2)$$

where D_{T} is the tangential deviation induced by the axis wobbly error, and R is the radius of the circular trajectory. As to the common mechanism, the range of the axis wobbly error is from several arcseconds to tens of arcseconds, which indicates that the measurement error induced by the axis wobbly error is too large to be ignored considering the radius of the circular trajectory (about 1 500″).



(a) The deviation of the reflective beam induced by the axis wobbly error



(b) The spot deviation induced by the axis wobbly error

Fig.2 Analyses of the measurement error induced by the axis wobbly error

According to Eq.(2), to decrease the measurement error induced by the axis wobbly error, we should reduce the axis wobbly error of the shaft fixing the mirror or enlarging the radius of the circular trajectory. As shown in Fig.3, the measured shaft is connected with the fine rotation shaft whose axis wobbly error is small. The mirror is fixed on the end of the fine rotation shaft, which ensures the spot deviation induced by the axis wobbly error is small enough. In the second measurement, the method of segmented measurements is used to enlarge the radius of the circular trajectory.

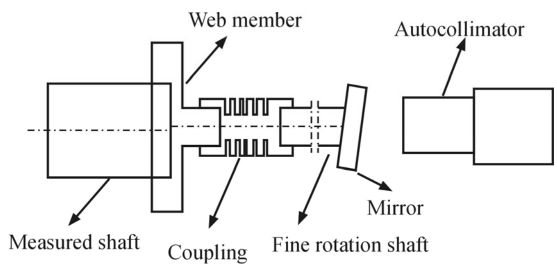


Fig.3 The improved measurement system conneting the measured shaft to the fine rotation shaft for decreasing the measurement error induced by the axis wobbly error

In order to verify the advantage of the proposed method, the compared experiments based on a bevel gear mechanism are performed using the original method presented in Fig.1(a) and the improved methods presented in Fig.3, respectively. The roll angle can be expressed as

$$\delta_i = \delta_{\text{mean}} + \Delta\delta_i \,, \tag{3}$$

where δ_{mean} is the mean value of the shaft roll angle during the measurement process, and $\Delta\delta_i$ is the fluctuation errors relative to the mean value. The maximum fluctuation error is the roll angle error of the mechanism. As shown in Fig.4(a), the roll angle errors of the bevel gear mechanism in the original and improved methods are ±0.52° and ±0.14°, respectively. Compared with the original method, the measurement error is decreased by ±0.38°, and the distribution of fluctuation errors gotten by the improved method is very close to the random distribution, which indicates that the measurement result can express the true behavior of the mechanism basically.

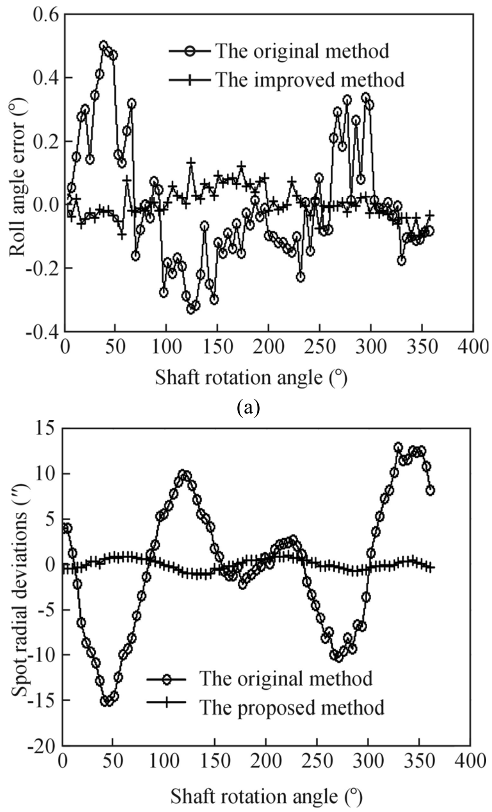


Fig.4 (a) The fluctuation errors of the rotation angle and (b) the spot radial deviation in two methods

Excepting the axis wobbly error, the spot tangential deviation depends on the transient transmission ratio of the bevel gear mechanism, while the spot radial deviation is only related to the axis wobbly error. So the spot radial deviation is used to analyze the measurement error induced by the axis wobbly error during the measurement process. As shown in Fig.4(b), the spot radial deviations in two methods are about ±16″ and ±1.3″, respectively. Paying attention to the force analysis in the bevel gear mechanism, the spot tangential deviation induced by the axis wobbly error is less than the spot radial deviation. Based on the method of segmented measurements, the radius of the spot circular trajectory comes up to 2 000″, which indicates that the measurement error induced by the axis wobbly error is less than ±2′.

Based on the photoelectronic autocollimator, a measurement method of the roll angle is proposed. It can measure the roll angle with a large range. Only a mirror, a coupling and a fine shaft are contained besides the photoelectronic autocollimator. In order to reduce the measurement error induced by the axis wobbly error, the fine rotation shaft is introduced, and the measurement of enlarging the radius of the spot circular trajectory is adopted. In the compared experiments, the roll angle errors of the mechanism gotten by the original and the improved methods are ±0.52°and ±0.14°, respectively. The measurement error is decreased by ±0.38°, and the measurement error induced by the axis wobbly error is about ±2′ in the experiment. The proposed method of the roll angle measurement can be widely used in the engineering fields.

Although the measurement error induced by the axis wobbly error is suppressed significantly, the residual spot deviation still affects the measurement precision. So looking for a method to eliminate the effect of the axis wobbly error on the measurement precision completely is the focus of our next work.

References

[1] H. Dong, Q. Fu, X. Zhao, Q. Quan and R. Zhang, Applied Optics **54**, 425 (2015).

[2] H.-T. Sun, H.-J. Sheng and W.-F. Liu, Optical Engineering **54**, 026104 (2015).

[3] J. Jin, L. Zhao and S. Xu, Journal of the Optical Society of America A **31**, 1401 (2014).

[4] HUANG Xiang-dong, YU Wen-bo and TAN Jiu-bin, Journal of Optoelectronics·Laser **25**, 299 (2014). (in Chinese)

[5] WANG He-shun, CHEN Ci-chang and HUANG Wei-gong, Journal of Optoelectronics·Laser **21**, 63 (2010). (in Chinese)

[6] SUN Bo, ZHU Ji-gui, REN Yu, GUO Yin and YANG Xue-you, Journal of Optoelectronics·Laser **25**, 311 (2014). (in Chinese)

[7] LI Ya-feng and LYU Yong, Journal of Beijing Information Science and Technology University **28**, 64 (2013). (in Chinese)

[8] LV Yong, SUN Peng, LIU Lishuang, GEN Rui, HAO Wenxia and MA Bin, Optical Technique **39**, 477 (2013). (in Chinese)

[9] HAO Wen-xia, LV Yong, LI Xiao-ying, CHEN Qing-shan, GENG Rui and ZHANG Ming-zhu, Journal of Applied Optics **35**, 281 (2014). (in Chinese)

[10] Y. Gao, X. Wang, C. Hu, Z. Huang and D. Zhan, Chinese Optics Letters **12**, 080401. (2014).

[11] M. Gao, Z. Dong, Z. Bian, Q. Ye, Z. Fang and R. Zhai, Chinese Optics Letters **9**, 091201 (2011).

[12] I. A. Konyakhin and T. V. Turgalieva, Journal of Optical Technology **80**, 772 (2013).