Research on angle setting error of diameter measurement based on laser displacement sensors

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Abstract: The diameter and roundness measurement of ring workpieces based on the laser displacement sensors is widely used in the measuring process of the product quality in the industrial site. The effect of angle setting errors of laser displacement sensors on the measurement of the workpiece's diameter was studied, and the calibration method of them was proposed. Firstly, the relationship between angle setting errors of displacement sensors and calculated errors of the diameter was analyzed quantitatively. Secondly, a calibration method was proposed, which could calculate the angle setting errors of the sensors in accordance with the measurement data of three displacement sensors, and the diameter of the standard circle was unknown. The modeling process of the calibration method was illustrated and the effectiveness of the method through simulations was confirmed. Finally, the angle setting errors were calibrated by using coordinate measuring machine. The experiment result shows that the absolute errors of diameter are improved from 20 μm to 1.5 μm after calibration.

Key words: angle setting error; diameter measurement; laser displacement sensor; least squares method

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基于激光位移传感器圆径测量的角度安装误差研究

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摘　要：基于激光位移传感器的工件圆径和圆度测量被广泛应用于工业现场的产品质量检测过程中。文中研究了激光位移传感器的角度安装误差对工件圆径测量结果的影响，并提出校准方法。首先，将定量分析位移传感器的角度安装误差与计算得到的圆径结果的误差之间的关系。其次，提出了一种位移传感器角度安装误差校准方法，该方法可在标准圆圆径未知的情况下，根据不同位置下的 3 个位移传感器的测量值，精确计算出传感器的角度安装误差。详细说明了该校准方法的建模过程，通过仿真确认角度安装误差校准方法的有效性。最后，利用三坐标测量仪对角度安装误差进行校准。实验结果表明，校准后的圆径测量误差从 20 μm 提高到 1.5 μm。

关键词：角度安装误差；　圆径测量；　激光位移传感器；　最小二乘法

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0 Introduction

It is always an important subject that the accurate measurement of key parameters in fields of manufacturing. The measuring accuracy of the outer diameter directly determines the assemble efficiency and products' quality[1]. The diameter is traditionally performed by micrometer, caliper gauge, and other telescopic mechanical tools[2−3]. In addition, the coordinate measuring machine (CMM) can undertake the dimension measurement tasks due to its high measurement accuracy and advanced technology[4−6]. However, the costs and measurement efficiency restricts the wide use of coordinate measuring machine[7]. To meet these requirements, the laser measurement plays is applied in the field of non-contact measurement due to its high precision and convenience[8].

In the numerous method of diameter measurement methods, the three-point method is widely applied in the precision machining because of the high accuracy and small errors, which is one of the important technical components of the manufacturing industry[9]. Aoki Yasuo first proposed the separation technique of roundness errors by in 1966. Basing on the frequency domain method of Fourier transform, the algorithm invloved a disadvantage of the loss of frequency components that the transfer function's denominator is zero[10−11]. A three-point method of three parallel displacement sensors was proposed by Hong Maisheng and he developed a algorithm which separate roundness errors and rotation errors successfully[12−13]. But the problem of haemonic suppression was not solved because of the angle setting errors. And in the percision measurement of diameters, little error can cause enormous deviation. So the angle setting errors has to be calibrated before measurement.

This paper studies a new model which is about angle setting errors of the diameter measurement based on three-point method, including the calibration and the experiment. According to the principle of a settled circle which is determined by three points not on the same straight line, we developed an outer diameter measuring system with three laser displacement sensors. The sensor is based on the laser triangulation method, which mainly uses the reflected and scattered beams of laser to accept the information of the target surface or distances between different targets[14], which is widely used in the measurement of length and distance in industry[15]. As for the three-point method, we do the simulation about angle setting errors and study their influences. Finally, we design and assemble the experimental device to confirm the effectiveness of the calibration. The main purposes of this paper are to put forward a scheme of calibration based on the least squares and the iterative method and to calibrate the angle setting errors. After the calibration, the outer diameter measurement device can independently measure the workpiece and extremely increase the accuracy of measurement.

1 Principle of measurement based on three-point method

The basic principle of three-point method is to set the three sensors at a fixed angle, such as 120°. The measurement axes of sensors intersect at one point. Then we can build the *XOY* coordinate system by taking the point as origin and get multiple sets of measurements when rotating the workpiece. At last, we calculate the diameter according to the coordinates of the three points on the circle. Figure1 illustrates the three-point method without considerations of the angle setting errors. Three sensors are 120° apart from each other along the measurement axis. O is the origin and P is the center of the circle. S is the rotation center of each displacement sensor. The coordinates of A, B and C (A_x, A_y, B_x, B_y, C_x, C_y) can be determined according to the measurements m_1, m_2 and m_3. Lastly, we can figure up the diameter and the position of P through the coordinates.

The calculation formula is as follows:

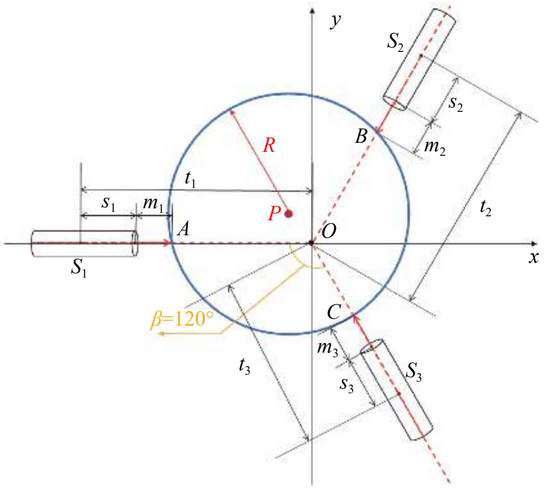

Fig.1 Three-point method without angel setting errors

$$\begin{cases} A_x = -(t_1 - s_1 - m_1), A_y = 0 \\ B_x = \dfrac{1}{2}(t_2 - s_2 - m_2), B_y = \dfrac{\sqrt{3}}{2}(t_2 - s_2 - m_2) \\ C_x = \dfrac{1}{2}(t_3 - s_3 - m_3), C_y = -\dfrac{\sqrt{3}}{2}(t_3 - s_3 - m_3) \end{cases} \tag{1}$$

As we can see from the Fig.1, s_1,s_2 and s_3 are the distances of the rotation center to the origin, t_1, t_2 and t_3 are the distances of the rotation center to the front end. s and t are never changed when the positions of sensors are settled. The radius r can be obtained by Eq.(2).

$$\begin{cases} (P_x - A_x)^2 + (P_y - A_y)^2 = r^2 \\ (P_x - B_x)^2 + (P_y - B_y)^2 = r^2 \\ (P_x - C_x)^2 + (P_y - C_y)^2 = r^2 \end{cases} \tag{2}$$

Figure 2 shows the three-point method with considerations of angel setting errors. In this model, we think that there exist one fixed point in each sensor and the probe will occur a small deflection around the point. The sensor turns around point S, which means the center of rotation in the measurement. This is the theoretical basis of the calibration and simulation.

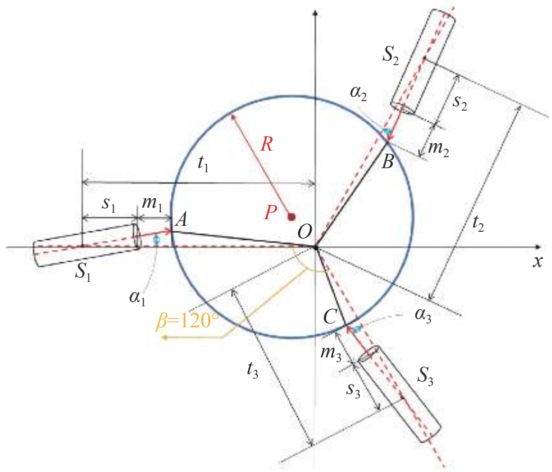

Fig.2 Three-point method with angel setting errors

2 Principle of the calibration based on the least squares and iterative method

It is known from the principle of three-point method that the position of origin O is determined by rotation centers of three sensors. The positions of sensors are never changed and the aims of the measurements are to examine different workpieces' diameters when we do the work in reality. So the position of O is settled by sensors and without errors. In addition, the fixed parameters are the distance s from the rotation center to the zero point of measurement, the distance t between O and S, and the angle setting error α in the model. The three parameters can be named as systemic parameters. And s and α are unknown to be calibrated. The measured value m and the position of circle are changed between different measurements. Therefore, sensors' values $\boldsymbol{m}$ are the input; the output are coordinates of centers ($\boldsymbol{P_1}$, $\boldsymbol{P_2}$) and the radius $\boldsymbol{r}$ in the whole system. γ is the angle that after rotations. The specific relationship of the parameters can be calculated by Eq.(2) and (3):

$$\begin{cases} A_x = -[t_1 - (s_1 + m_1)]\cos\gamma_1, A_y = (s_1 + m_1)\sin\gamma_1 \\ B_x = [t_2 - (s_2 + m_2)]\cos\gamma_2, B_y = (t_2 - s_2 - m_2)\sin\gamma_2 \\ C_x = [t_3 - (s_3 + m_3)]\cos\gamma_3, C_y = -[t_3 - (s_3 + m_3)]\sin\gamma_3 \end{cases} \tag{3}$$

Due to the nonlinearity of the equations, that we cannot get the analytical expression. Then we choose to use the least squares and the lterative method to do the calibration. Solving the Eq.(3), the forward kinematic solution $\boldsymbol{P}$, the position of the workpiece and the radius in the coordinate system, is given by:

$$\boldsymbol{P} = F(\boldsymbol{M}, \boldsymbol{S}) \tag{4}$$

where $\boldsymbol{M}$ is the measured values and $\boldsymbol{S}$ is the systemic parameter vector as follows:

$$\boldsymbol{S} = [s_1\ s_2\ s_3\ \alpha_1\ \alpha_2\ \alpha_3]^{\mathrm{T}} \tag{5}$$

When we measure the workpiece m times, the observation equations vector is given by:

$$\boldsymbol{R}=\left\{\begin{array}{c} C[F(\boldsymbol{M}_1,\boldsymbol{S})] \\ \vdots \\ C[F(\boldsymbol{M}_j,\boldsymbol{S})] \\ \vdots \\ C[F(\boldsymbol{M}_m,\boldsymbol{S})] \end{array}\right\} \tag{6}$$

where $\boldsymbol{R}$ is the function vector of the forward solution $F(\boldsymbol{M}, \boldsymbol{S})$ and $\boldsymbol{M}_j$ is the measured value at the jth measurement.

The the least squares solution of systemic parameter by the lterative method is as follows:

$$\boldsymbol{S}_{\rm new}=\boldsymbol{S}_{\rm old}+(\boldsymbol{J}^{\rm T}\boldsymbol{W}^{-1}\boldsymbol{J})^{-1}\boldsymbol{J}^{\rm T}\boldsymbol{W}^{-1}\boldsymbol{R} \tag{7}$$

Where the Jacobian matrix $\boldsymbol{J}$ is

$$\boldsymbol{J}=\begin{bmatrix} \dfrac{\partial \boldsymbol{R}_1}{\partial s_1} & \dfrac{\partial \boldsymbol{R}_1}{\partial s_2} & \dfrac{\partial \boldsymbol{R}_1}{\partial s_3} & \dfrac{\partial \boldsymbol{R}_1}{\partial \alpha_1} & \dfrac{\partial \boldsymbol{R}_1}{\partial \alpha_2} & \dfrac{\partial \boldsymbol{R}_1}{\partial \alpha_3} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \dfrac{\partial \boldsymbol{R}_m}{\partial s_1} & \dfrac{\partial \boldsymbol{R}_m}{\partial s_2} & \dfrac{\partial \boldsymbol{R}_m}{\partial s_3} & \dfrac{\partial \boldsymbol{R}_m}{\partial \alpha_1} & \dfrac{\partial \boldsymbol{R}_m}{\partial \alpha_2} & \dfrac{\partial \boldsymbol{R}_m}{\partial \alpha_3} \end{bmatrix} \tag{8}$$

And the error matrix $\boldsymbol{W}$ is

$$W_{ij}=\left\{\begin{array}{ll} \sigma_{\boldsymbol{R}}^2+\sigma_M^2\sum\limits_{k=1}^{m}\left(\dfrac{\partial \boldsymbol{R}_i}{\partial \boldsymbol{M}_k}\right)^2, & i=j \\ 0, & i\neq j \end{array}\right. \tag{9}$$

where σ_R is the standard deviation of radius error and σ_M is the standard deviation of measured value of sensors. After several iterations, we can obtain the stable systemic parameters.

3 Simulation of the measuring system

To verify the accuracy of this calibration method, simulations are performed with the measuring model by Matlab. The simulation about the radius errors caused by angle setting errors is implemented to ensure the necessity of calibrations.

3.1 Simulation about the angle setting errors

The whole simulation can be divided into three processes. Firstly, we get the measured value m by setting the radius, the position of the center P and the distance from the rotation center to the front end of sensors. In general, the position accuracy of the workpiece can be controlled within 30 μm. Therefore, we settle the length of OP to vary from 0 to 30 μm. Secondly, the calculated radius can be obtained by the measured value through the model of Fig.1. Finally, we select the range of calculated value and the settled radius as the evaluation of the influence caused by angle setting error.

Table 1 is the result of differences of radius when angle setting errors range from 0.5° to 3.0°. In this simulation, the settled radius is 20 mm and the distance from the rotation center to the measuring zero point of sensors is 15 mm. It can be found that the radius error can reach 8 μm, which can not be ignored.

Tab.1 Max radius difference with angle errors

Angle error/(°)	Fixed distance/mm	Radius error/μm
0.5	15	0.483
1.0	15	1.789
1.5	15	3.234
2.0	15	4.759
2.5	15	6.374
3.0	15	8.124

3.2 Simulation of the systemic parameters

It is known from the calibration principle that the initial value of systemic parameters plays an important role in the accuracy of calibration. The flow chart of the simulation is as follows (Fig.3).

In this simulation process, we do the calibration of

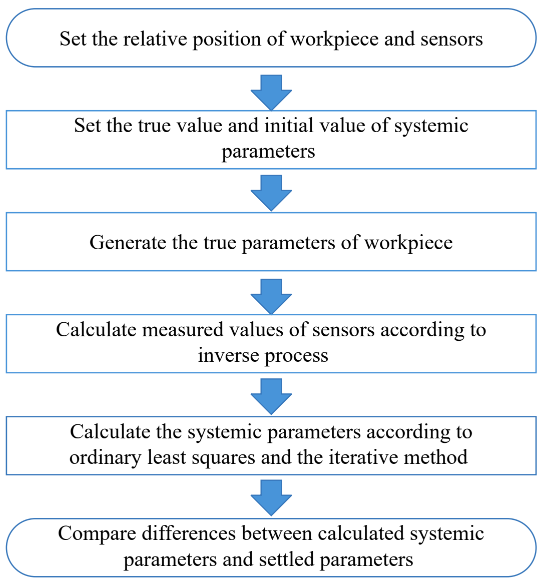

Fig.3 Flow chart of calibration

systemic parameters without noise of measurement value firstly. The truth of radius is set as 20 mm and *t* of three sensors' are respectively are 30 mm, 29.8 mm, 30.2 mm. Ten standard circle positions are chosen in each group simulation, so 10 groups of circle centers' coordinates can be obtained from this. Afterwards, the sensor measurement value is obtained through the inverse calculation process. The pre-parameters required for the calibration have been determined so far.

Next we take one of the calibrations as an example. The data in Tab. respectively are the design value (initial value), true value, and calibrated value of the systemic parameters. The error between calibrated value and true value is shown in the fifth column of Tab.2. It is known that the absolute error of distance diameter has reached the level of nanometer. For the angle error parameter, it can also reach 10^{-6} rad orders of magnitude. In summary, the method proposed in this paper yields high accuracy of systemic parameters.

Tab.2 Simulation results of systemic parameters

Systemic parameters	Designed value	True value	Calibrated value	Absolute error
s_1/mm	15	15.3039	15.3039065	0.0000065
s_2/mm	15	14.6943	14.6943028	0.0000028
s_3/mm	15	15.2077	15.2076977	0.0000013
α_1/(°)	1	1.05	1.0503227	0.0003227
α_2/(°)	−1	−1.05	−1.0505857	−0.0005857
α_3/(°)	1	1.001	1.0051009	0.0004899

After obtaining the calibrated system parameters, we substitute the calibrated values into the three-point diameter measurement model, and use the sensor measurement values to obtain the calibrated center position and radius of the workpiece. After ten measurements, the simulation results of circle diameter measurement are shown in Fig.4.

It can be seen that the error of the radius after calibration is lower than 1 μm, and the repeatability accuracy can reach 0.2 μm; its error is relatively stable and mainly determined by the accuracy of systemic

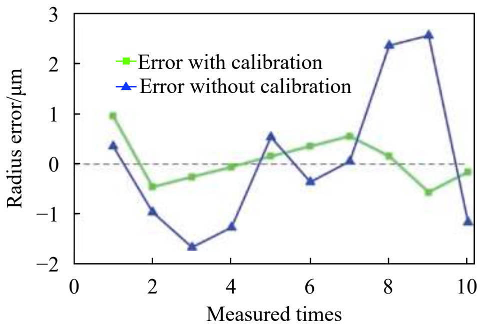

Fig.4 Radius error in different measurements

parameters. Both the absolute error and the repeatability are far better than those don't consider angle setting errors. The calibration is valid for the measurement system.

4 Experiments and discussions

To verify the feasibility in the real measurement of this method, we design and set up the experiment device. The peripheral instruments used in the experiment are laser displacement sensors (Keyence LJ-G015K) and CMM (Hexagon Inspector). The measuring range of sensors is (15±2.3) mm. And we set a one-dimensional manual sliding table under each sensor to adjust the distance to workpiece. The micrometers of different directions are arranged under the workpiece to fine-tune its position, which simulates the replacement of workpiece.

As shown in Fig.5 and Fig.6, the whole process is that CMM gets the coordinates of circle centers and radius by fitting measuring points on the circumference of the workpiece. The sensors obtain measured value through laser measurement. And the signal is converted to digital received by computers. Lastly, the computer returns the instruction to adjust the position of workpiece and repeats the next measurement.

The data in Tab.3 respectively are the calculated radius with calibration, calculated radius without calibration, absolute error between calibrated radii with the truth. Taking one of the measurement experiments for example, the workpeice was measured nine times in different positions. The average value of radii measured

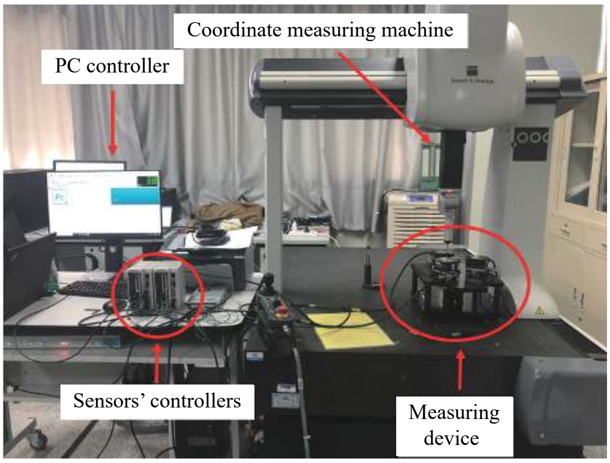

Fig.5 Experiment platform of diameter's measurement

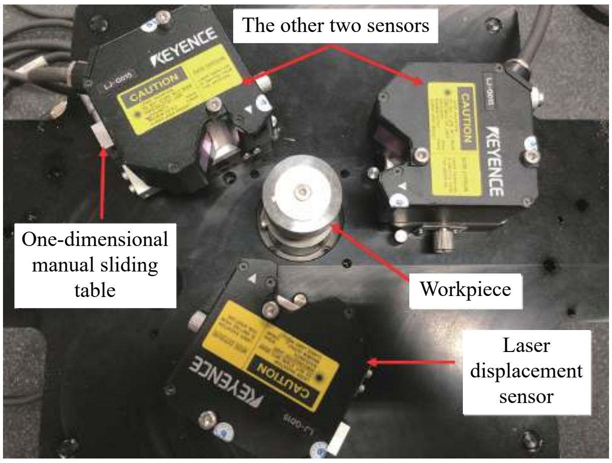

Fig.6 Top view of measuring device

Tab.3 Experiment results of radius

Radius with calibration/mm	Error with calibration/μm	Radius without calibration/m	Error without calibration/μm
18.07686	−0.33	18.05303	−24.15
18.07734	−0.20	18.05435	−23.19
18.07763	−0.83	18.05546	−21.34
18.07788	−0.55	18.05655	−21.88
18.07760	−0.18	18.05710	−20.69
18.07681	−1.07	18.05714	−20.73
18.07615	−1.40	18.05146	−26.09
18.07672	−1.25	18.04759	−30.53
18.07750	−0.10	18.04438	−33.22

by CMM was selected as true value. And the error is the difference between calculated radii and the true value. We can find that the absolute error of radius with calibration is lower than 1.5 μm and the repeatability accuracy is 0.3 μm. As a contrast, the absolute error without calibration is more than 20 μm and the repeatability accuracy is 1.3 μm. We can find that the method not only increase the absolute accuracy, but also make the measurement more stable to improve the repeatability accuracy.

5 Conclusion

This paper proposes a calibration for angle setting errors of laser displacement sensors in the diameter measurement. The angle setting errors can be obtained by measuring values of three displacement sensors at different workpiece positions. The results of simulation have shown that the errors of angles can reach 10^{-6} rad orders of magnitude and the errors of diameter measurement can be lower than 1 μm after calibration. The experiment results have shown that the absolute error of diameter is improved from 20 μm to 1.5 μm and the repeatability accuracy is increased from 1.3 μm to 0.3 μm.

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