# Research on the method of detecting the roundness error of cylindrical inner-hole by using coaxial hollow laser

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**Abstract:** A new method of detecting roundness error of cylindrical inner-hole based on coaxial hollow laser technology was presented. In view of the optical properties of cone lens and structural characteristics of cylindrical inner-hole, a detecting optical system which permits to reflect the detecting beam only once was presented. In the experiment, the roundness error of the cylindrical part was tested, and the test data was analyzed with the least square method. The result shows that the detection accuracy can reach 0.1 μm. The method shows the advantages of optical detection technology such as non-destructiveness, non-contact, high precision and thus it can be used to detect the morphology and position error.

**Key words:** geometric optics; coaxial hollow laser; cylindrical inner-hole; cone lens; roundness error

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# 同轴空心激光检测圆柱内孔圆度误差的方法研究

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**摘 要：** 文中提出了一种基于同轴空心激光检测圆柱形内孔圆度误差的新方法。根据圆锥透镜的几何光学特性和圆柱内孔的物理结构特征，设计了一种一次反射检测光学系统，并进行了实验，实现了对某圆柱内孔圆度误差的测量。采用最小二乘法分析了测量数据，结果表明：检测精度可达 0.1 μm。该方法具备非破坏性、非接触、高精度、低成本等优点，可广泛用于检测形变和位置误差。

**关键词：** 几何光学； 同轴空心激光； 圆柱内孔； 圆锥透镜； 圆度误差

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## 0 Introduction

Cylinder hole exists in all kinds of spare parts (such as piston, aviation hydraulic pump, fuel pump, cone lens, etc.), and the cylindrical inner hole of the precision machining is an important part in mechanical engineering. Roundness error is an important form of precision index of cylindrical hole. The test and evaluation of roundness error are full of difficulties, and many researchers pay close attention to find a way to detect roundness error conveniently and accurately[1-9].

At present, inside caliper and micrometer are main tools in the detection of cylindrical hole parts. These methods are simple, but with low precision, and tends to cause inner hole scratch. Another way is to use the three coordinate measuring machine, which can reach a higher precision than the former one. However, the procedure is complex, and it takes a long time to detect the error and has a serious effect on the result. In the calculation of roundness error, Kim proposed a new procedure for measuring roundness errors by computing a pair of concentric circles with the minimum radial separation for assessing the errors by constructing the discrete farthest and nearest Voronoi diagrams[10]. Chen established a mathematical model of the minimum inscribed circle to get the roundness error of CNN[11]. Gadelmawla developed a simple and efficient algorithm to evaluate the roundness error by using CMM to collect points and analyze data with genetic algorithm, compared with other algorithm, this method is more convenient and effective[12]. Lei put forward a method for roundness error evaluating through using polar coordinate system. By comparing each polar radius relative to each polar coordinate system, they got minimum circumscribed center point, maximum inscribed center point and minimum zone center point, with accurate center point, higher precision can be given[13]. Li proposed a method to solve circularity problem, they calculated the data from coordinate measuring machine by using curvature technique, the method can be used in roundness error measurement of the shaft and the bore[14]. E. Gleason and H. Schwenket set the surface of sphere as a benchmark by using the principle of three point method and then detected the roundness error of sphere with high accuracy[15].

In order to solve a series of problems in the roundness error detection, in this paper, we put forward a new way to get roundness error based on coaxial hollow laser beam. Besides, the detection system is set up and the inner hole′s roundness error of the cylindrical part with 80 mm length is test. The experiment data is processed by the least square method, and the 0.1 μm roundness error is obtained.

## 1 Detecting system

The detection system consists of parallel incident all-solid state laser, variable aperture, cone lens, the cylindrical inner hole to be test, receiving screen and so on, which is shown in Fig.1. There is a hole

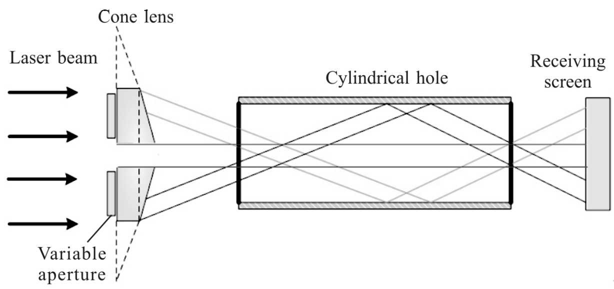


Fig.1 Optical system of coaxial hollow laser beam detecting roundness error of cylindrical inner hole

in the middle of cone lens, and when incident beam irradiates on cone lens, the center part of incident beam will go through the hole and arrive at receiving screen, and we set it as reference beam, and used to be position baseline. The other part of beam is refracted by the cone lens and generate the hollow beam, we set it as detecting beam, then the detecting beam is reflected only once by the inner surface of cylindrical inner hole and finally arrives at receiving screen. The defect of the ring on the screen reflect the morphology and position error of cylindrical inner hole. In this detecting system, the position at which the detecting beam is reflected can be adjusted by changing the size of variable aperture. Therefore this detection system can test the roundness error of any cross section of the cylindrical inner hole.

## 2 Experiment research

Using the devices shown in Fig.1, in which the laser wavelength is 532 nm, the cone lens is k9 glass and its basic angle is 10°, the length of the cylindrical inner hole is 80 mm. By changing the variable aperture, the rings reflected by the cylindrical inner hole at different longitudinal position are obtained and shown in Fig.2, in which all the spaces between neighboring detecting position are the same so that we can gain experiment data conveniently and analyze them easily. From the figure we can find that the width of the ring is increased as the detecting depth increasing, and the defect of the inner hole can be detected by calculating the corresponding inner ring′s roundness error.

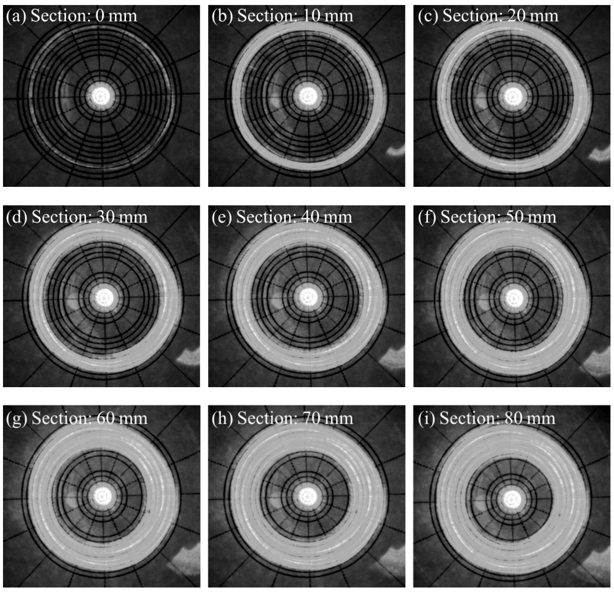


Fig.2 Light intensity distribution of each section

For the experiment data processing, center pixel coordinate is determined firstly, then the coordinate points every 22.5° are picked up, and 16 pixel coordinates in a circle is got with setting their coordinates as $(X_i,Y_i)$ $(i=1,2,3,\cdots,16)$, respectively. Defining the distance between the sample points and center of least square circle as $D_i$,

$$D_i=\sqrt{(X_i-X_0)^2+(Y_i-Y_0)^2} \tag{1}$$

Then the difference of $D_i^2$ and $R_0^2$ can be written as:

$$\delta_i=D_i^2-R_0^2=(X_i-X_0)^2+(Y_i-Y_0)^2-R_0^2=X_i^2+Y_i^2+AX_i+BY_i+C \tag{2}$$

Here, $R_0$ is the radius of the least square circle. According to the principle of least square circle, the problem is changed into finding the values of $A$,$B$, and $C$ which meet with minimum $\delta_i$, set $F$ $(A,B,C)$ as quadratic sum of $\delta_i$, then we have:

$$F(A,B,C)=\sum_{i=1}^{16}\delta_i^2=\sum_{i=1}^{16}[(X_i^2+Y_i^2+AX_i+BY_i+C)]^2 \tag{3}$$

Solving parameters $A$, $B$, $C$ to make $F(A,B,C)$ minimum. The partial derivatives of $A$, $B$, $C$ are made, making the partial derivative equations to be zero, then we can get:

$$A=\frac{eb-cd}{ad-b^2} \tag{4}$$

$$B=\frac{ea-cb}{b^2-da} \tag{5}$$

$$C=\frac{\sum_{i=1}^{16}(X_i^2+Y_i^2)+A\sum_{i=1}^{16}X_i+B\sum_{i=1}^{16}Y_i}{16} \tag{6}$$

where,

$$a=(16\sum_{i=1}^{16}X_i^2-\sum_{i=1}^{16}X_i\sum_{i=1}^{16}X_i)$$

$$b=(16\sum_{i=1}^{16}X_iY_i-\sum_{i=1}^{16}X_i\sum_{i=1}^{16}Y_i)$$

$$c=[16\sum_{i=1}^{16}X_i^3+16\sum_{i=1}^{16}X_iY_i^2-\sum_{i=1}^{16}(X_i^2+Y_i^2)\sum_{i=1}^{16}X_i]$$

$$d=(16\sum_{i=1}^{16}Y_i^2-\sum_{i=1}^{16}Y_i\sum_{i=1}^{16}Y_i)$$

$$e=[16\sum_{i=1}^{16}X_i^2Y_i+16\sum_{i=1}^{16}Y_i^3-\sum_{i=1}^{16}(X_i^2+Y_i^2)\sum_{i=1}^{16}Y_i]$$

Substituting the $(X_i, Y_i)$ into the Eq.(4)-(6), then the center coordinate and radius of the least square circle can be obtained. According to the formula of least square method, the roundness error of the cylindrical inner hole can be calculated, that is $\Delta C = D_{max} - D_{min}$. Finally, the processed experiment data are shown in Tab.1.

**Tab.1 Processed experiment data**

| Position | $X_0$ | $Y_0$ | $\Delta C$ |
|---|---|---|---|
| Section 80 mm | −0.001 3 | 0.002 9 | 0.056 8 |
| Section 70 mm | 0.022 0 | 0.001 5 | 0.154 2 |
| Section 60 mm | −0.015 4 | −0.001 4 | 0.276 1 |
| Section 50 mm | 0.001 1 | −0.017 4 | 0.246 4 |
| Section 40 mm | −0.000 8 | 0.015 8 | 0.297 9 |
| Section 30 mm | 0.001 2 | 0.015 2 | 0.325 5 |
| Section 20 mm | 0.000 6 | 0.000 5 | 0.025 5 |
| Section 10 mm | −0.000 5 | 0.001 2 | 0.136 5 |

From the table we can find that the roundness error of the different sections are obtained by using the least square method, and the precision can reach 0.1 μm.

## 3 Conclusion

A new method to detect the roundness error of cylindrical parts by using the coaxial hollow laser technology has been put forward. Taking into account the optical properties of cone lens and structural characteristics of cylindrical parts, a detecting optical system which can reflect the detecting beam only once has been presented. In the experiment, the detecting source was 532 nm green laser, the cone lens was k9 glass and its basic angle was 10°, and the length of the cylindrical part to be test was 80 mm, the rings reflected by the different inner hole sections were received and the experimental data were analyzed by using the least square method, and the results shown that the roundness error precision could reach 0.1 μm. This method made non-destructive, non-contact, high precision detection of roundness error in cylindrical parts possible. It provide a new direction for detection of morphology and position error of cylindrical parts, and which is significant for the further research.

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