Research Article

A High-Precision and Wide Range Method for Inner Diameter Measurement

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Inner diameter measurement technology with high precision and wide measuring ranges is a difficult area to master. It is challenging to achieve high precision and a wide measuring range for inner diameter measurement. The dispersive confocal technique is used to describe a high accuracy, large range approach for measuring inner diameter. The inner diameter is measured utilizing a rotating scanning approach that combines the dispersive confocal technique with least squares. Meanwhile, a plane mirror deflects the optical path of a dispersive confocal sensor, focusing monochromatic light of a certain wavelength on the object’s surface in the radial direction. The measuring range of the device may be modified to fit different objects by modifying the distance between the dispersive confocal sensor and the plane mirror, as well as the eccentricity of the dispersive confocal sensor. Furthermore, this study examines the method’s accuracy and suggests a calibration technique. As a consequence, the procedure may ensure measurement precision as well as a measurement range. Finally, experiments are utilized to test the validity of the strategy. To accomplish a 3 μm inner diameter measurement precision and a measuring range of 76 mm to 150 mm, a dispersive confocal sensor with a range of just 20 mm was utilized.

1. Introduction

In the aerospace and military sectors, high-precision measurement of inner diameter has long been a significant aspect of component manufacturing inspection and a challenging challenge to address [1–3]. Contact measurement technology [4], such as coordinate measuring machines (CMM), has a high degree of precision and a wide measurement range and can execute the inner diameter measurement duty with the greatest accuracy [5–7]. The contact probe is readily damaged and destroyed, and it is difficult to measure objects with a large length-to-diameter factor, due to the size, high cost, and low measurement efficiency of CMMs. Noncontact measurement methods have also gained popularity since they are faster and safer than contact measurement methods and do not harm the surface being measured.

Eddy current [8], spherical dispersed electric field [9], structured light [10, 11], interferometric [12–14], and laser triangulation methods [15, 16] are examples of noncontact inner diameter measuring techniques. Because of the advantages of assuring high-precision measurements, the use of dispersive confocal methods to tiny displacement and morphological studies has recently become a research hotspot. The measuring point does not change when the item is slanted or twisted, and there is no aberration interference [17]. Wang et al. [18] proposed employing confocal methods to estimate the radius of unpolished spheres with less than 20 ppm measurement error. Liu et al. [19] suggested employing the dispersive confocal method to create a displacement measurement device in 2019. Xiaoyun et al. [20] suggested a confocal X-ray scattering technique for measuring the outer and inner diameters of a single capillary based on X-ray capillary optics in 2019. And there is just a 3.6 percent relative inaccuracy. However, this method’s measuring range is just around 0.15 mm to 0.25 mm. Tang et al. [21] suggested a transverse differential confocal radius measurement
(TDCRM) method for measuring the radius of curvature of the cat’s eye in 2021, based on virtual pinhole technology. The method’s standard deviation is 0.001014 mm, with a relative standard deviation of 3.4 ppm. Because of its size and measuring range, the dispersive confocal sensor is mostly employed to evaluate exterior surface characteristics and microdiameters. As a result, traditional noncontact inner diameter measuring technology cannot match confocal measurement technology in terms of precision, while confocal measurement technology cannot measure large inner diameters.

We use a high-precision dispersion confocal sensor, combined with a plane mirror and an adjusting bracket to turn and accurately adjust the optical path. It is possible to measure inner diameters with high precision ranging from 76 mm to 150 mm.

2. Principle

2.1. Measuring Principle and System Components. As shown in Figure 1, the white light emitted from the white light source can be approximated as a point source after passing through the pinhole, and after passing through the dispersive objective lens, a series of focused spots of different wavelengths are formed on the optical axis in a continuous distribution. The excitation light is focused on the inner surface of the measured object, while the emission light is focused on the pinhole. The dispersive confocal lens is coupled to optical fibre. And the scattered light from the surface of the measured object again enters the optical fibre coupler through the dispersion objective lens and the optical fibre in the opposite direction. Fibre optic and SC optical fibre splice can link the fibre coupler and fibre optic spectrometer. Only the light of specific wavelength meets the confocal condition, scatters from the surface, and enters the spectrometer through the optical fibre coupler and optical fibre. The optical fibre is connected with white light source, spectrometer, probe, and optical fibre coupler through SC optical fibre splice. The location of the pinhole is conjugated to the location of the measured surface, so the wavelength of monochromatic light satisfies the confocal condition and will account for the largest luminous flux in the emitted light signal, while the luminous flux of other spectral components is relatively small. The spectral measurement system is used to solve the spectrum of the light signal from the pinhole and to determine the peak wavelength of the signal.

The relationship between the light intensity $I(u)$ detected at the confocal position and the normalized axial optical coordinate $u$ can be described as [22]

$$I(u) = \left(\frac{\sin \left(\frac{u}{4}\right)}{\frac{u}{4}}\right)^4,$$

where $u$ is the normalized axial coordinate, and $u = (2\pi a^2/\lambda f^2)\Delta l_v$, where $a$ is the aperture of the imaging lens, $\lambda$ is the wavelength of the incident light, and $f$ is the focal length of the imaging lens.

Then, the relationship between the light intensity $I(\Delta r)$ and the dimension change $\Delta l_v$ can be given as

$$I(\Delta r) = \left(\frac{\sin \left(\frac{(\pi a^2/2\pi f^2)\Delta l_v}{\pi a^2/2\pi f^2}\right)}{\left(\pi a^2/2\pi f^2\right)\Delta l_v}\right)^4.$$

The value shown on the dispersive confocal sensor can be described as

$$l_v = l_{v0} + \Delta l_v.$$

The measuring device, as illustrated in Figure 2, is made up of two parts: a moving component and a measuring portion. A linear displacement stage and a rotating stage are among the moving parts, while a measuring rod, an adjustment bracket, a dispersive confocal sensor, and a plane mirror are among the measuring parts. The absolute coordinate

*Figure 1: Principle of dispersive confocal sensor.*
system is $O_0 - x_0y_0z_0$, while the measurement coordinate system is $OM - x_My_Mz_M$. Although the dispersive confocal sensor has a range of 20 mm, it is too big to be placed radially to measure directly on the object being measured. With a range of 20 mm, the dispersive confocal sensor is utilized, but it is too large to be put radially to measure directly on the measured object. In order to increase the measuring range of the device while using a large-sized and small-range dispersive confocal sensor, the dispersive confocal sensor and the plane mirror are mounted eccentrically on the measuring rod, using the plane mirror to rotate the optical path. The eccentricity distance is $S$, and the distance between the dispersive confocal sensor and the plane mirror is $l_S$. The distance between the optical axis of the dispersed confocal sensor and the object to be measured is $l_{ij}$, which can be obtained by equation (4):

$$l_{ij} = l_r - l_s. \quad (4)$$

The eccentricity distance ($l_s$) and the distance between the dispersive confocal sensor and the plane mirror ($l_r$) can be changed to vary the device’s measurement range ($S$). The measuring range is increased by increasing $S$ and lowering $l_s$; conversely, the measuring range is decreased by increasing $S$ and decreasing $l_s$. The measuring rod is also linked to a linear displacement stage, which may be used to measure the inner diameter of a cylinder with a large length-to-diameter factor by regulating the linear displacement stage. The object to be measured is placed on a rotating stage, and the device’s scanning measurement is accomplished by rotating the object through the rotating stage. The device is approximately 280 mm long, 505 mm broad, and 1148 mm tall.

2.2. The Ideal Mathematical Model. The measurement model for the inner diameter is shown in Figure 3. $O_0$ is the center of the circle of the object to be measured and the center of the circle of the measuring device. $P_0$ is the turning point of the optical path, and $P_{ij}$ is the $j$-th measuring point of the $i$-th measuring surface. The ideal coordinate value of $P_{ij}$ in the measurement coordinate system is expressed as

$$\begin{align*}
    x_{ij} &= (S + l_{ij}) \cos \phi_{ij}, \\
    y_{ij} &= (S + l_{ij}) \sin \phi_{ij}, \\
    z_{ij} &= H_i,
\end{align*} \quad (5)$$

where $1 \leq i \leq M$, $1 \leq j \leq N$, and $\phi_{ij} = 2\pi j/N$, which is the angle that the $j$-th measuring point of the $i$-th measuring surface turns relative to the first measuring point of the plane.

Ideally, the $O_M - z_{ij}$ axis of the device coincides with the rotation center of the measured object and is perpendicular to the measuring light $P_0P_{ij}$. And the plane mirror has no assembly uncertainty, the scanning surface formed by the rotation of the measuring light intersects with the inner surface of the measured object to form a circle. In the $OM -$
plane, the inner diameter measured from the j-th measuring point of the i-th measuring surface of the measured object can be expressed as

\[ r^2 = (l_{ij} + S)^2. \] (6)

After scanning the surface, we can get enough measurement points. The \( O_M - x_M'y_M' \) plane, the circle for the cross section of the hole wall is described below:

\[ (x - x_{00})^2 + (y - y_{00})^2 = r^2, \] (7)

where \((x_{ij}, y_{ij})\) is the coordinate of j-th measuring point of the i-th measuring surface.

Therefore, the calculation of \( r \) can be transformed into the optimal solution of the overdetermined nonlinear equations by the least square method [23–25]:

\[ \Delta f = \sum_{i=1}^{n} \left[ \sqrt{(x_{ij} - x_{00})^2 + (y_{ij} - y_{00})^2} - r \right]. \] (8)

According to the method of Kasa [26], we can convert the calculation of \( r \) to the optimal solution of linear equations with the least squares method:

\[ \Delta K = \sum_{i=1}^{n} \left[ (x_{ij} - x_{00})^2 + (y_{ij} - y_{00})^2 - r^2 \right]. \] (9)

Assuming \( A = -2x_{00}, B = -2y_{00}, \) and \( C = x_{00}^2 + y_{00}^2 - r^2, \) then \( \Delta K = \sum_{i=1}^{n} (x_{ij}^2 + y_{ij}^2 + Ax_{ij} + By_{ij} + C)^2. \) We can figure out the value of \( A, B, \) and \( C \) by using Eigens. Therefore, the fitting values of the best fitting circle center coordinates \((x_0, y_0)\) and radius are obtained:

\[
\begin{align*}
x_{00} &= \frac{A}{2}, \\
y_{00} &= \frac{B}{2}, \\
r &= \frac{1}{2} \sqrt{A^2 + B^2 - 4C}.
\end{align*}
\] (10)

3. Uncertainty of the Measuring Device

By rotating the object under test numerous times and reading the observed value of the dispersive confocal sensor, all diameters of a component may be determined from the least square value of \( K \) using equation (9). In a real measurement procedure, however, optimal experimental circumstances are not accessible, and there are two elements that might impact the uncertainty of the results: systematic uncertainty and random uncertainty.

3.1. Systematic Uncertainty. The systematic uncertainty includes the manufacturing uncertainty of the measuring rod, the installation uncertainty of the plane mirror, and the position uncertainty between the measuring rod and the rotating stage.

3.1.1. Manufacturing Uncertainty of Measuring Rod. The measuring rod’s axis should be aligned with the measuring coordinate system’s \( O_M - x_M \) axis in the device. However, because of the roundness of the measuring rod and the straightness of the measuring rod’s axis, the measuring rod’s axis may not coincide with the \( O_M - x_M \) axis. Figure 4 shows that \( O_M \) is the ideal measuring rod center, \( O_M' \) is the actual measuring rod center, and \( P_{ij} \) and \( P_{ij}' \) are the ideal and actual measurement points, respectively.

In the ideal measurement coordinate system, \( O_M' \) coordinates are \((\Delta x, \Delta y)\), while the coordinates of the actual measurement point in the measurement coordinate system are

\[
\begin{align*}
x_{ij} &= (S + l_{ij}) \cos \varphi_{ij} + \Delta x, \\
y_{ij} &= (S + l_{ij}) \sin \varphi_{ij} + \Delta y, \\
z_{ij} &= h_{ij},
\end{align*}
\] (11)

The direction of the real measuring light is affected by the straightness of the measuring rod axis during production, with the actual measuring light not being perfectly perpendicular to the measuring rod axis. Figure 5 depicts the angles \( \alpha \) and \( \beta \) created by the light as a result of manufacturing error in the measuring rod, where angle \( \alpha \) denotes the inclination of the actual measuring light in the measuring plane \( O_M - x_M'y_M' \) in relation to the ideal measuring light and angle \( \beta \) denotes the inclination of the measuring light in relation to the ideal measuring plane \( O_M - x_M'y_M' \).

As a result, the coordinates of the actual measurement point \( P_{ij}' \) are

\[
\begin{align*}
x_{ij} &= (S + l_{ij}) \cos (\varphi_{ij} + \alpha) \cos \beta + \Delta x, \\
y_{ij} &= (S + l_{ij}) \sin (\varphi_{ij} + \alpha) \cos \beta + \Delta y, \\
z_{ij} &= h_{ij} + l_{ij} \sin \beta.
\end{align*}
\] (12)

We utilize the CMM to measure the measuring rod, as shown in Figure 6. Under the processing condition of IT5 [27], the measuring rod can meet the following: \( \Delta x < 0.007 \) mm, \( \Delta y < 0.007 \) mm, and \( \beta < 0.16^\circ. \) As a result, the radius uncertainty produced by the measuring rod’s manufacturing uncertainty may be calculated as follows:

\[
\Delta r_M = \sqrt{[(S + l_{ij}) \cos \beta]^2 + [(\Delta x)^2 + (\Delta y)^2] - (S + l_{ij})}.
\] (13)

The simulation findings of the influence of the measuring rod’s manufacturing uncertainty are shown in Figure 7.

The effect of measuring rod manufacturing uncertainty on measurement outcomes under IT5 manufacturing uncertainty is observed. The highest uncertainty resulting from
The measuring uncertainty is due to roundness of the measuring rod.

The measurement experiment of measuring rod.

The measuring uncertainty is due to manufacturing uncertainty of measuring rod.

The measuring uncertainty is due to roundness of the measuring rod.

The measurement experiment of measuring rod.

Measuring uncertainty caused by manufacturing uncertainty in measuring rods.
As shown in equation (16), Figures 10 and 11, we can calculate the uncertainty $\Delta r_I < 0.78 \ \mu m$.

3.1.3. The Position Uncertainty between the Measuring Rod and the Rotating Stage. After each section measurement, the measuring device must advance a modest distance along the axial direction of the object to be measured during the measurement procedure. The next part is then measured. However, during installation, the measuring rod will always be eccentric and tilted, causing the measuring coordinate system to differ from the absolute coordinate system, causing the measuring light to be perpendicular to the $O-z$ axis under the absolute coordinate system. The measurement trajectory of the actual measurement point $P_{ij}$ is a three-dimensional elliptical curve in space, as shown in Figure 12. The noncoincidence between the two coordinate systems results in the measurement trajectory of the actual measurement point $P_{ij}$ as a three-dimensional elliptical curve in space, as shown in Figure 12.

The offset and tilt of the measurement coordinate system are included in the position uncertainty between the measurement coordinate system and the absolute coordinate system, as shown in Figure 13. The displacement matrix $T$...
where the rotation matrix $R$ can be used to rectify the uncertainty between the two coordinate systems.

The transformation of the measurement coordinate system to an absolute coordinate system can be done using the Bursa-Wolf [29] model with the transformation equation shown below:

$$
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} = \lambda R \cdot 
\begin{bmatrix}
  x_M \\
  y_M \\
  z_M
\end{bmatrix} + T,
$$

(17)

where rotation matrix $R = \begin{bmatrix}
  \cos \theta_y & \sin \theta_y & \cos \theta_x \sin \theta_y \\
  -\sin \theta_x & \cos \theta_x & \sin \theta_x \cos \theta_y \\
  \sin \theta_y & -\sin \theta_y & \cos \theta_x \cos \theta_y
\end{bmatrix}$, scale factor $\lambda = 1$, and displacement matrix $T = \begin{bmatrix}
  x_T \\
  y_T \\
  z_T
\end{bmatrix}$.

The uncertainty between the measurement coordinate system and the absolute coordinate system caused by the installation uncertainty of the measuring rod can be corrected by calibration experiments.

### 3.2. Random Uncertainty

The location offset of the laser convergence point, the size of the pinhole, the physical properties of the measured object, the dispersive confocal sensor’s measurement uncertainty, the rotary stage’s radial runout, and the linearity of the linear displacement stage are all random uncertainties of measuring device.

When measuring the inner diameter, the laser will converge on a small area of the dispersive lens. If the convergence region does not coincide with the optimal reference sphere, uncertainty will be introduced. This uncertainty can be compensated by the PV value of the standard reference plane:

$$
\Delta r_p = 0.1PV = 0.1 \times 0.1\lambda \leq 0.0076 \mu\text{m}.
$$

(18)

In [22], it is obvious that the size of the pinhole will affect the axial resolution of the color confocal sensor. According to the mature analysis method of confocal optical system, when the confocal pinhole has a finite size, the confocal axial response of the system is [30]

$$
I(u) = \int_0^{r_p} \int_0^1 P(\rho) \exp \left( j u \rho^2 / 2 \right) J_0(\nu_p \rho) \rho d\rho \right|^2 d\nu,
$$

(19)

where $u$ and $v$ are normalized axial and radial optical coordinates, respectively, $P(\rho)$ is the pupil function of spectral confocal optical system, $J_0$ is a kind of Bessel function of zero order, and $V_\rho$ is the normalized radial optical coordinate value of the confocal aperture radius on the measured object surface. It can be expressed as

$$
\nu_p = \frac{2\pi}{\lambda} NA(\lambda) \frac{r_p}{m(\lambda)},
$$

(20)

where $r_p$ is the actual radius of the confocal pinhole. The size deviation of the aperture radius will increase the spectral bandwidth, affect the axial resolution of the dispersive confocal sensor, and increase the measurement uncertainty.

Meanwhile, the physical properties of the measured object, such as color, material, and roughness, will also increase the measurement uncertainty [31]. However, these factors have little influence on the uncertainty, which can be ignored here.

With an eccentricity distance $S > 4 \text{mm}$, the dispersive confocal sensor is positioned eccentrically. The distance between the plane mirror and the confocal probe may be adjusted to modify the measuring device’s measurement range. The dispersive confocal sensor utilized in this experiment has a measuring range of $20 \text{mm}$ and a linearity of $2.2 \mu\text{m}$. Under ideal assembly circumstances, the probe’s principal measurement error is expected to be linearity. As a result, $\Delta r_{E} = 2.2 \mu\text{m}$ is the overall confirmed systematic uncertainty.

The rotating stage impacts the measuring device’s scanning measurement, and the radial runout uncertainty.
created during the rotary stage’s rotation affects the measurement findings, which is a random uncertainty. The rotary stage utilized in this work has a radial runout uncertainty of \(\Delta r_T = 1.5 \mu m\).

The measuring equipment uses a linear displacement stage to produce up and down movement throughout the measurement process, allowing for the measurement of various regions of the same measured item. As a result, the measurement findings are influenced by the linear displacement stage’s straightness uncertainty. The linear displacement stage utilized in this device has a linearity uncertainty of \(\Delta r_L = 0.7 \mu m\).

Therefore, the random uncertainty of the measuring device can be described as

\[
\Delta r_{RA} = \sqrt{(\Delta r_d)^2 + (\Delta r_T)^2 + (\Delta r_L)^2 + (\Delta r_P)^2}. \tag{21}
\]

And we can obtain that \(\Delta r_{RA} = 2.59 \mu m\).

3.3. Total Diameter Measurement Uncertainty of the Device.

The measurement uncertainty of the measuring device originates from several factors mentioned above, among which the installation uncertainty of the measuring rod can be corrected by calibration experiments. Therefore, the biggest influencing factor of the measurement uncertainty is the linearity uncertainty of the dispersive confocal sensor in the random uncertainty. The total diameter measurement uncertainty can be obtained by the equation (22):

\[
\Delta r_{\text{sum}} = \sqrt{(\Delta r_M)^2 + (\Delta r_T)^2 + (\Delta r_{RA})^2}. \tag{22}
\]

When \(r < 75 \text{ mm}\), the measuring rod roundness uncertainty can meet the following: \(\Delta x < 0.007 \text{ mm}\) and \(\Delta y < 0.007 \text{ mm}\); the measuring rod straightness uncertainty can meet the following: \(\beta < 0.16^\circ\); the installation uncertainty of the reflector can guarantee \(|e_1| < 1 \mu m\), \(|e_2| < 1 \mu m\), \(\gamma \times 0.1^\circ\), and \(\delta < 0.1^\circ\). Thus, the total diameter measurement uncertainty of the device is \(\Delta r_{\text{sum}} = 2.72 \mu m\).

4. Experiment

4.1. Calibration Experiments. As shown in Figure 14, the calibration device consists of a linear displacement stage and a rotating stage, a measuring rod, an adjustment bracket, a dispersive confocal sensor, a plane mirror, and the ring gauge. The ring gauge has an inner diameter of 150 mm. By rotating the measuring ring gauge, find out the center and central axis of each measured section. Compared with the ideal ring gauge axis, matrix \(R\) and matrix \(T\) are obtained. And the calibration procedure is as follows:

First of all, adjust the measuring device to a position close to the center axis of the ring gauge. Secondly, position the measuring device to the ring gauge hole while slowly adjusting the displacement meter. Then, begin the inner diameter measurement near the end face and record the measurement data. What is more, move to the other end face of the change gauge and take an inner diameter measurement, recording the data. Finally, repeat steps (3) and (4) three times.

The results of the calibration experiments are shown in Figure 15, and the values of the inner diameter of the ring gauge calculated by the least squares method are shown in Table 1.
The rotation matrix $R$ and the displacement matrix $T$ can be derived from the results of calibration experiments as follows:

$$
R = \begin{bmatrix}
0.99999 & 0.00009 & 0.00002 \\
0 & 0.99999 & -0.00009 \\
-0.00001 & 0.00009 & 0.99999
\end{bmatrix},
$$

$$
T = \begin{bmatrix}
0.0016 \\
0 \\
0
\end{bmatrix}.
$$

We can use the rotation matrix $R$ and the displacement matrix $T$ derived from calibration experiments to correct for boring uncertainty due to measuring rod mounting uncertainty.

4.2. Diameter Measurement Experiments. A schematic diagram of the measuring device is shown in Figure 16, with the measuring device consisting of a moving part and a measuring part. The moving part includes a linear displacement stage and a rotating stage, and the measuring part includes a measuring rod, an adjustment bracket, a dispersive confocal sensor, and a plane mirror. The measured ring gauge diameter is compared with the reference value to evaluate the uncertainty and reliability of the measurement results.

The steps of the measurement experiment are shown below:

1. Adjust the measuring device to a position close to the center axis of the ring gauge
2. Slowly adjust the displacement table to move the measuring device towards the bore of the ring gauge
3. Start the inner diameter measurement close to the end face and record the measurement data
4. Control the linear displacement stage to move down to another section of the ring gauge and take an inner diameter measurement of the second section, recording the data
5. Continue to measure downwards until sufficient points have been collected after 6 sections have been measured

In this paper, measurement experiments were carried out on 75 mm, 110 mm, and 125 mm ring gauges, and the results are shown in Figure 17. The inner diameter values of the two ring gauges are shown in Table 2.

From Table 2, it is obvious that the measured values are very close to the reference values, with a maximum...
uncertainty of 2 μm, no greater than Δr_sum < 2.72 μm analyzed in Section 3.

5. Conclusions

This paper presents a method for measuring the inner diameter based on the dispersive confocal technique, which enables the measurement of the inner diameter of large diameters without changing the range of the dispersive confocal sensor. We also present an uncertainty analysis of the measuring device and a calibration method to reduce the measurement uncertainty of the measuring device. In the experiment, 75 mm ring gauge, 110 mm ring gauge, and 125 mm ring gauge are used to verify the inner diameter measurement method. It is proven that the measurement precision of this method has achieved 3 μm using the 2 μm linearity CDS. This method is effective and reliable for measuring the inner diameter of 76 mm-150 mm hole.
Data Availability
The [DATASET] data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare no conflict of interest.

Authors’ Contributions
Z.Z., Y.Y., and L.G. conceived and designed the experiments; Z.Z., Y.Y., and L.G. performed the experiments; Z.Z. analyzed the data; Y.Y. and X.Y. contributed the materials used; Z.Z. wrote the paper.

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