Visual inspection method for inner wall of small hole based on internal reflection principle

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Abstract. This paper introduces a new image acquisition scheme based on the principle of internal reflection for the inner wall of the small hole, and visually inspects small hole workpieces with an inner diameter of 2-10mm. The customized reflector is inserted into the small hole, and the internal wall image is displayed in the CCD industrial camera through the reflection of light, and then the subsequent image processing is performed. The feasibility of the scheme is verified by theoretical calculations, and the obtained inner wall image resolution can reach 10 μm, which has high practical value.

1. Introduction

The workpiece with micro-aperture is widely used in aerospace, precision manufacturing and other fields. The quality inspection of the inner wall surface of the hole is of great significance. For small-hole workpieces with an inner diameter of 2-10 mm, how to detect possible flaws and defects on the inner wall is a difficult problem. The existing inner wall detection methods include non-visual detection methods such as eddy current detection method [1], magnetic leakage detection method [2], and ultrasonic method [3], and visual detection methods such as industrial endoscope and structured light method [4]. Using non-visual inspection methods can detect defects on the inner wall, but the scope of application is limited, and it is difficult to intuitively obtain or restore the true image of the inner wall surface, which is not conducive to subsequent information retention and traceability. Most of the existing visual inspection methods are based on the workpiece with a relatively large aperture or the inner wall of the pipeline [5], and the detection scheme applicable to small-sized workpiece with a diameter of less than 5mm is still limited.

This paper introduces a visual inspection scheme for the inner wall of small holes based on the principle of internal reflection mirror and performs feasibility analysis, error analysis and construction of experimental platform. The reflector inserts into the small hole from top to bottom to observe a clear image of the inner wall, and then, with the continuous rotation of the workpiece, a complete image of the inner wall is obtained by image stitching technology.

2. Feasibility analysis of detection scheme

2.1. Detection principle

As shown in Figure 1, the optical mirror of this scheme is a 45-degree inclined plane cut on a cylinder, and the surface is coated with a reflective film. Insert the optical reflector into the cavity of
the hole from above and ensure that the mirror and the workpiece remain coaxial. The light emitted by
the upper light source is reflected to the inner wall from the inside of the reflection film, then returns
along the original optical path, and finally forms an image in the CCD camera. After the measured
workpiece rotating for one circumference, the entire inner wall image at a certain height position is
acquired by the CCD, and the reflector needs to be moved down by one step to complete the scanning
inspection of the entire inner wall of the micro-hole workpiece.

The advantage of this scheme is that the illumination source and the reflector are on the same side
of the workpiece, so that it is not only suitable for through-hole workpiece, but also for the visual
inspection of non-through-hole workpiece. Moreover, the transparent glass cylinder of the mirror also
plays a role in enhancing the lighting effect inside the small hole.

![Figure 1. Detection principle](image)

2.2. Resolution calculation

Define the resolution along the axis of the inner wall of the small hole as the vertical resolution,
and the resolution in the circumferential direction of the inner wall of the small hole as the horizontal
resolution. The optical parameters used in the theoretical calculation are shown in Table 1.

**Table 1. Optical system parameters**

| Parameter Name                        | Parameter Value |
|---------------------------------------|-----------------|
| 45 degree mirror diameter             | 4.2mm           |
| Inner wall diameter of workpiece      | 4.5mm           |
| Telecentric lens magnification        | 1.0             |
| Telecentric lens depth of field       | 500μm           |
| CCD resolution                        | 4.8×4.8μm/pix   |
| K9 optical glass refractive index     | 1.516           |

The top view of measurement is shown in Figure 2. O₁ is the center of the inner wall of the
workpiece and mirror cylinder, the radius of the inner wall of the workpiece is recorded as R, the
selected measurement width as l, the corresponding center angle to circle O₁ is α and the chord length
of ab is w. The corresponding depth of field distance on the inner wall of is f. The following
theoretical calculations are performed to verify whether the horizontal and vertical resolution of the
test image satisfy the requirements of the detection system.

According to the maximum depth of field value of the telecentric lens, the corresponding maximum
center angle β on circle O₁ can be calculated. The distance between the center angle and the depth of
field has the following geometric relationship:

\[ f = R - R \cos(\alpha/2) \]  (1)
Substituting $f = f_{\text{max}}$ into the formula above can obtain:

$$\beta = \alpha_{\text{max}} = 2 \arccos \left(1 - \frac{f_{\text{max}}}{R}\right)$$

(2)

The largest chord $w_{\text{max}}$ can be obtained by calculation:

$$w_{\text{max}} = 2 \sqrt{R^2 - \left(R - f_{\text{max}}\right)^2}$$

(3)

If the maximum chord length exceeds the diameter of the mirror, the entire reflection plane is within the effective measurement range, so the inner wall image can be reflected to the CCD camera without distortion. Otherwise, the maximum effective measurement range limited by the maximum depth of field distance is $l_{\text{max}} = w_{\text{max}}$.

For the tilt angle of the mirror cut surface is 45 degree, the vertical and horizontal components of the measurement area on the mirror are the same, therefore, the height of each measurement is the same as the length $h$ of the area in the top view of the measurement:

$$h = 2 \sqrt{r^2 - \left(r - w/2\right)^2}$$

(4)

According to Figure 2, the width of the reflection image formed by the mirror on the inner wall is $w$, so the horizontal resolution can be calculated by the following formula:

$$S_x = S_{\text{CCD}} \cdot \frac{2\pi Ra / 360^\circ}{2R \sin \left(\alpha / 2\right)} = S_{\text{CCD}} \cdot \frac{\pi \alpha}{360^\circ \sin \left(\alpha / 2\right)}$$

(5)

The inclination of the plane mirror is 45 degrees, and there is no enlargement or reduction in the vertical direction. The vertical resolution is the pixel resolution of the CCD camera.

Substituting into the calculation of the optical system parameters, the maximum center angle $\beta = 38.942^\circ$, $w_{\text{max}} = 2.828\text{mm}$, the maximum chord length is smaller than the diameter of the mirror, let $\alpha = \beta$, $h = 3.97\text{ mm}$, horizontal resolution $S_x = 4.89 \mu\text{m} / \text{pixel}$, vertical resolution $S_y = 4.8 \mu\text{m} / \text{pixel}$.

During the propagation of the light, the light will be refracted at the interface between the glass and the air. In order to reduce the lens distortion caused by the light refraction, the measurement angle $\alpha$ must be as small as possible. The angle of incidence is $\alpha / 2$. According to the refractive index $n$, the refraction angle $\theta$ can be obtained:

$$\theta = \arcsin(n \sin \frac{\alpha}{2})$$

(6)

Since $n > 1$, there is $\theta > \alpha / 2$, the light is deflected toward the horizontal axis. Compared to the case without refraction, the depth of field is smaller and the resolution is higher, so all indicators are also satisfied after refraction. The circle center angle corresponding to the maximum measurement range of the telecentric lens is $30^\circ$. Considering the imaging quality, if $\alpha$ is too large, the image distortion caused by refraction becomes more serious, let $\alpha = 10^\circ$, and at least 36 pictures are needed for stitching during rotating.

![Figure 2. Top view of inner wall measurement](image)
2.3. Image processing

The image processing process is shown in Figure 3. After obtaining a stitched whole circumference image of the inner wall, stitching in the vertical direction can obtain a complete view of the inner wall of the small hole.

![Figure 3. Image processing](image)

3. Error calculation

The main error source during inspection is mechanical positioning error, which has great impacts on the system. For example, if the measured workpiece and the reflector cannot be coaxial, it will not only seriously affect the experimental measurement results, the mirror lens may also scratch the inner wall during the continuous rotation, causing damage to the workpiece. Therefore, in the detection scheme based on the principle of internal reflection, the most important mechanical positioning error is the offset error between the center of the mirror and the center of the workpiece.

![Figure 4. Measurement coordinate system](image)

The coordinate system shown in Figure 4 is established, and the offset error in the y direction is e, the influence of e is that the AB segment of the inner wall originally measured becomes A'B'. Take the center point of the workpiece inner wall as the origin and let $\alpha = 10^\circ$, $R = 2.25$ mm, $e = 150 \mu$m, the four points can be calculated: $A(2.2414,0.1961)$, $B(2.2414,-0.1961)$, $A'(2.2235,0.3445)$, $B'(2.2495,-0.0468)$.

Substitute the value and calculate the $A'B'$ chord length:

$$d_{A'B'} = \sqrt{(x_{A'} - x_B)^2 + (y_{A'} - y_B)^2} = 0.39216mm$$

(7)
Calculate the corresponding center angle $\alpha'$ on the circle $O_2$:

$$\alpha' = 2 \arcsin \frac{\alpha B}{2R} = 9.9990^\circ$$  

(8)

Calculate the absolute error:

$$\Delta l = l_{AB} - l_{\alpha'B} = 2\pi R \cdot (10 - 9.9990)/360 = 3.927 \times 10^{-5} \text{mm}$$  

(9)

Calculate the relative error:

$$\sigma = \frac{(0.001 \div 10) \times 100\%}{100\%} = 0.01\%$$  

(10)

For a workpiece with an inner diameter of 4.5 mm and a reflector with a diameter of 4.2 mm, if they are completely concentric, the annular gap between the two circles is 150 $\mu$m. From the error calculation above, it can be known that when the center angle of each measurement is 10°, the relative error can be controlled within 0.01% which can be ignored.

4. **Experimental result**

Based on the established experimental platform, an image of a circumference of the inner wall of the workpiece is obtained after image stitching processing as shown in Figure 5.

![Mosaic image of one circumference of the inner wall](image)

**Figure 5.** Mosaic image of one circumference of the inner wall

5. **Conclusion**

This paper introduces the principle and implementation of a method for visual inspection of the inner wall of a micro-hole workpiece based on the principle of internal reflection. Since the scope of the inner wall image that can be observed with each single shot is limited, continuous rotation measurement and image stitching are used to obtain a complete image of the inner wall of the small hole. Compared with traditional detection methods, this scheme is suitable for both through-hole and non-through-hole workpieces with an inner diameter of 2-10 mm, and has high resolution, which can reach the level of 10 $\mu$m, small positioning errors, high image reduction, and high feasibility.

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