Calibration of WLI Lateral Indication Error with 2D Micro/Nano Pitch Standard

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Abstract. White light interferometer (WLI) is one of the common machines that are used to characterize surface structures. The indication errors of WLI are key metrologic characteristics, which may affect evaluation result of WLI. In this paper, a two-dimensional micro/nano pitch (2D pitch) standard is introduced to calibrate the lateral indication error of WLI. The calibrating experiments are carried out in four measurement positions. The results and the uncertainty is analyzied. And the expanded uncertainty of WLI in lateral measurement (x50) is evaluated as tens of nanometer.

1. Introduction
With advantages [1] of non-contact, large measurement range, high resolution, WLI is widely applied in the measurement of optical element surface [2] and microstructure [3]. Thus it's necessary to accurately calibrate and evaluate the lateral indication error of WLI.

WLI needs a certain height to generate interferometric fringe. Instead of line scale, which is usually used to calibrate imaging probe measuring machines, 2D pitch standard with the features of both lateral and vertical information and high resolution is suitable for calibrating the lateral indication error of WLI.

2. Theory

2.1. Theory of WLI
Using a wide spectrum light source, coherent peak of WLI appears in a limited range. Surface structure of the sample can be measured by moving the scanning platform, and the measurement data contains the relative height information of the test area. Surface structure can be obtained by reconstructing the measurement data [4]. Select a line on and paralleled to the edge of the pitch, intercept periods and calculate the average pitch distance. The basic structure of the WLI is shown in figure 1.
2.2. Structure and traceability of 2D pitch standard

2D pitch standard is used to calibrate the lateral indication error of high-precision micro/nano measuring instruments, such as scanning probe microscopes, electron microscopes (transmission electron microscopes and scanning electron microscopes), profile meters, and step profilers [5]. The typical structure of a 2D pitch standard is shown in figure 2. Compared with the one-dimensional pitch standard, the 2D pitch standard, which includes the information of X direction, Y direction, and the angle between them, is more convenient for evaluating two-dimensional coordinates.

Figure 1. The basic structure of the WLI.

Figure 2. The typical structure of a 2D pitch.

Traceability system of 2D pitch standard is shown in figure 3.
3. Calibration method

Calibrate the WLI with STS2-1800P made by VLSI.

Place and measure the 2D pitch standard along the XY direction and the diagonal direction [6], as shown in figure 4. Measure the 4 measurement positions with WLI: X direction, Y direction, diagonal direction 1, diagonal direction 2. Measure 5 sets of intervals at each measurement position, and measure 3 times for each set of intervals [7].

As shown in figure 5, intercept complete pitch periods in each set of interval image, and calculate average pitch distance of each set of interval and the measurement position. According the nominal
quantity value of the 2D pitch standard, which is 4.999 μm, get the indication error of the standard \(^8\).

With the experimental data of 3 measurements in each set of interval, use poor formula to calculate experimental standard deviation, and obtain the combined sample standard deviations of each measurement position, as shown in table 1.

| Table 1. Measurement result. |
|-----------------------------|
| measurement position | interval length | average pitch distance/μm | indication error/μm | experimental standard deviation /μm | combined sample standard deviation/μm |
|------------------------|-----------------|--------------------------|------------------|--------------------------|-----------------|
| X direction            | 2 pitches       | 5.0149                   | 5.006            | E_x=0.007               | 0.0231          |
|                        | 10 pitches      | 5.0134                   |                  |                         |                 |
|                        | 10 pitches      | 5.0045                   |                  |                         |                 |
|                        | 10 pitches      | 4.9963                   |                  |                         |                 |
|                        | 20 pitches      | 5.0011                   |                  |                         | 0.0030          |
| Y direction            | 2 pitches       | 4.9833                   | 4.989            | E_y=0.010               | 0.0035          |
|                        | 10 pitches      | 4.9909                   |                  |                         | 0.0061          |
|                        | 10 pitches      | 4.9848                   |                  |                         | 0.0117          |
|                        | 10 pitches      | 4.9862                   |                  |                         | 0.0014          |
|                        | 20 pitches      | 4.9996                   |                  |                         | 0.0035          |
| diagonal direction 1   | 2 pitches       | 4.9938                   | 4.997            | E_1=0.002               | 0.0059          |
|                        | 15 pitches      | 4.9921                   |                  |                         | 0.0054          |
|                        | 15 pitches      | 4.9936                   |                  |                         | 0.0091          |
|                        | 15 pitches      | 4.9979                   |                  |                         | 0.0104          |
|                        | 28 pitches      | 5.0081                   |                  |                         | 0.0053          |
| diagonal direction 2   | 2 pitches       | 5.0031                   | 4.997            | E_2=0.002               | 0.0103          |
|                        | 15 pitches      | 4.9922                   |                  |                         | 0.0016          |
|                        | 15 pitches      | 4.9939                   |                  |                         | 0.0122          |
|                        | 15 pitches      | 4.9915                   |                  |                         | 0.0016          |
|                        | 28 pitches      | 5.0053                   |                  |                         | 0.0021          |

4. Uncertainty evaluation

Combined standard uncertainty \(u_c\) of WLI is\(^9\)

\[
u_c = \sqrt{u^2(\Delta l_1) + u^2(\Delta l_2) + u^2(\Delta l_3) + u^2(\Delta l_4)}
\] (1)

Where \(u(\Delta l_i)\) is standard uncertainty introduced by repeated measurement or indication resolution. \(u(\Delta l_i)\) standard uncertainty introduced by 2D pitch standard. \(u(\Delta l_i)\) is standard uncertainty introduced by temperature changes. \(u(\Delta l_i)\) is standard uncertainty introduced by Abbe error.

4.1. Standard uncertainty introduced by repeated measurement or indication resolution \(u(\Delta l_i)\)

(1) Standard uncertainty introduced by repeated measurement \(u(\Delta l_i)\)

\(u(\Delta l_i)\) belongs to type A evaluation of measurement uncertainty, is combined sample standard deviation in table 1. And \(u(\Delta l_i)\) in each measurement position is:

| measurement position | \(u(\Delta l_i)/\mu m\) |
|----------------------|------------------------|
| X direction          | 0.0112                 |
| Y direction          | 0.0079                 |
| diagonal direction 1 | 0.0075                 |
| diagonal direction 2 | 0.0073                 |

(2) Standard uncertainty introduced by indication resolution\(^10\).

\(u(\Delta l_i)\) belongs to type B evaluation of measurement uncertainty. Indication resolution of WLI can reach 1nm, and \(u(\Delta l_i)\) is
Thus, \( u(\Delta l_1) = u(\Delta l_2) \).

### 4.2. Standard uncertainty introduced by 2D pitch standard \( u(l_s) \) (Type B evaluation of measurement uncertainty)

Calibration certificate of the 2D pitch standard shows its uncertainty as: \( U = 0.008 \mu m \), \( k = 2 \). And \( u(l_s) \) is

\[
u(l_s) = 0.004 \mu m \tag{3}
\]

### 4.3. Standard uncertainty introduced by temperature changes \( u(\Delta l_e) \) (Type B evaluation of measurement uncertainty)

The 2D pitch standard used in calibration is made by silicon, which thermal expansion coefficient is \( 2.5 \times 10^{-6}/\degree C \) \cite{11}. During calibration, temperature changes in 1°C, and half-width is 0.5°C. Assuming that the standard uncertainty introduced by temperature changes obeys uniform distribution, then

\[
u(\Delta l_e) = \frac{2.5 \times 10^{-6} \times 0.5 \times 1.999}{\sqrt{3}} = 3.61 \times 10^{-6} \mu m \tag{4}
\]

Compared with other uncertainties, \( u(\Delta l_e) \) is small and can be ignored.

### 4.4. Standard uncertainty introduced by Abbe error \( u(\Delta l_a) \) (Type B evaluation of measurement uncertainty)

During the measurement, the selected line does not parallel to the measurement direction, causing an angle \( \theta \), shown in figure 6.

**Figure 6.** Schematic diagram of Abbe error.

Introduced Abbe error is

\[
\Delta l_a = l - l_0 = l(1 - \cos \theta) \tag{5}
\]

Where \( \Delta l_a \) is Abbe error/\( \mu m \). \( l \) is measured average pitch distance of the measurement position/\( \mu m \). \( l_0 \) is theoretical average pitch distance of the measurement position/\( \mu m \). \( \theta \) is the angle between the selected line and measurement direction/°.

\( \theta \) is less than 1°. According to average pitch distance of each measurement in table 1, Abbe error can be acquired.

\[
u(\Delta l_a) = \frac{\Delta l_a}{2 \sqrt{3}} \tag{6}
\]

Abbe error and standard uncertainty of each measurement position are shown in table 2.

**Table 2.** Abbe error and standard uncertainty of each measurement position.

| measurement position     | \( \Delta l_a/\mu m \) | \( u(\Delta l_a)/\mu m \) |
|--------------------------|------------------------|---------------------------|
| X direction              | 0.0008                 | 0.0002                    |
| Y direction              | 0.0008                 | 0.0002                    |
| diagonal direction 1     | 0.0008                 | 0.0002                    |
| diagonal direction 2     | 0.0008                 | 0.0002                    |
4.5. Combined standard uncertainty and expanded uncertainty

Combined standard uncertainty $u_c$ can be got from equation (1).

Expanded uncertainty $U$ is

$$U=ku_c$$ (7)

Where $k$ is coverage factor, and $k=2$.

Combined standard uncertainty $u_c$ and Expanded uncertainty $U$ of WLI are shown in table 3.

| measurement position | $u_c/\mu m$ | $U/\mu m$, $k=2$ |
|----------------------|-------------|------------------|
| X direction          | 0.0119      | 0.024            |
| Y direction          | 0.0088      | 0.018            |
| diagonal direction 1 | 0.0085      | 0.017            |
| diagonal direction 2 | 0.0083      | 0.017            |

5. Conclusion

This paper uses 2D pitch standard to calibrate 4 measurement positions of WLI and obtain the measurement results. According to the theory of white light interference, the measurement results and the factors that may affect them are analyzed. The calibration result of WLI is: X direction - indication error $E_X=0.007\mu m$, Expanded uncertainty $U=0.024\mu m$, $k=2$. Y direction - indication error $E_Y=0.010\mu m$, Expanded uncertainty $U=0.018\mu m$, $k=2$. Diagonal direction 1- indication error $E_1=0.002\mu m$, Expanded uncertainty $U=0.017\mu m$, $k=2$. Diagonal direction 2- indication error $E_2=0.002\mu m$, Expanded uncertainty $U=0.017\mu m$, $k=2$.

6. Acknowledgments

This work was financially supported by National Key R&D Program of China “Basic Technology and Key Components on Manufacturing” (2019YFB2004904), Science and Technology Plan of Shanghai Administration for Market Regulation (2019-02) and Shanghai sailing program (19YF1441700).

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