A straightness error measurement method matched new generation GPS

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Abstract. The axis of the non-diffracting beam produced by an axicon is very stable and can be adopted as the datum line to measure the spatial straightness error in continuous working distance, which may be short, medium or long. Though combining the non-diffracting beam datum-line with LVDT displace detector, a new straightness error measurement method is developed. Because the Non-diffracting beam datum-line amends the straightness error gauged by LVDT, the straightness error is reliable and this method is matchs new generation GPS.

1. Introduction
Measurement of the straightness error is one of the traditional, basic, and important dimensional measurement items [1]. The enlarged laser beam of the He-Ne laser is one of the most successful datum-lines for contemporary straightness error measurement’s methods [2-4]. The measuring resolution of this measurement datum-line is usually about 1˝ and the maximum of the error is nearly 4.9µm·m

In order to reduce the error of the datum-line, the non-diffracting beam is adopted as a datum-line for measurement of the straightness error.

The study of the theory and the realization of the non-diffracting beam began in 1983. Durnin [5] gave the solution with the type of zero-order Bessel function in 1987. Since then, many ways have been developed to produce non-diffracting beams, such as axicons [6], holograms, spatial light modulators, phase gratings, and spherical aberration lenses. Among all these methods, an axicon is the most efficient for producing nearly non-diffracting beams [7].

The axis of the non-diffracting beam produced by an axicon is very stable [8-10] and it can be adopted as the datum line to measure the spatial straightness error in continuous working distance, which may be short, medium or long. Though combining the non-diffracting beam datum-line with LVDT displace detector, a new straightness error measurement method is developed.

2. Principle of the straightness error measuring system
The principle of the straightness error measuring system is shown in figure 1.

The coordinates are shown in figure 1, the datum-line of the straightness error measurement is along Z-direction and the displacement detector is fixed along the vertical direction, Y-direction. The imaging detector is CCD which is fixed on the same rod as the displacement detector is.

The principle of the straightness error measuring system is as follows:

Firstly, a Z-direction linear worktable drives the displacement detector and the CCD to the positions along Z-direction and this makes sure that the measuring error gauged by the displacement detector is in its measuring range and the Bessel fringe rings’ image of the Non-diffracting beam can always illuminate CCD.

Secondly, set the initial value of the surface of workpiece Yi=0. Z-direction the linear worktable drives the displacement detector and the CCD to the position Zi=z0. The displacement detector gauges the first value (Yi) of the surface of the workpiece. At the same time, the CCD captures the Bessel fringe rings’ image of
Figure 1. The principle of the straightness error measuring system

the non-diffracting beam. The Bessel fringe rings and their centers on every section which is perpendicular to Z-axis contain the required information of non-diffracting beam datum-line. After the Bessel fringe rings are detected by the CCD, their center is obtained. Therefore, the offset of the pre-set datum-point of the CCD to the center of the Bessel fringe rings means the same as the offset of pre-set datum-point of the CCD to the non-diffracting beam datum-line. The offset of the CCD embodies the offset of the designed point of the displacement detector in the cross-section perpendicular to the non-diffracting beam datum-line.

Thirdly, the Z-direction linear worktable drives the displacement detector to the position \( z \). Obtains the relative displacement error of the surface of the workpiece and the offset of the designed point of the displacement detector. For different position \( z \) of the Z-direction linear worktable, repeat the above steps to obtain all the displacement errors and the set of the offset of the designed point of the displacement detector.

Finally, the relative displacement errors of the surface of the workpiece are amended with the corresponding offset of the designed point of the displacement detector. So the displacement error of the surface of workpiece is acquired on the non-diffracting beam datum-line and the straightness error is calculated.

3. Characteristics

International organization for standardization, ISO/TC 213, has publicized new generation Dimensional Geometrical Product Specification and Verification (GPS), for example: ISO14660 [11] and ISO 12780 [12] since 1999. Its theoretical basis is metrology and it defines using the set of measured points to represent the real surface.

This straightness error measuring method can gauge how many points of measured surface needed to represent the measured real surface and it is not just a gauge of several points of the measured surface that are equal span, so it is matches new generation GPS.

The straightness error measuring method is reliable when the non-diffracting beam datum-line is isolated and for it is not interfered by the other sets of the measuring system.

4. Testing results and error analysis

Figure 2. The setup of the straightness error measuring system

Figure 2 shows the setup of the straightness error measuring system (The setup of the measuring system can also be improved to measure the coaxiality of a hole). The displacement detector in the system is LVDT and \( Y_i = 0 \mu m \). The working area of CCD is \( \pm 1 \text{mm} \times \pm 0.975 \text{mm} \).

Figure 3 is one Bessel fringe rings’ image of the non-diffracting beam.

The test data of spatial straightness error are obtained by the straightness error measurement method using non-diffracting beam as the datum-line. The sampling method to obtain the following test data is same as ordinary equ-space sampling method. The unit of \( y \), \( ry \), \( y_1 \) and \( dy \) to the reference line of error evaluation is \( \mu m \) and that of \( z \) is \( mm \).
4.1. The test data of GJZ optical bench and its assessment

The straight rail, GJZ optical bench, is produced by the workshop of HUST. Its work length is 1530mm and its straight error along the x-direction is less than 30µm /1m.

Measure the straight rail under the same conditions as above. Set $z_0=400mm$ (corresponding to the position 100mm of the straight rail) and increase due span per step is +70mm along Z-direction. The measuring distance range is 0.4-1.8m behind the axicon.

The offset $y(z_i)$ at position $z_i$ to the reference of the non-diffracting beam is calculated from the Bessel fringe rings' image of the non-diffracting beam measured by CCD. All of the offsets at the different positions are shown in Table 1.

Table 1. All of the offsets at position $z_i$ on GJZ optical bench

| $z_i$ (mm) | 400 | 470 | 540 | 610 | 680 | 750 | 820 | 890 | 960 | 1030 | 1100 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| $y_i$ (µm)| 1.2 | 12.1| 20.0| 16.6| 12.8| 3.5 | -5.8| 7.3 | 15.0| 23.1 | 3.7  |

The relative displacement errors, $r_y$, of the surface of workpiece obtained are shown in figure 4.

The displacement errors, $y_f$, that are amended with the corresponding offset of the designed point of the displacement detector are shown in figure 5.

Error evaluation based on minimum zone condition method, the maximum straightness error along Z-direction: $d_{x_{max}} = 36.4017µm$.

Based on least squares sum condition, the reference line of error evaluation is given[13,14] from Table 1 as follows:

$$ x = -0.0213z + 17.2435 $$

The straightness deviations, $d_y$, are shown in figure 6 on the reference line of error evaluation. The straightness deviation is -19.8607µm at position $z=1170mm$ and the straightness deviation is 17.9892µm at position $z=540mm$, so the maximum straightness error $d_{x_{max}} = -37.8499µm$.

4.2. Error analysis.
The errors of the system are produced by the following sources:

![Graph showing the straightness error](image)

Figure 6. The straightness error

4.2.1. The measuring uncertainty related to the Non-diffracting beam datum-line. The excursion uncertainty of the non-diffracting beam datum-line, which is the maximum excursion error of the center of the Bessel fringe rings to its average position, is 0.2333 μm within 45 minutes after laser is turned on for half an hour and the working distance is within 1.5 m.

Assume the calculating precision of the centers of the Bessel fringe rings’ image of the non-diffracting beam is ±1/20 of the pixel dimension—± 0.325 μm, so the measuring uncertainty of the CCD related to the non-diffracting beam datum-line is about ± 0.65 μm. Abbe error is less than 0.2 μm when the CCD is fixed inclined ± 0.8102°. So the measuring uncertainty related to the datum-line is close to 0.7190 μm.

4.2.2. The measuring uncertainty of LVDT is about ± 0.4 μm when error measuring range is -200~+200 μm.

4.2.3. The other errors is less than ± 0.3 μm from other influences which are not investigated.

4.2.4. Therefore, the whole measuring uncertainty is estimated as

\[ U_y = \sqrt{\sum \Delta r^2} = 0.8757 \ (\mu m) \]

Which is less than 0.9 μm within 1.5 m.

5. Conclusions

It is concluded that

1. Combining the Non-diffracting beam datum-line with LVDT displacement measuring technology, a straightness error measurement method is developed in this paper and it is matched the new GPS.

2. The related measuring uncertainty of this straightness error measuring system related to the datum line is less than 0.7190 μm when measuring distance range is within 1.5 m and the measuring uncertainty of this system is less than 0.9 μm.

3. The straightness error measuring method is reliable for the non-diffracting beam datum-line when isolated and when it is not interfered by the other sets of the measuring system. It is simple, easy to operate, small in size, durable and cheap. It can be widely applied under present technology conditions.

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