A novel two-point method for straightness profile measurement based on a shifting reference plate

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Abstract

The present study deals with a novel two-point method for measuring straightness profile. Through analytical and experimental verification, the method was revealed that random noise of displacement sensor increases uncertainty in final measurement result and level meter uncertainty causes parabolic deviation in the result. Some smoothing techniques using digital filters might be necessary to reduce such unfavourable components.

1 Introduction

Recently, a much more practical straightness measuring method is needed in industry. The fundamental two-point method based on software datum[1],[2] was proposed in order to reduce lifting component of traversing displacement sensor. In this paper a modified two-point method utilizing a shifting reference plate is newly proposed. This method possesses the advantage of simple operations with high accuracy. Some analytical results on measurement uncertainty[2] are shown.

2 Measuring principle of developed system

The measuring principle of the proposed method is illustrated in Fig.1 with its measurement procedures.

(i) Measure the pitching (slope) of reference plate by level meter.

(ii) Measure the gap between reference plate and surface plate by displacement sensor at every sampling point in the traversing direction.

(iii) After shifting the reference plate by s which is equal to p, measure the pitching of the reference plate by level meter. Then repeat (ii) again.

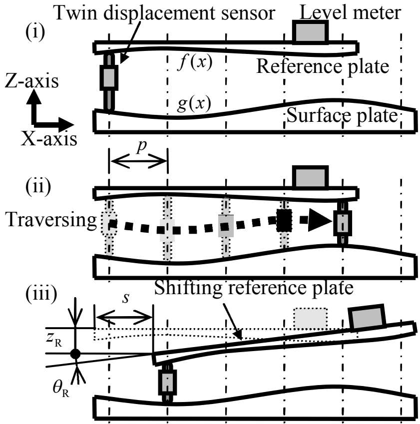

Figure 1: Illustration of two-point method utilizing a shifting reference plate

2.1 Influence of sensor motion error on profile measurement

In the case of (ii), twin displacement sensor such as twin heads air micrometer can measure always real gap even if the sensor head moves up and down because both the measuring axes are parallel and their directions are opposite. Due to about $\phi 1$mm sensing areas of the air micrometer, it is less sensitive to micro-geometry of target surfaces. And also dust on the surfaces can be blown away.

2.2 Consideration of reference plate profile and its motion error

When shifting the reference plate (iii), its profile deviation and attitude change should be considered. Displacement sensor readings, $m_1(x)$ before shift and $m_2(x)$ after shift, can be expressed as follows.

$$m_1(x) = -g(x) + f(x) \tag{1}$$

$$m_2(x) = -g(x+s) + f'(x) = -g(x+s) + f(x) + z_R + \theta_R \cdot x \tag{2}$$

where, x is distance from the origin in X-axis, $f(x)$ is profile of reference plate, $g(x)$ is surface plate profile at the begining, reference plate profile after shift is $f'(x)$, its shifting space is s, and lifting and pitching of reference plate after shift are z_R and θ_R respectively. Then, from the difference between eqs. (1) and (2), following equations for obtaining $g(x)$ can be drawn.

$$g(x+s) = g(x) + m_1(x) - m_2(x) + z_R + \theta_R \cdot x \tag{3}$$

$$g(x_{k+1}) = g(x_k) + m_1(x_k) - m_2(x_k) + z_R + \theta_R \cdot x_k \tag{4}$$

where, total sampling point number is n, sequential sampling points are $k = 0, 1, 2, \cdots, n\text{-}1$, and discrete distances in X-axis are $x_k = ks = 0, s, 2s, \cdots, (n\text{-}1)\, s$.

Finally, we can introduce general recursion formula as follows.

$$g(x_k) = g(x_0) + \sum_{i=0}^{k-1} \{m_1(x_i) - m_2(x_i)\} + z_{\mathrm{R}} k + \theta_{\mathrm{R}} k(k+1)s/2 \qquad (5)$$

It is neccessary to remove trend component of surface plate. By knowing the data (x_0, $g(x_0)$) and ($x_{n\text{-}1}$, $g(x_{n\text{-}1})$) at start and end points, the straightness profile of surface plate to be measured $g^*(x)$ can be expressed by the following equation.

$$g^*(x_k) = \sum_{i=0}^{k-1} \{m_1(x_i) - m_2(x_i)\} - \frac{k}{n-1} \sum_{i=0}^{n-2} \{m_1(x_i) - m_2(x_i)\} - \theta_{\mathrm{R}} k(n-1-k)s/2 \qquad (6)$$

Here, we can say that $g^*(x)$ is not affected by reference plate profile $f(x)$ and lifting of reference plate z_{R}. Measuring $m_1(x_k)$ and $m_2(x_k)$ by twin type displacement sensor and θ_{R} by a level meter, we can obtain $g^*(x)$ in a recursive way.

3 Measurement uncertainty analysis by simulation

Measurement uncertainty of the proposed method consists of 1) uncertainty of level meter and that of displacement sensor, 2) uncertainty due to drift(temperature), 3) variation of measuring position, 4) aging effect and so on. The most significant component might be 1), and so we analysed its influences by simulation under a sinusoidal straightness profile of 300mm in length and 0.1μm in amplitude.

3.1 Parabolic deviation based on uncertainty of level meter

Considering the third term of Eq (6), we can say that parabolic convex deviation with null values $g^*(x_0)$ (start point) and $g^*(x_{n\text{-}1})$ (end point) is caused. The maximum value of this deviation P is given by the following equation.

$$max\, P(x_k) = P(x_{(n-1)s/2}) = \Delta\theta_{\mathrm{R}} (n-1)^2 s/8 = \Delta\theta_{\mathrm{R}} (n-1) L/8 \qquad (7)$$

where, $\Delta\theta_{\mathrm{R}}$ is uncertainty of level meter. When sampling point number n = 31, sampling interval p, which is identical to shifting space s, becomes 10mm under the condition that L = 300mm. And if $\Delta\theta_{\mathrm{R}}$ = 0.3μm/m, $P_{\max}$ becomes 0.3μm.

3.2 Random noise propagation of displacement sensor

Fig.2 and Fig.3 show simulation results when random noise of displacement sensor follows a normal distribution with 0.03μm standard deviation u_{S}. Maximum uncertainty u of straightness profile becomes 0.08μm as shown by error bar in the middle of Fig.2. In other words, measurement uncertainty of straightness profile is amplified from the sensor uncertainty of 0.03μm up to 0.08μm. Additionally from Fig.3, it is clear that the standard uncertainty is increased with sampling point number.

As a countermeasure to increase in the measurement uncertainty, ensemble averaging is a trick. But it is a time-consuming work. Smoothing the displacement sensor readings $m_1(x)$ and $m_2(x)$ by Spline filter or Gaussian filter might be a better solution.

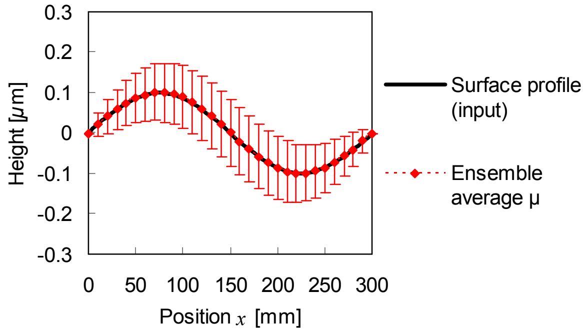

Figure 2: Standard uncertainty due to random noise of displacement sensor (n=31)

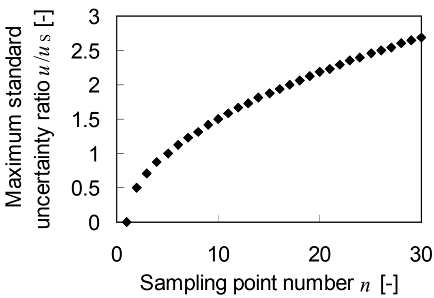

Figure 3: Relationship between sampling point number and the standard uncertainty

4 Conclusions

We proposed a new two-point method for straightness profile measurement in this paper. Through analytical simulation, following concluding remarks were obtained.

1) Owing to the measuring principle, inevitable parabolic deviation arises in measured straightness profile by uncertainty of the level meter.
2) The displacement sensor uncertainty can be propagated for the uncertainty of obtained straightness profile.
3) The uncertainty of 2) is increased with sampling point number. Certain smoothing technique is needed to reduce the noise component of the sensor.

References:

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[2] Eiki Okuyama, Precision Engineering, Vol.34, No.4, (2010), 683–691.