STRAIGHTNESS MEASUREMENT OF CYLINDER BY MULTI-PROBE METHOD

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Abstract: This paper presents a new multi-probe method for accurately measuring straightness profiles of cylinders. This scanning probe method is developed from the traditional three-probe method, which can measure the profile accurately without the influence of motion errors of the scanning stage. Two sets of three-probe method sensor units are used in the developed method so that the zero-adjustment errors between the probes can be evaluated. The two sensor units are placed in the two sides of the cylindrical workpiece and are used to scan the two opposed generatrices of the cylindrical workpiece simultaneously. The workpiece is then rotated 180 degrees and scanned by the probe units again. The zero-adjustment error, as well as the straightness profiles of the workpiece can be accurately evaluated from the output data of the two measurements. The effectiveness of this method is confirmed by theoretical analyses and experimental results. The problem in another method, which was previously used by the authors to measure the zero-adjustment error between the probes, is also discussed.

Keywords: multi-probe method, straightness, zero-adjustment error

1   INTRODUCTION

In order to improve accuracy in the precision machining of cylindrical workpieces, on-machine straightness measurements have become increasingly important. The scanning probe method is the only way that can be used for this purpose. In this method, a displacement probe, which is mounted on the carriage of the machine tool, is moved axially to scan the generatrix of the cylindrical workpiece. The linear feed motion of the machine is used as the measurement reference. The output of the displacement probe includes the term for the profile height of the workpiece straightness as well as the translation error and tilt error of the scanning stage. To accurately measure straightness profiles of cylindrical workpieces in on-machine conditions, it is important to separate the profile from motion errors of the scanning stage. Basically, there are two kinds of error separation methods [1]. One is the reversal technique, and the other is the multi-probe method. Reversal technique, which employs only one probe, is simple and effective when motion errors are repeatable. Compared with the reversal technique, multi-probe methods are more suitable for on-machine measurements, because the repeatability of the motion error is not necessary.

The two-probe method [2][3] using two displacement probes is the simplest multi-probe method. This method can be used only when the tilt error of the scanning stage is relatively small. In contrast, the three-probe method [4], which uses three displacement probes, can eliminate the influence of the tilt error as well as the translation error. The differential laser autocollimation (DLA) method [5] which employs two angular probes, and the mixed method [6], which employs two displacement probes and one angular probes, can also eliminate the tilt error. These methods, however, share the inherent problem that their zero-adjustment error among probes [7] introduces a parabolic error in the measured profile. So far, zero-adjustment has been accomplished by measuring an accurate reference surface. However this method is not efficient for straightness measurement of long cylinders since the parabolic error is proportional to the square of the measurement length and even a small zero-adjustment error introduced by the flatness error of the reference surface will cause a large profile measurement error. For this reason, the zero-adjustment error is the largest error source for straightness measurement of long cylinders by multi-probe methods.

In this paper, we develop a new method that can eliminate the effect of the zero-adjustment error by using only the output data of the probes. Principle and experimental results are shown in this paper.
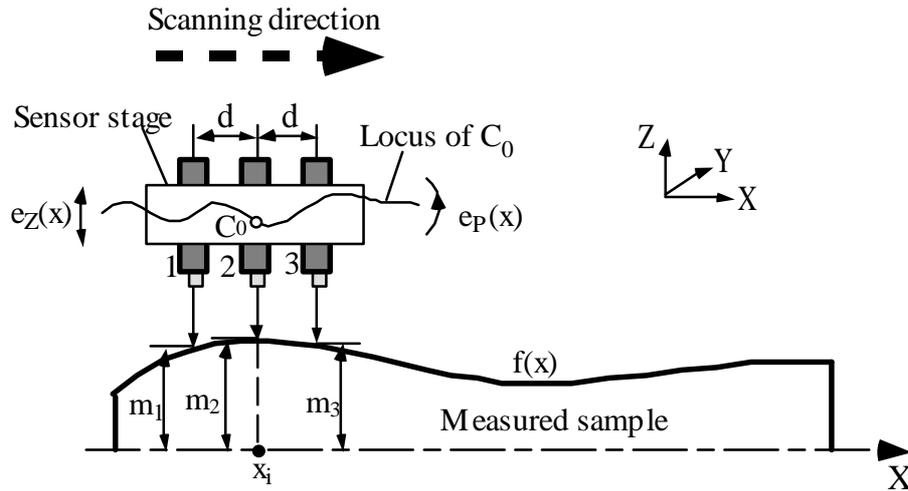
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Figure 1. Principle of the three-probe method

The problem in another method [8], which was previously used by the authors to measure the zero-adjustment error between the probes, is also discussed.

2   THREE-PROBE METHOD AND THE ZERO-ADJUSTMENT

Figure 1 shows the principle of the three-probe method. In this method, three probes are mounted on the scanning stage and used to scan the profile $f(x)$ of the workpiece. Let the probe outputs be m_1, m_2 and m_3, they can be expressed as:

$$m_1(x_i) = f(x_i - d) + e_z(x_i) - d e_p(x_i) \tag{1}$$

$$m_2(x_i) = f(x_i) + e_z(x_i) \tag{2}$$

$$m_3(x_i) = f(x_i + d) + e_z(x_i) + d e_p(x_i) \qquad (i=1,\dots N) \tag{3}$$

where x_i is the sampling position and N is the sampling number. e_z and e_p are the translation error and tilt error of the scanning stage, respectively.

A differential output m_s is calculated to cancel the influence of the scanning errors:

$$\begin{aligned} m_s(x) &= \frac{m_3(x) - 2m_2(x) + m_1(x)}{d^2} \\ &= \frac{f(x_i + d) - 2f(x_i) + f(x_i - d)}{d^2} \\ &\approx f''(x_i) \end{aligned} \tag{4}$$

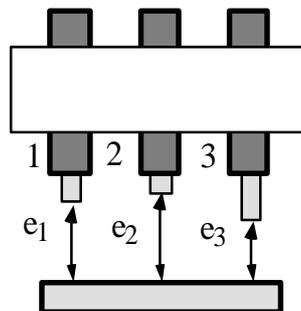The profile can thus be calculated from double integration of $f''(x)$ without the influence of the scanning errors.

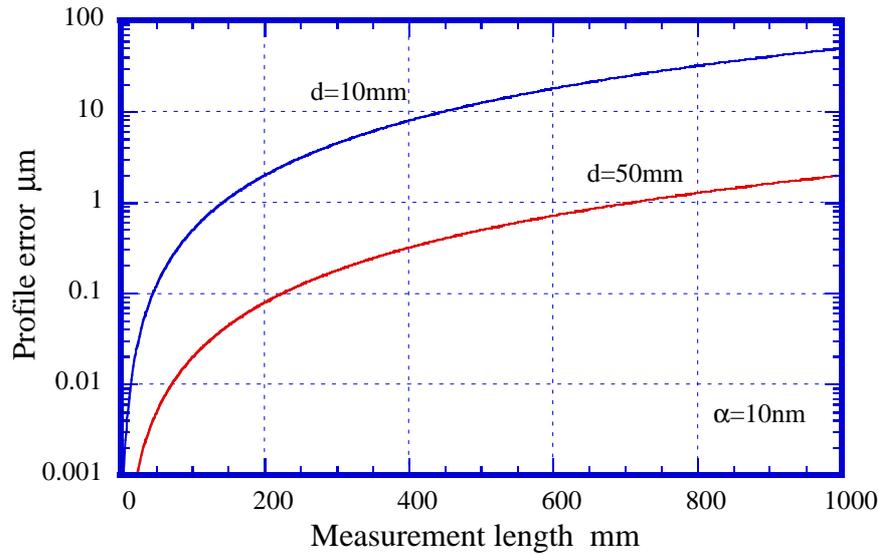**Figure 2.** Zero-adjustment error between probes

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Figure 3. Profile error caused by the zero-adjustment error

$$f_1(x) = \iint f''(x)\,dx \tag{5}$$

On the other hand, however, the zero-adjustment error between probes will introduce an error in the calculated profile. As can be seen in Figure 2, assume that the probe outputs are e_1, e_2, e_3 when the probes are used to measure a perfect flat surface. The differential output m_s will become:

$$m_s(x) = f''(x) + \frac{a}{d^2} \tag{6}$$

where, α is called as the zero-adjustment error α of the three-probe method, and is denoted as:

$$a = e_3 - 2e_2 + e_1 \tag{7}$$

The calculated profile $f_1(x)$ then becomes:

$$f_1(x) = f(x) + \frac{a}{2d^2}\,x^2 \tag{8}$$

It can be seen that a parabolic error term in the calculated profile is caused by the zero-adjustment error. Since this profile error is proportional to the square of the measurement length, large profile errors will be caused in the measurement of long profiles. As can be seen in Figure 4, a 10 nm zero-adjustment error will cause a profile error of 50 μm and 2 μm when the probe distance is set to be 10 mm and 50 mm respectively for a measurement length of 1 m. It is obvious that it is difficult to get a reference that is flat enough to accomplish the zero-adjustment between probes.

3   A NEW ZERO-ADJUSTMENT METHOD

In this method two sets of three-probe sensor units are used. As shown in Figure 4, the two sensor units are placed in the two sides of the cylindrical workpiece and are used to scan the two opposed generatrices of the cylindrical workpiece simultaneously. The following equations can be obtained from the measurements:

$$m_1'(x_i) = \frac{m_2(x_i) - m_1(x_i)}{d} = \frac{f(x_i) - f(x_i - d)}{d} + e_{p1}(x_i) \tag{9}$$

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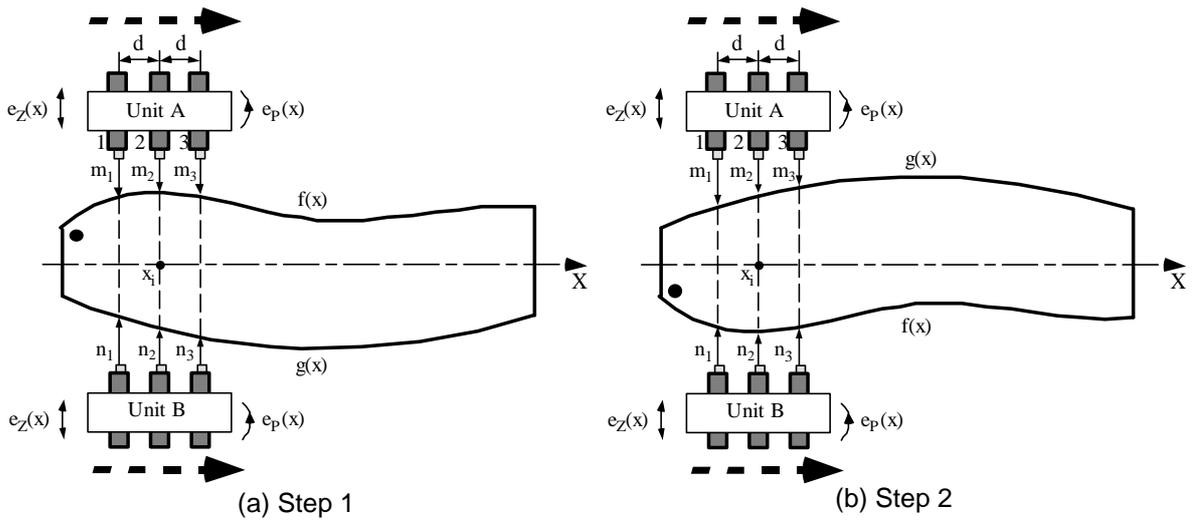(a) Step 1   (b) Step 2

Figure 4. Principle of the zero-adjustment method

$$m'_2(x_i) = \frac{m_3(x_i) - m_2(x_i)}{d} = \frac{f(x_i + d) - f(x_i)}{d} + e_{p1}(x_i) + \frac{a}{d} \tag{10}$$

$$n'_1(x_i) = \frac{n_2(x_i) - n_1(x_i)}{d} = \frac{g(x_i) - g(x_i - d)}{d} - e_{p1}(x_i) \tag{11}$$

$$n'_2(x_i) = \frac{n_3(x_i) - n_2(x_i)}{d} = \frac{g(x_i + d) - g(x_i)}{d} - e_{p1}(x_i) + \frac{b}{d} \tag{12}$$

where α and β are the zero-adjustment errors of the two sensor units. $f(x)$ and $g(x)$ are the profiles of the two generatrices. $e_{p1}(x)$ is the tilt error during scanning.

The workpiece is then rotated 180 degrees and scanned by the probe units again. The following equations can be obtained as follows, where $e_{p2}(x)$ is the tilt error during the second scanning.

$$m'_{1r}(x_i) = \frac{m_{2r}(x_i) - m_{1r}(x_i)}{d} = \frac{g(x_i) - g(x_i - d)}{d} + e_{p2}(x_i) \tag{13}$$

$$m'_{2r}(x_i) = \frac{m_{3r}(x_i) - m_{2r}(x_i)}{d} = \frac{g(x_i + d) - g(x_i)}{d} + e_{p2}(x_i) + \frac{a}{d} \tag{14}$$

$$n'_{1r}(x_i) = \frac{n_{2r}(x_i) - n_{1r}(x_i)}{d} = \frac{f(x_i) - f(x_i - d)}{d} - e_{p2}(x_i) \tag{15}$$

$$n'_{2r}(x_i) = \frac{n_{3r}(x_i) - n_{2r}(x_i)}{d} = \frac{f(x_i + d) - f(x_i)}{d} - e_{p2}(x_i) + \frac{b}{d} \tag{16}$$

The zero-adjustment errors α and β can then be calculated from the following equations:

$$b - a = \frac{d}{2N} \sum_{i=1}^{N} \left\{ \begin{array}{l} (n'_{2r}(x_i) - n'_{1r}(x_i)) \\ - (m'_2(x_i) - m'_1(x_i)) \\ + (n'_2(x_i) - n'_1(x_i)) \\ - (m'_{2r}(x_i) - m'_{1r}(x_i)) \end{array} \right\} \tag{17}$$

$$a + b = -\frac{d}{2(N-D)} \sum_{i=1}^{N-d} \left[\begin{array}{l} \left\{ \begin{array}{l} m'_1(x_i + d) - m'_2(x_i) \\ + n'_1(x_i + d) - n'_2(x_i) \end{array} \right\} \\ + \left\{ \begin{array}{l} m'_{1r}(x_i + d) - m'_{2r}(x_i) \\ + n'_{1r}(x_i + d) - n'_{2r}(x_i) \end{array} \right\} \end{array} \right] \tag{18}$$

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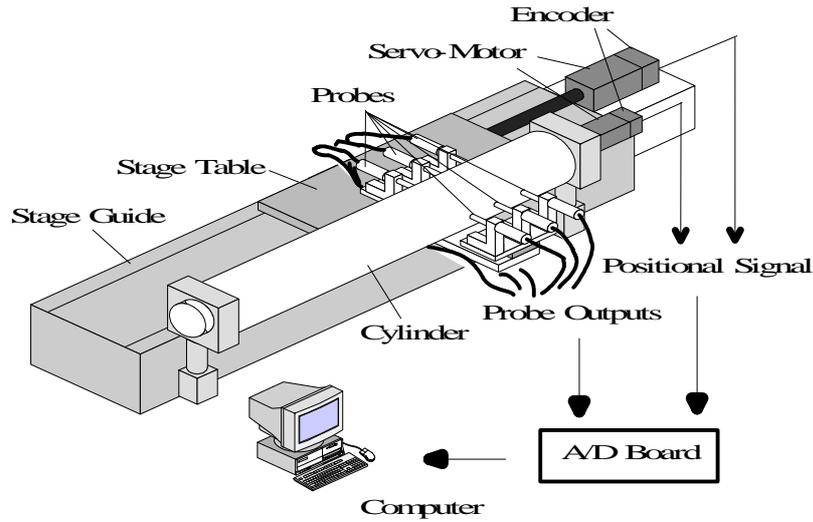Vienna, AUSTRIA, 2000, September 25-28

Figure 5. Experimental setup for measuring straightness of a long cylinder

4   EXPERIMENTS

An experimental setup based on the proposed method was constructed to measure a cylindrical workpiece of 1 m in length (Figure 5). Six capacitance probes with a resolution of several nanometers were employed. The probe distance was set to be 50 mm. Figure 6 shows the same profile g(x) measured by the two sensor units respectively. The difference between the two results was approximately 0.4 µm, which indicates the zero-adjustment was carried out to an accuracy of 20 nm.

5   DISCUSSIONS

In a previous research [8], the authors have tried a zero-adjustment method using the probe outputs of only one three-probe sensor unit. Here we show the problem of this previous method.

For the sake of clarity, the profile f(x) is assumed as a parabolic function qx^2. To determine zero-adjustment error α, $m_1'(x)$ and $m_2'(x)$ shown in Equations (9) and (10) used as follows:

$$T_1(x) = \int_0^x m_1'(x)dx = qx^2 - qdx + E_{p1}(x) - E_{p1}(0) \tag{19}$$

$$T_2(x) = \int_0^x m_2'(x)dx = qx^2 + qdx + ax + E_{p1}(x) - E_{p1}(0) \tag{20}$$

where $E_{p1}(x)$ is the integration of $e_{p1}(x)$.

Taking the difference of the average values of $T_1(x)$ and $T_2(x)$ over the range from x=0 to x=L-d (L is the measurement range) eliminates the effect of $e_{p1}(x)$ in Equations (19) and (20) and yields:
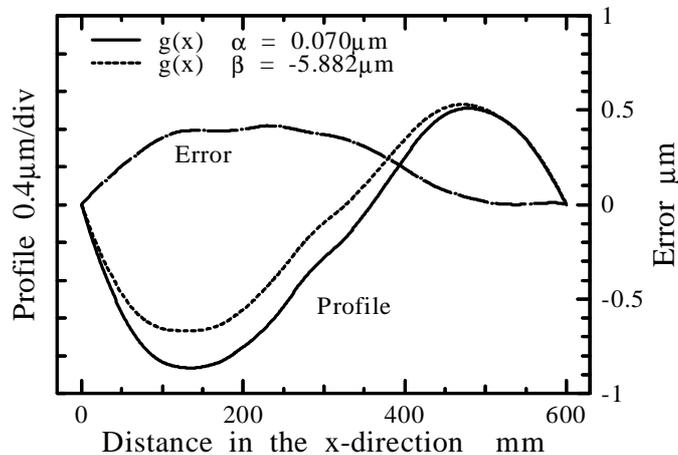

Figure 6. Measurement results of long cylinder

$$m_{ave} = \int_0^{L-d} \{T_2(x) - T_1(x)\}dx/(L-d) = df + a(L-d)/2 - qd^2 \tag{21}$$

where $df = \{\int_{L-d}^{L} f(x)dx - \int_0^d f(x)\,dx\}/(L-d) = qLd$ (22)

On the other hand, $f_1(x)$ in Equation (8) can be rewritten as:

$$f_1(x) = \int_0^x \int_0^x m_s(x)dxdx = qx^2 + ax^2/2d \tag{23}$$

Replacing f(x) in Equation (22) with this $f_1(x)$ gives:

$$df_1 = \{\int_{L-d}^{L} f_1(x)\,dx - \int_0^d f_1(x)dx\}/(L-d) = qLd + aL/2 = df + aL/2 \tag{24}$$

Then the zero-adjustment error a is evaluated as:

$$a_1 = 2(df_1 - m_{ave})/d = a + 2qd \tag{25}$$

As can be seen in the above equation, the evaluated zero-adjustment error α_1 includes the parabolic coefficient q of the profile and will not give the correct α.

6   CONCLUSIONS

A new method has been proposed to evaluate the zero-adjustment error between probes in multi-probe methods. The zero-adjustment error can be evaluated from only the data of the profile measurement without using any accurate flat surfaces as references. The influence of the positioning error of sampling and the random errors in the outputs of the probes can be reduced greatly from the data processing shown above. This method can be used to evaluate zero-adjustment errors of any multi-probe methods that are employed to eliminate the translation error and the tilt error of the scanning stage.

This method has been applied to straightness measurement of a long cylindrical workpiece. Experimental results have shown that the zero-adjustment error was evaluated to an accuracy of 20 nm.

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