

A three-probe method for measuring parallelism and straightness of a pair of rails for ultra precision machine tools

Jooho Hwang^{a,c}, Chun-Hong Park^a, Wei Gao^b, Seung-Woo Kim^c

^a Ultra-precision Machine Team, Intelligent Machine system, Korea Institute of Machinery and Materials, 171, Jang-dong, Yuseong-Gu, Daejeon, 305-343, S. Korea

^b Department of Nanomechanics, Tohoku University, Aramaki Aza Aoba 01, Aoba-ku, Sendai 980-8579, Japan

^c School of Mechanical engineering, Korea Advanced Institute of Science and Technology, 373-1, Gusung-dong, Yuseong-Gu, Daejeon, 305-751, S. Korea

1. Introduction

The guide-ways of precision machine tools are one of important element of machine tools. It has usually a pair of surfaces for constraint of one direction with bearing. In the case of ultra precision machine tools, non-contact bearing such as hydrostatic bearing and aerostatic bearing is adopted usually. In this case, profiles of rails have effect on straightness and the clearance of bearing has effect on stiffness of guide way, which becomes higher if clearance changes to smaller. The clearance is varied along moving table according to relative distance of pair of rails. The relative distance of pair of rail can be divided by three properties. First and second properties are straightness of each pair of rail and bearing pad. And, third is parallelism about pair of rails and pairs of bearing pad. There are several methods for measuring straightness of each surface such as reversal method, sequential two point method, and way straightness. These straightness measuring methods are always acquiring deviation of profile from eliminating linear fitted inclined line and don't have the information of parallelism. Therefore, to get the small clearance for high stiffness, the straightness of rail and bearing pad and parallelism about pair of rails and pair of bearing pads should be measured simultaneously for correction such as regrinding, scrapping and lapping.

In this paper, new and easy method for measuring parallelism and straightness of pair of guide ways are suggested. Using three displacement probes and probe stage, which is scanned with three displacement probes, the relative distance of pair of guide ways and each deviation were measured. The simulation and experiment was accomplished about pair of horizontal guide way for confirmation of simultaneous measuring parallelism and straightness of a pairs of rails.

2. Parallelism measurement algorithm

The schematic diagram for measurement of parallelism and straightness using three-probe method are shown in Fig. 1. A probe stage, which is carrying on three probes, moves along the pairs of rails. Two of three probes p_1 and p_2 are used for parallelism measurement. The profile of rail₁ and rail₂ are defined as $f(x)$ and $g(x)$ respectively. The measurement data of p_1 and p_2 will be $m_1(x)$ and $m_2(x)$ respectively and acquired as

$$\begin{aligned} m_1(x_i) &= f(x_i) - \delta_y(x_i) - t_{x1}\varepsilon_z(x_i) + t_{z1}\varepsilon_x(x_i) \\ m_2(x_i) &= -(g(x_i) - \delta_y(x_i) - t_{x2}\varepsilon_z(x_i) + t_{z2}\varepsilon_x(x_i)) \end{aligned} \quad (1)$$

Where, $\delta_y(x_i)$ and $\varepsilon_z(x_i)$ are y direction straightness and yaw error of probe stage along x axis; $t_{x1}(x_i)$, $t_{x2}(x_i)$, $t_{z1}(x_i)$ and $t_{z2}(x_i)$ are x and z direction constant offset value of p1 and p2. The minus sign of $m_2(x_i)$ in equation (1) means negative sensitivity of p2 for +y direction. From the summation of two measured data of equation (1) in the case of $t_{x1}=t_{x2}$ and $t_{z1}=t_{z2}$ will be

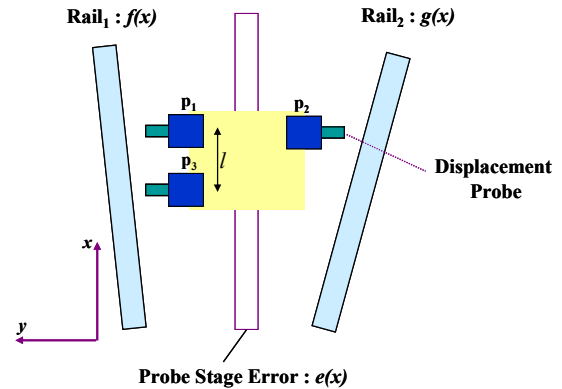


Fig. 1 Schematic diagram of equipment for measuring parallelism and profile of rails

expressed as

$$\begin{aligned} p(x_i) &= m_1(x_i) + m_2(x_i) \\ &= f(x_i) - g(x_i) - t_{x1}\varepsilon_z(x_i) + t_{z1}\varepsilon_x(x_i) + t_{x2}\varepsilon_z(x_i) - t_{z2}\varepsilon_x(x_i) \quad (2) \\ &= f(x_i) - g(x_i) \end{aligned}$$

The equation (2) describes deviation of two profiles along x axis which means parallelism of a pair of rails. The slope value between two rails is defined as linear least square fit method and expressed as

$$\begin{aligned} \alpha &= \frac{n \sum_{i=1}^n x_i P(x_i) - \sum_{i=1}^n x_i \sum_{i=1}^n P(x_i)}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2} \\ &= \frac{n \sum_{i=1}^n x_i f(x_i) + n \sum_{i=1}^n x_i f(x_i) - \sum_{i=1}^n x_i \sum_{i=1}^n g(x_i) - \sum_{i=1}^n x_i \sum_{i=1}^n g(x_i)}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2} \quad (3) \\ &= a_1 - a_2 \end{aligned}$$

Where, a_1 and a_2 are slope of $f(x)$ and $g(x)$ respectively. As shown in equation (3) the principle of allotment can be applicable in acquiring slope. Therefore difference of slope between two rails can be calculated.

To confirm the effect of parallelism measurement algorithm, each profile of rails and error of stage are defined as

$$f(x) = 6 \sin\left(0.6 \frac{x}{L} 2\pi\right) + \sin\left(2 \frac{x}{L} 2\pi\right) + 0.03x \quad (4)$$

$$g(x) = -5 \sin\left(\frac{x}{L} 2\pi\right) + 1.5 \sin\left(3 \frac{x}{L} 2\pi\right) - 0.06x$$

$$e(x) = \delta_y(x_i) + t_{x1}\varepsilon_z(x_i) - t_{z1}\varepsilon_x(x_i) = -3 \sin\left(\frac{x}{L} 2\pi\right) + 0.01x$$

Where, $f(x)$, $g(x)$ and $e(x)$ are profile of rail₁, profile of rail₂ and summation of measurement error, which is due to straightness, rolling and yawing error of probe stage, respectively in μm as shown in Fig. 2. L is length of rail in mm. From the linear least squares method

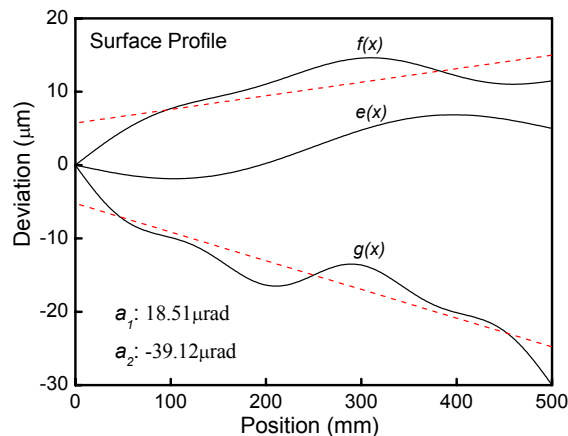


Fig. 2 Surface profiles of rails

fitted line of each profile of rails is shown as dashed line of Fig. 2 and the slopes of each rails are $a_1 = 18.51 \mu\text{rad}$ and $a_2 = -39.12 \mu\text{rad}$ respectively. From the equation (1), simulated measuring data will be displayed as solid lines in Fig. 3. And, the dashed line of Fig. 3 is linear fitted line of $f(x) - g(x)$, the angle α is exactly same as value of $a_1 - a_2$, in Fig. 2, which is expressed in equation (3).

3. Experiment of parallelism measurement

To confirm the parallelism measurement method, two parallel rails were fixed on moving table as shown in Fig. 4. The moving table was moved from 0 to 500mm, a pairs of rails are scanned with two laser displacement probe. The initial parallelism and its linear fitted line of a pair of rails are drawn as solid line and dashed line. The angle of linear fitted line is $-16.95 \mu\text{rad}$ as shown in Fig. 5(a). To correct the angle between a pair of rails to 0, rail₂ was rotated $16.95 \mu\text{rad}$, which was calculated from relative displacement between two probes 700mm apart along the rail₂. After rotation for correction, the angle between each rails were decreased to $0.46 \mu\text{m}$. From the experiment, the parallelism measurement method seems to be effective.

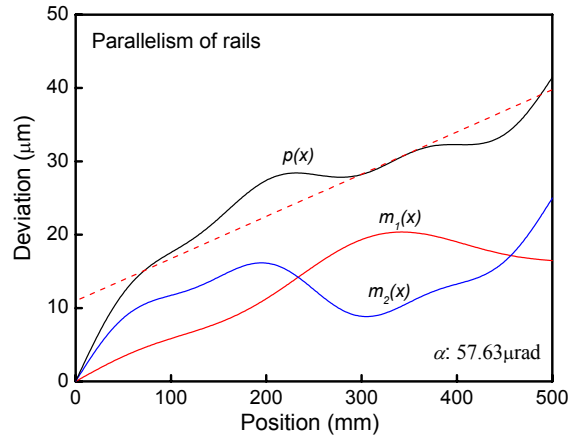


Fig. 3 Parallelism of rails

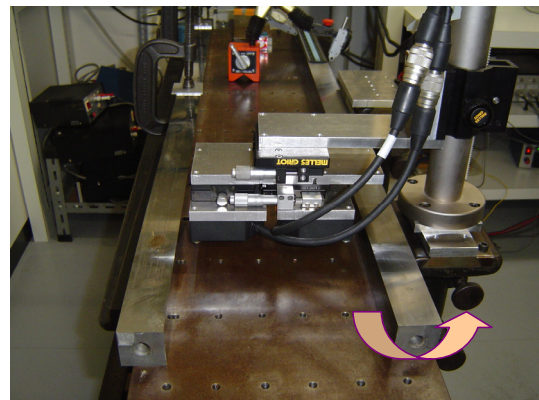


Fig. 4 Experimental setup

4. Simultaneous measurement of parallelism and straightness

The straightness of each rails are important factor of guide ways for ultra precision machine tools. To measure the straightness of each rails third displacement probe was attached as shown in Fig. 1. The measured data of each probes are will be acquired as

$$\begin{aligned} m_1(x_i) &= z(x_i) - \delta_y(x_i) - t_{x1}\varepsilon_z(x_i) + t_{z1}\varepsilon_x(x_i) \\ m_3(x_i) &= z(x_{i-1}) - \delta_y(x_i) - t_{x3}\varepsilon_z(x_i) + t_{z3}\varepsilon_x(x_i) \end{aligned} \quad (5)$$

Where, $z(x)$ is similar but different profile with $f(x)$ because of 0 initial measured value of $m_1(x)$ and $m_2(x)$. In the case of $t_{z1}=t_{z3}$ from the measured data the profile of rail₁ is calculated as

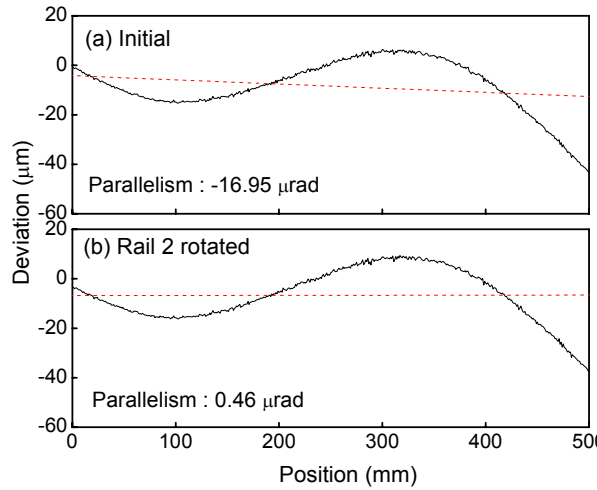


Fig. 5 Experimental results of measuring parallelism

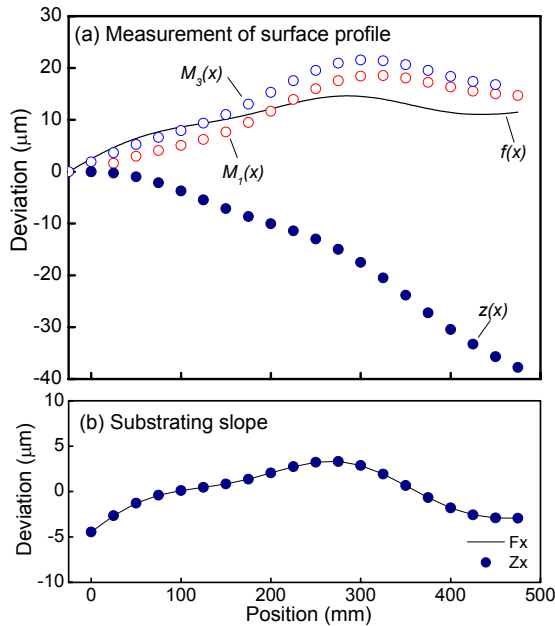


Fig. 6 Straightness profile using sequential two point method

$$z(x_i) = m_1(x_i) - m_3(x_i) + z(x_{i-1}) + l\varepsilon_z(x_i) \quad (6)$$

Where, l is $t_{x1}-t_{x3}$, which is distance from probe1 to probe3.

When the profiles of each rail are same as profiles of Fig. 2 and yaw error of stage is neglected, the measured data of probe 1 and 3 will be acquired as hollow circle of Fig. 6(a). If the distance between the m_1 and m_2 probe is assumed as 25mm, and the start point of measuring profile is $x=25mm$ of Fig. 2, the profile of rails are calculated from equation (6) as shown in solid circle of Fig. 6(a). The calculated profile $z(x)$ doesn't have information about slope of rail. The straightness of rail is calculated from elimination of profile. As shown in Fig. 6(b), the straightness of calculated rail₁ is very similar with defined $f(x)$.

The profile of rail₂ is calculated from equation (2) with $f(x) \approx z(x)$ and expressed as

$$g_z(x_i) \approx g(x_i) \approx P(x_i) - Z(x_i) \quad (7)$$

As shown in Fig. 6, the difference of slope has effect on profiles. To minimize correction process such as lapping and scrapping, each slope of measured data is rotated same angle to meet $a_1+a_2=0$ and $a_1-a_2=\alpha$. The comparison of mathematically defined profile, which is rotated to meet $a_1+a_2=0$ and $a_1-a_2=\alpha$, and measured profile of a pairs of rails are shown in Fig. 7. The difference between defined profile and measured data are less than $\pm 2 \times 10^{-14}$ as shown in Fig. 7(b). The result of Fig. 7 shows that proposed method has good effectiveness in simultaneous measurement of parallelism and straightness for a pair of rails.

5. Experiment for simultaneous measurement of parallelism and straightness

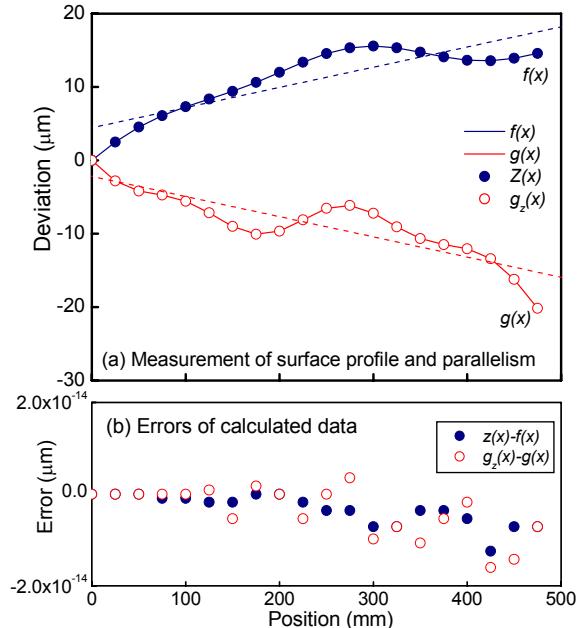


Fig. 7 Rotated Profile of a pair of rails

To investigate proposed method, three-probe method was applied to a pairs of straight edge, which is made of zerdur® bar coated with aluminum and less than $0.1\mu\text{m}$ straightness. Three capacitive type probes (ADE, Microsense3401) were used for measuring profiles of rails. And the yaw angle of probe stage was measured by a angle sensor of laser interferometer system(Agilent,5529A). The simultaneous measured signal m_1 , m_2 , m_3 and $\varepsilon_z \times l$ are displayed in Fig. 9. As shown the figure, each measured data of three probes are varied about $0.3\mu\text{m}$, and the m_3 data has reverse variation compared to m_1 and m_2 , if the linear slope is eliminated. It is expected that most of measured errors are from errors of stage. The profile of each straight edge is calculated from equation (2), (3), (6) and (7) and displayed in Fig. 10(a). As shown in Fig. 10(a), most of stage error is eliminated. After eliminating probe stage error, each of straightness is about $0.05\mu\text{m}$, which is about specification of straightedge. From the above results, suggested three-probe method for simultaneous measuring parallelism and straightness of a pairs of rails is effective method for ultra precision

guide ways.

6. Conclusion

In this paper, a three-probe method for measuring parallelism and straightness of a pair of rails for ultra precision machine tools is proposed. To confirm the algorithm of proposed method, profiles of rail and probe stage error are mathematically defined and elimination of probe stage error in measurement data is proved. And, the experiment for confirmation of three-probe method was performed to $0.1\mu\text{m}$ straight edge. From the simulation of algorithm and experiment, it is confirmed that the proposed method has good effectiveness in simultaneous measurement for parallelism and straightness of a pairs of rails.

References

- [1] Kiyono, S., "Profile Measurement Using Software Datums," J. of JSPE, Vol. 61, No. 8, pp. 1059-1063, 1995.
- [2] Gao, W., and Kiyono, S., "High accuracy profile measurement of a machined surface by the combined method," Measurement, Vol. 19, No. 1, pp. 55-64, 1996.
- [3] Fung, E. H. K., and Yang, S. M., "An approach to on-machine motion error measurement of a linear slide," Measurement, Vol. 29, pp. 51-62, 2001.
- [4] Kounosu, K., and Kishi, T., "Measurement of Surface Profile Using Smoothed Serial Three Point Method," J. of JSPE, Vol. 61, No. 5, pp. 641-645, 1995

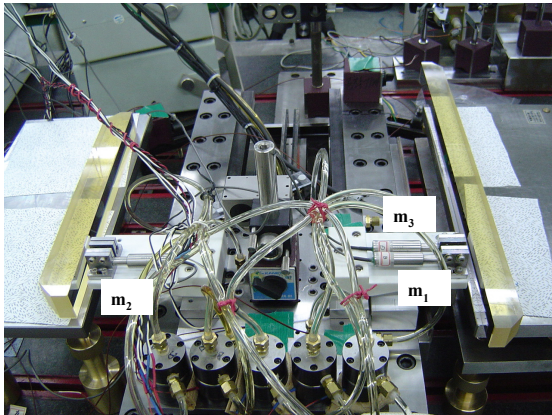


Fig. 8 Experimental setup for simultaneous measurement of straightness and parallelism

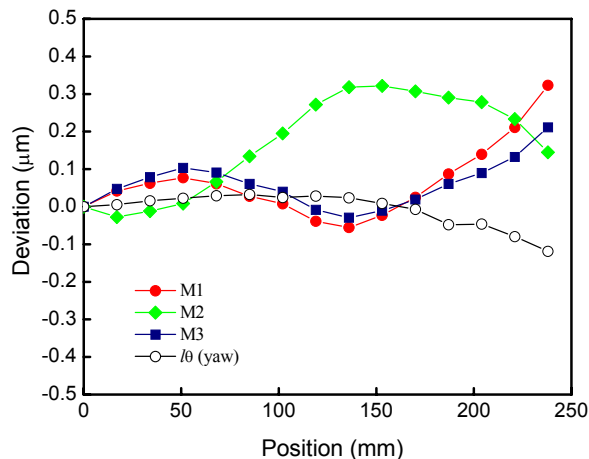


Fig. 9 Measured data for straightness and parallelism

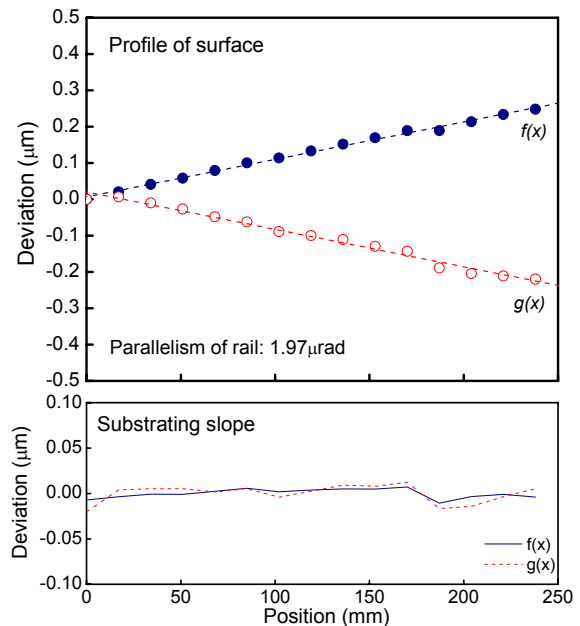


Fig. 10 Simultaneous measurement of parallelism and straightness of a pair of rails