Proceedings in Manufacturing Systems, Volume 11, Issue 2, 2016, 77–82 ISSN 2067-9238

PROFILE MEASUREMENT WITHOUT REFERENCE ERROR COMPARING TWO PARALLEL LINEAR STAGES

Ryoshu FURUTANI [1,*], Akira SUGIHARA [2], Miyu OZAKI [3]

[1)] Prof., Dr. Engineering, Department of Mechanical Eng., Tokyo Denki University, Tokyo, Japan
[2)] Master of Engineering, Department of Mechanical Eng., Tokyo Denki University, Tokyo, Japan
[3)] Associate Prof., Dr. Engineering, Department of Mechanical Eng., Nippon Institute of Technology, Saitama, Japan

Abstract: *In general, the profile measuring machine uses the displacement sensor attached on movable mechanism in order to measure the object. It could measure the object profile by the amount of movement of the displacement sensor and output of the displacement sensor. When measuring the object, metrological frame is important as a reference. If the metrological frame has some profile errors, the output of the displacement sensor includes the profile error of the metrological frame. We proposed a new method to distinguish the profile error of the metrological frame from the output of the displacement sensor. The proposed method requires two linear stages and the displacement sensor. Two linear stages are set and aligned in parallel; displacement sensor and object are mounted on each stage. The output of the displacement sensor can be obtained by the combination of the position of the two linear stages. The object profile and profile error of the movable mechanism are determined by calculation using only the output of the displacement sensor. The validity of the new method was confirmed by the simulation and experiment. It was confirmed to be possible to construct metrological frame less than 1μm.*

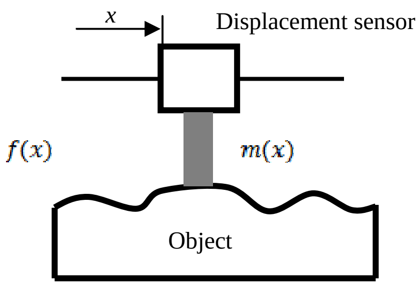
Key words: *metrological frame, profile error, error separation, profile measurement, Linear Stages.*

1. INTRODUCTION

Profile measuring machine can measure the profile of the object with high accuracy and widely used in industry. In general, the profile measuring machine uses the displacement sensor attached on movable mechanism in order to measure the object. It could measure the object profile by the amount of movement of the displacement sensor and output of the displacement sensor. When measuring the object, metrological frame as a reference is important. If the metrological frame does not have any profile errors as shown in Fig. 1, where the amount of movement of the displacement sensor is expressed as x, the relationship between the object profile $f(x)$ and output of the displacement sensor $m(x)$ is expressed as Eq. (1).

$$f(x) = m(x) + a \cdot x + c\,, \tag{1}$$

where $ax + c$ is the slope and offset of the movable mechanism to the object. In these cases, it is possible to measure the object profile because the output of the displacement sensor agrees with the object profile. However, when the metrological frame has some profile errors as shown in Fig. 2, the output of the displacement sensor includes both of the profile of the object and the profile error of the metrological frame. The relationship between the profile of the object f(x) and output of the displacement sensor m(x) is expressed as Eq. (2).



$m(x)$: Output of the displacement sensor
$f(x)$: Object profile

Fig. 1. Profile measuring machine consists of a displacement sensor and movable mechanism in case of movable mechanism without profile error.

$$f(x) = g(x) + m(x) + a \cdot x + c\,, \tag{2}$$

where $g(x)$ is the profile error of the metrological frame. So, it is necessary to distinguish the profile error of the movable mechanism from the output of the displacement sensor to measure the object profile more accurately [1]. The reversal method and multi-point method were proposed as the method to measure the profile error of the movable mechanism and the object profile [2–5]. In the reversal method, after the object is measured, either the object or the displacement sensor is rotated with 180 degrees and the object is measured again. By using both measurement results before rotation and after that, it is

* Corresponding author: 7-3-1 Hongo, Bunkyo-ku,Tokyo, 113-8656, Japan,
Tel.: :+81-3-5841-6300;
Fax: :+81-3-3818-0835;
E-mail addresses: *ryo@cck.dendai.ac.jp* (R. Furutani),.

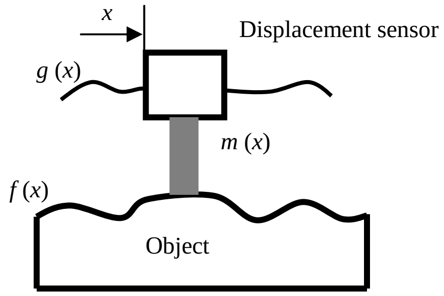


Fig. 2. Profile measuring machine consists of displacement sensor and movable mechanism in case of movable mechanism with profile errors.

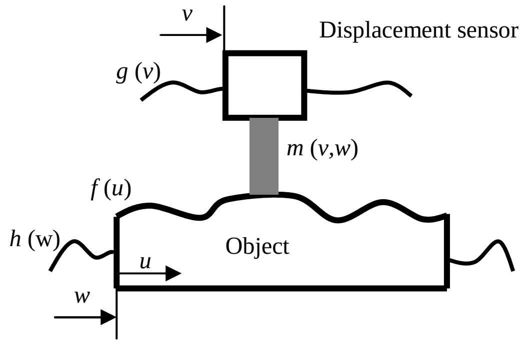


Fig. 3. The new method composed of two linear stages.

possible to separate the profile error of the movable mechanism from the output of the displacement sensor and measure the object profile.

However, the reversal method requires the complicated mechanism and the large scaled equipment to rotate either the object or the displacement sensor. In the multi-point method, the object profile is measured by using some multi- sensors mounted on same stage and the object profile is determined from the relationship between the outputs of the multi-sensors. In this state, it is possible to distinguish the profile error of the movable mechanism from output of the object profile. However, the multi-point method uses multi-sensors so it is necessary to zero point adjustment of multi-sensors. If the zero point of sensors is not adjusted, the calculated profile includes the errors of the zero-point adjustment.

The new method to distinguish the object profile and the profile error of the movable mechanism from the output of the displacement sensor is proposed, which is not dependent on the issues of the reversal method and multi-point method. In this paper, the principle of the proposed method to determine the object profile and the profile error of the movable mechanism is shown. The new method is evaluated by simulations and the experiments, and then the results are shown.

2. PRINCIPLE

The concept of the new method that distinguishes the profile error of the movable mechanism from the output of the displacement sensor is shown in Fig. 3. The new method requires two linear stages and one displacement sensor. Two linear stages are set and aligned in parallel; the displacement sensor and the object are mounted on each stage. The object and the displacement sensor can move and locate with the movement of each linear stage. The relationship between positions of object and displacement sensor on each of movable stages, the object profile f(u) can be expressed as Eq. (3).

$$f(u) = g(v) + h(w) + m(v,w) + a \cdot v + b \cdot w + c\,, \quad (3)$$

where: $g(v)$ is the profile error of the displacement sensor axis; $h(w)$ – the profile error of object axis; $m(v,w)$ is the output of displacement sensor; a, b – slope of the linear stage to the object; c – offset of the linear stage with the displacement sensor from the object.

As two linear stages are in parallel, the relationship between the positions of linear stages of the displacement sensor and the object is $u = v - w$. The several different outputs of the displacement sensor are obtained at any positions of the displacement sensor and the object. Eq.(3) is transformed to Eq.(3)'.

$$f(u) - g(v) - h(w) - a \cdot v - b \cdot w - c = m(v,w) \quad (3)'$$

In order to construct the matrix and the vector. The position u,v and w are discretized as Eq.(4).

$$u = i\Delta u; \quad v = j\Delta v; \quad w = k\Delta w. \quad (4)$$

Eq. (3)' is expressed as Eq.(5).

$$f(i) - g(j) - h(k) - a \cdot j - b \cdot k - c = m(j,k)\,. \quad (5)$$

Eq. (5) is expressed as linear equation of Eq. (6).

$$\mathrm{Ax} = \mathrm{b}\,, \quad (6)$$

where vector **x** is vector of unknown parameters, which is a set of the object profile, the profile error of the stage mounted with the displacement sensor and the profile error of the stage mounted with the object at measured positions. The matrix A is Jacobian of left side of Eq.(5), and the vector **b** is a set of the outputs of the displacement sensor at measured positions.

However, Eq. (6) cannot be solved because the rank of matrix **A** is less than the number of the unknown parameters. Therefore, the unknown parameters should be reduced by the additional constraints.

The object profile, the movement axis of the displacement sensor and the movement axis of the object can take any posture with regard to coordinate system. So even if both ends of the movement axis and object profile can be cut off, e.g. they are set to zero, the profile of the movement axis and the object profile can keep the own profiles. As a result, it is possible to solve linear equation as Eq. (7) because the rank of matrix A is consistent with the number of unknown parameters.

$$\mathbf{x} = \left(\mathbf{A}^{t}\mathbf{A}\right)^{-1}\mathbf{A}^{t}\mathbf{b}\,. \qquad (7)$$

So, the object profile, the profile error of the object axis and the profile error of the displacement sensor axis can be calculated by Eq. (7). Finally, the object profile can be separated from the output of the displacement sensor and calculated without the profile errors of both linear stages.

3. SIMULATION

The simulation was performed to verify new method that separates the object profile and the profile error of movement axis. In the simulation, the object profile and the profile errors of two linear stages are generated arbitrarily. The generated object is set on one linear stage with the generated profile error, and the displacement sensor is set on the other linear stage with generated profile error. After that, two linear stages move step by step independently, the output of the displacement sensor is calculated by the relationship between two linear stages. In this simulation, the number of points of generated profile is shown in Table 1.

The simulation results are shown in Fig. 4. From the simulation, the calculation results are consistent with the generated profiles. The difference between the generated profiles and the calculated profiles is less than 1nm. The end part of profile is lost because the end portions of the axes and object were set to zero as shown in principle. In this simulation, slope of each profile is removed once and revived by the recalculation. The calculation results could be correct. From this simulation, the proposed error separation method is proved effective.

4. EXPERIMENT

4.1. Experimental Equipment

The experimental equipment is shown in Fig. 5. The experimental equipment consists of two linear stages, the displacement sensor and the measurement object. Two linear stages are set and aligned in parallel. The positions of two linear stages are measured by the inner scale.

The measurement principle of the displacement sensor is the triangular method. The measurement object is made of Duralumin and is processed by wire cut. Its picture is shown in Fig. 6.

The displacement sensor is mounted on one stage and the measurement object is mounted on the other stage. The specifications of the linear stage and the displacement sensor are shown in Table 2.

Table 1

Condition of the simulation

Profile	Number of Measurement Points
Profile of object: f(u)	99
Profile of axis for object: h(w)	50
Profile of axis for displacement sensor:g(v)	50

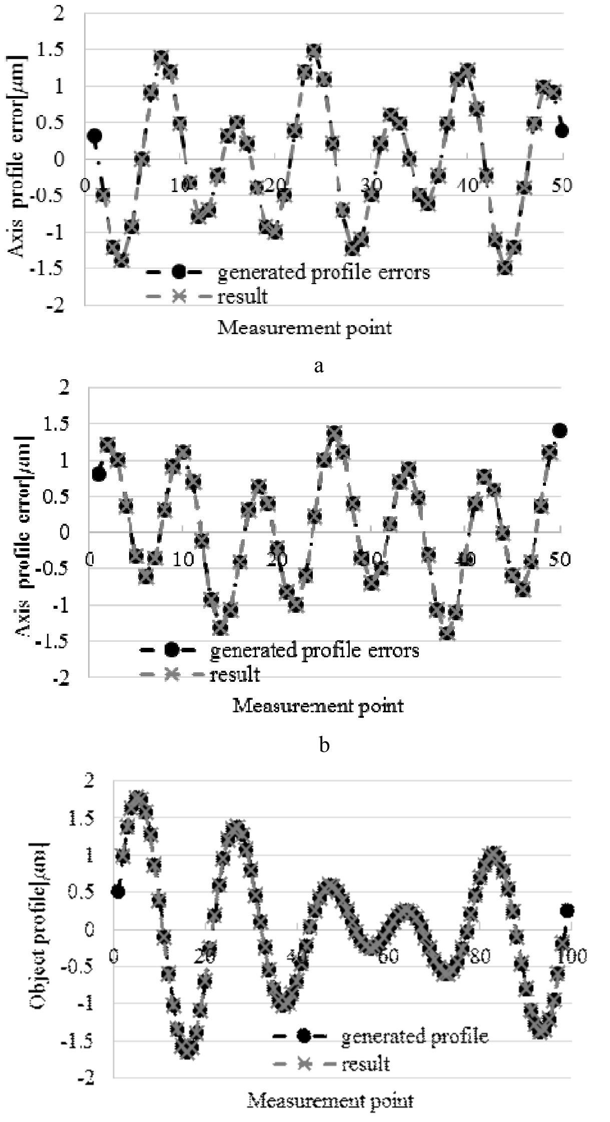


Fig. 4. The generated profile and calculated profile in simulation: *a* – profile error of the linear stage mounted with the displacement sensor; *b* – profile error of the linear stage mounted with the object; *c* – the object profile.

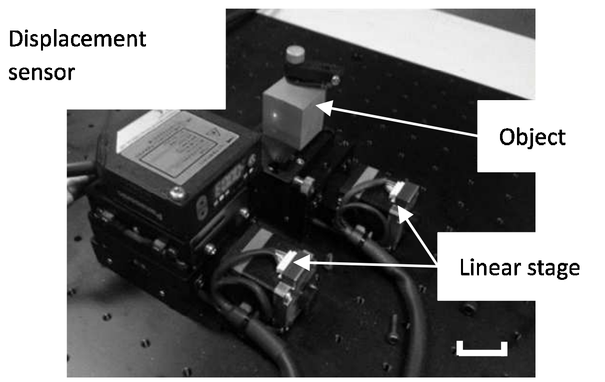


Fig. 5. Experimental equipment to measure the object consists of two linear stages and the displacement sensor.

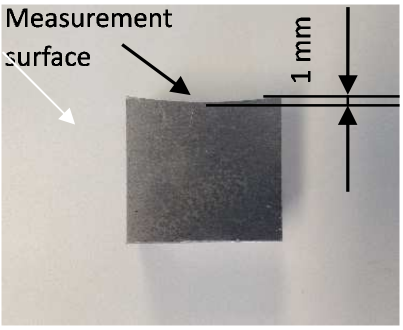


Fig. 6. Measurement object used in the experiment.

Table 2

Specification of the equipment

Linear stage	Resolution	50 nm
	Positioning accuracy	0.3μm
	Repeatability	Less than 5μm
	Range	20 mm
Displacement sensor	Type	Triangular Method
	Resolution	500 nm
	Measuring range	6 mm
Object	Size	25 mm
	Processing method	Wire cut
	Processing depth	1 mm
	Ra	12.5

The linear stages and the displacement sensor are controlled by personal computer. The positions of two linear stages, i.e. the positions of the displacement sensor and the measurement object, and the output of displacement sensor are recorded.

At first, the stage mounted with the displacement sensor moves step by step and the output of the displacement sensor is recorded. After the stage mounted with the displacement sensor reaches to the end of the moving range, it returns to home position and the other stage moves by one step. This process is repeated until the stage mounted with measurement object reaches the end of moving range.

The object profile, the profile errors of the stages mounted with the displacement sensor and measurement object are calculated as shown in Eq. (7) using the outputs of the displacement sensor.

4.2. Experimental method

In the experiment, the stage mounted with the displacement sensor moves by 100 steps and the other stage moves also by 100 steps. So, the object is totally measured at 10000 measured points. The length of each step of the stages is 100μm.

The profile errors of the stages are calculated at 100 points and the object profile is calculated at 199 points.

This experiment is repeated 3 times.

4.3. Result

Fig. 7 shows the experimental result calculated from the outputs of the displacement sensor and the inner sensors of the stages based on Eq. (7). The experiments are repeated 3 times. Fig. 7(a) shows the profile errors of the stages mounted with the displacement sensor. It is

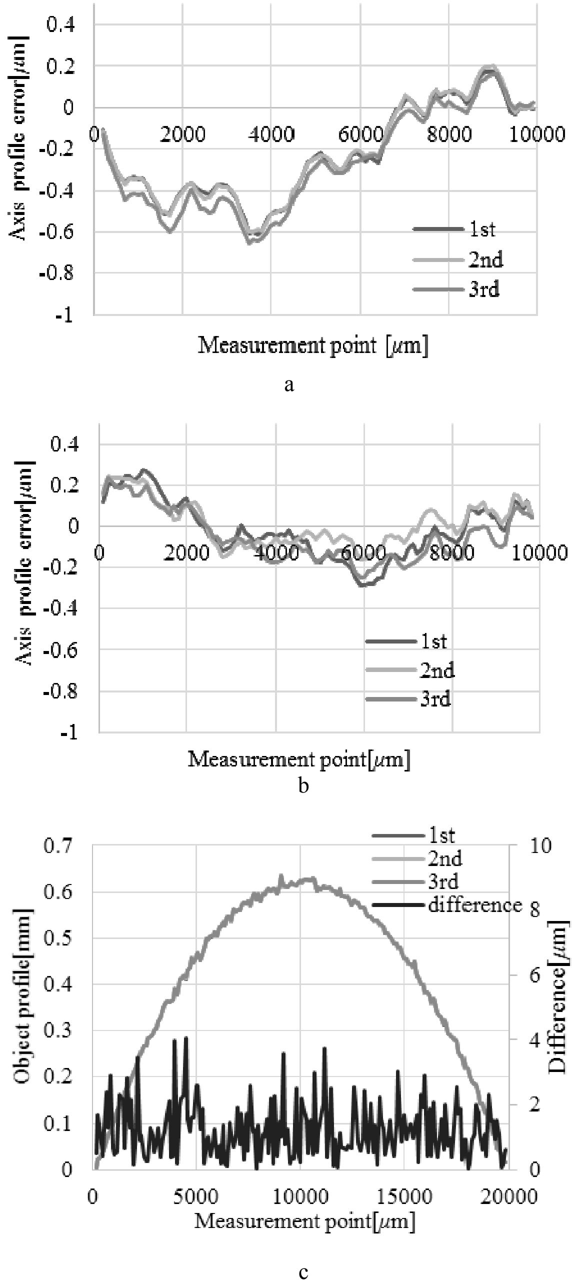


Fig. 7. Three profile calculated as the experiment result: *a* – profile error of the linear stage mounted with the displacement sensor; *b* – profile error of the linear stage mounted with the object; *c* – the object profile.

proved that the repeatability is not good in 3 times. Fig. 7(b) shows the profile errors of the stages mounted with the measurement object and Fig. 7(c) shows the object profiles. In addition, Fig. 7(c) shows the maximum difference of object profiles at each point in 3 times experiments. The maximum difference is about 4.0μm.

In the result of the profile errors of the stages, the maximum difference of the profile error of the stage with the displacement sensor is smaller than that of the stage with the measurement object in 3 times experiments.

It is proved that the profile error of the stage with the displacement sensor can be measured more correctly than the profile error of the stage with the measurement object and the profile of the measurement object from Fig. 7 and Table 3.

Table 3

The maximum difference of the calculation results

Profile error of the linear stage with the displacement sensor	0.1μm
Profile error of the linear stage with the object	0.2μm
Object profile	4.0 μm

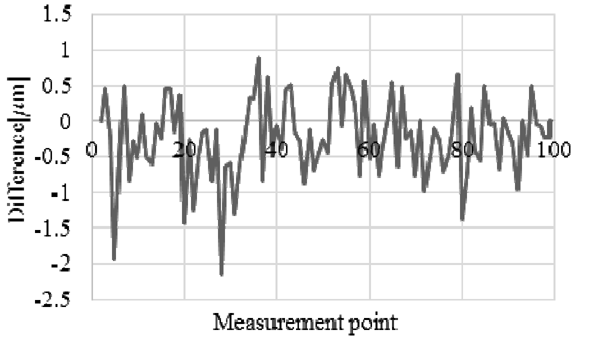


Fig. 8. Difference between the object profile by calculation result and the output of the displacement sensor.

The output of the displacement sensor and calculated object profile are compared. The profile error of the stage is the output of the displacement sensor minus the calculated object profile by Eq. (3). Fig. 8 shows the difference between the output of the displacement sensor and the calculated object profile at 99 points. It is proved that the profile error of the stages could be separated from the object profile. But, there is a difference of 2.1 μm at the maximum as shown in Fig. 8. This is larger than the calculation result of the profile error of the stages comparing with Table 3.

This difference is caused by the random errors. The output of displacement sensor and the profile errors of the stages have random errors. Considering random errors, Eq. (3) should be express as Eq. (8).

$$\begin{aligned} f(u) &= g(v) + h(w) + m(v,w) + a\cdot v + b\cdot w + c \\ &+ eg(v) + eh(w) + em(v,w), \end{aligned} \tag{8}$$

where $eg(v)$, $eh(w)$ and $em(v,w)$ are random errors.

By the measurement procedure, the stage mounted with the displacement sensor moves larger times than the stage with the measurement object. Considering the measurement procedure, Eq.(8) is expressed as Eq.(9).

$$\begin{aligned} f(u) &= g(v) + h(w) + m(v,w) + a\cdot v + b\cdot w + c \\ &+ eg(v,w) + eh(w) + em(v,w). \end{aligned} \tag{9}$$

By the summation of Eq.(9) with v considering u=v-w and that eg(v,w),eh(w) and em(v,w) are random errors, Eq.(10) is obtained.

$$\begin{aligned} \sum_v f(v-w) &= \sum_v (g(v) + m(v,w) + a\cdot v) \\ &+ (h(w) + b\cdot w + c + eh(w))\sum_v 1. \end{aligned} \tag{10}$$

By the summation of Eq. (9) with w, Eq. (11) is obtained.

$$\begin{aligned} \sum_w f(v-w) &= \sum_w (h(w) + m(v,w) + b\cdot w) \\ &+ (g(v) + a\cdot v + c)\sum_w 1. \end{aligned} \tag{11}$$

The random error of profile error eg(v,w) is averaged and should be zero in both cases, whereas the random error of profile error $eh(w)$ is left in the summation with v. This is the reason why the profile error of the stage with the displacement sensor is smaller than that of the stage with measurement object in Fig. 7 and Table 3.

5. SUMMARY

In this study, the new method of separating the object profile from the profile error of the stage is proposed.

This method requires two stages and the displacement sensor. The displacement sensor is mounted on the stage, and the measurement object is mounted on the other stage. Both stages are in parallel. The position of the stages and the output of the displacement sensor are recorded.

The simulation was performed to verify that the proposed method can separate the object profile and the profile errors of the stages. The calculation results were consistent with the generated profiles. The new method is confirmed to be effective.

The experiments were performed. As a result, it is possible to separate the profile error of two stages from the output of the displacement sensor. The repeatability of the calculation results of the profile error of the stages is less than 1 μm. It is proved that the profile error of the more moved stage is more precisely calculated than that of the other stage. As the difference of the calculation results of the profile error of the stage is less than 1 μm, in the present environment, it is confirmed to be possible to construct metrological frame less than 1 μm.

In future, we will examine how large influence is propagated by the random error.

REFERENCES

[1] K. Iori, M. Ozaki, R. Furutani, *Evaluation of Straightness of Two-Axes Stage*, Key Engineering and Materials, Vol. 625, 2014, pp. 47–52.

[2] E. Okuyama, *Multi-probe method for straightness profile measurement based on least uncertainty propagation (1st report) Two-point method considering cross-axis translational motion and sensor's random error*, Precision Engineering, Vol. 34, No. 1, 2010, pp. 49–54.

[3] W. Gao, S. Kiyono, *High accuracy profile measurement of a machined surface by the combined method*, Measurement, Vol. 19, No. 1, 1996, pp. 55–64.

[4] Y. Zi-qiang, L. Sheng-yi, *High accuracy error separation technique for on-machine measuring straightness*, Precision Engineering, Vol. 30, No. 2, 2006, pp. 192–200.

[5] O. Brisov, S. Fletcher, A. Longstaff, A. Myers, *New low cost sensing head and taut wire method for automated straightness measurement of machine tool axes*, Optical and Lasers in Engineering, Vol. 51, No. 8, 2013, pp. 978–985.