Estimation of deviations between stylus position and CMM scales indication in high speed probing

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The Estimation of the Deviations between the Stylus Position and CMM Scales Indication in High Speed Probing*

Ryoshu FURUTANI**, Leon LEVASIER*** and Pieter SCHELLEKENS***

The Coordinate Measuring Machine (CMM) is a flexible and useful machine for a lot of measuring tasks. But it is not used for measuring all the mechanical parts in manufacturing lines, because this takes too much time. In order to reduce time to measure, it is important to increase the velocity in probing. However, the deviations between the position of the stylus and the position measured by the linear scales of the CMM become larger in high speed probing by bending of beams and rotations around axis due to the acceleration forces. These deviations become then an important measuring error. Therefore, in order to reduce these deviations, we analysed the deviations when the CMM X-Guideway moved along the direction of the y-axis and found a relation between the deviations, the velocity and the acceleration. Finally we have compensated these deviations numerically with the reading of the linear scales of this CMM.

Key words: high speed probing, coordinate measuring machine, dynamic behavior, calibration, bending, rotation

1. Introduction

The Coordinate Measuring Machine (CMM) is a flexible and useful machine to measure the geometrical quantities and the form of mechanical parts. As the CMM takes too much time, it is not used for measuring all the mechanical parts in manufacturing lines. The states of the CMM are the measuring mode, in which the stylus approaches to the measuring object and contacts it, and the moving mode, in which the stylus moves to an adequate position. The velocity in the measuring mode is low (3mm/s) and the velocity in the moving mode is high (max. 70mm/s). Therefore, if the velocity in the measuring mode becomes as high as the velocity in the moving mode, it is possible to reduce the measuring time.

However as the deviations between the position of the stylus and the position measured by the linear scales of the CMM become larger by bending of the pinoles and rotations around axis due to the acceleration forces in high speed movement, the measurement error becomes larger.

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In order to reduce these deviations, it was researched how to control the signal for the acceleration and the deceleration. Especially the technique of input shaping was applied to the CMM. However, it is difficult to apply these techniques to the measuring mode of the CMM, because the CMM should be unexpectedly decelerated and stop when the stylus contacts the measuring object in the measuring mode.

In another research project at TUE all of the rotation angles of the CMM were measured with several sensors. The dynamic behavior of the CMM was modeled and the dynamic errors were predicted based on this model. However, it is difficult to find the adequate dynamic model and parameters accurately.

An extra linear scale may be used to reduce the measuring error by measuring the major rotation around the z-axis in a commercial product. This technique also requires an extra sensor.

Therefore in this research, we did not control the signal for the acceleration and the deceleration of the CMM but tried to reconstruct the acceleration signal from the linear scale signals. We directly observed how large deviations between the position of the stylus and the position measured by the linear scales of the CMM occurred in high speed movement and measurement, and tried to compensate these deviations.
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Fig. 2 Measurement results while the X-Guideway moves with maximum velocity up to 70 mm/s along the y-axis

Table 1 The specifications of the used instruments

<table>
<thead>
<tr>
<th></th>
<th>Laser Interferometer (MP-10)</th>
<th>Counter (PCL833)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>0.1 μm</td>
<td>1 μm</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>5 kHz</td>
<td>5 kHz</td>
</tr>
</tbody>
</table>

2. Principle of Measurement

In high speed movement, the deviations between the position of the stylus and the position measured by the linear scales of the CMM become larger by bending of the pinoles and rotations around axis. In this research, we directly measured these deviations and tried to compensate these deviations numerically with the reading of the linear scale of the CMM and a few sensors. Figure 1 shows the experimental set-up for the measurement of the deviations between the position of the stylus and the position measured by the linear scale of the CMM (FN905: manufactured by MITUTOYO). At this kind of CMM, the largest deviations due to inertia effects may occur in the y-axis, when the X-Guideway moves along the direction of the y-axis. Therefore the experiments were performed about the movement of the X-Guideway along the direction of the y-axis.

A retro-reflector (RR) was attached to the Z-pinole instead of the stylus to measure the position of the stylus. The position of the stylus was measured by the laser interferometer (MP10: manufactured by Renishaw). The position of the X-Guideway was measured by the y linear scale of the CMM, while the encoded signal from the y linear scale was directly counted by a PC and the counted values were latched.
by the trigger signal from the laser interferometer with a rate of 5kHz. This counted value means the position of the X-Guideway and the y-coordinates. The positions of the X-Guideway were measured synchronized with the measurement of the positions of the retro-reflecto. Table 1 shows the specification of these instruments.

3. Experiments in High Speed Movement

Figure 2 shows the results that the X-Guideway moved with maximum velocity up to 70mm/s along the direction of the y-axis. Figure 2 (a) shows the position of the X-Guideway measured by the y linear scale of the CMM. Figures 2 (b) and (c) show the velocity and the acceleration of the X-Guideway. Figure 2 (d) shows the deviations between the position of the retro-reflecto and the position of the X-Guideway. As these deviations become the errors in high speed movement, the purpose of this research is reduction of these deviations.

1. It is shown in Fig.2(b) that the X-Guideway was accelerated up to 70 mm/s and moved in maximum velocity and was decelerated and stopped. 

2. Figure 2 (c) and (d) show that the curve of the deviations is similar to the curve of the acceleration. This was also measured by other experiments

Because of these results, it was first assumed that the deviations could be estimated by eq.(1):

\[ Y_e - Y_L = a \dot{Y}_e + b \]  

(1)

Where \( Y_e \) is the position of the X-Guideway measured by the y linear scale of the CMM, \( Y_L \) is the position of the retro-reflecto measured by the laser interferometer. \( \dot{Y}_e \) is calculated from \( Y_e \), a and b are the unknown parameters.

The unknown parameters are determined by applying the data as shown in Figs.2 (c) and (d) to eq.(1). In this case, \( a = 3.509e^{-5} [s^2] \), \( b = -1.273e^{-3} [mm] \).

Figure 3 shows the difference between the estimated deviations and the actual deviations about the data with maximum velocity up to 70mm/s and 50mm/s along the direction of the y-axis. These estimated deviations are calculated by applying above parameters to eq.(1).

Equation (1) can estimate the deviations from the position of the X-Guideway in high speed movement. We got almost same result from eq.(2):

\[ Y_e - Y_L = a \dot{Y}_L + b \]  

(2)

In this experiment, \( \dot{Y}_L \) was calculated from \( Y_L \). However, as the laser interferometer can not be used in a practical situation, an additional sensor for \( \dot{Y}_L \) is necessary. So the method described by eq.(1) is better than eq.(2) in practical situations.

4. Experiments in High Speed Movement and Probing
To measure mechanical parts by the CMM probing is necessary. So, in order to improve the performance of the CMM, the deviations should be estimated not only in moving but also in probing.

However, as rapid acceleration and deceleration may occur in high speed probing, eq.(1) is not adequate to estimate the deviations in high speed probing. Figure 4 shows this matter. Figure 4 (a) shows that the X-Guideway was accelerated to maximum velocity (70mm/s) but then the stylus contacted the measuring object and as a result the X-Guideway moved backwards. Figure 4 (b) shows the deviations between the position of the X-Guideway and the position of the retro-reflector. Figure 4 (c) shows the difference between the estimated deviations by eq.(1) and the actual deviations. The deviations are still too large.

Therefore eq.(3) was introduced considering the CMM slides as spring-mass systems:

\[ Y_c - Y_L = a_c \ddot{Y}_c + a_L \ddot{Y}_L + b_c \dot{Y}_c + b_L \dot{Y}_L + d \]  
(3)

\( a_c, a_L, b_c, b_L, d \) are the unknown parameters. \( \dot{Y}_c, \ddot{Y}_c \) are the velocity and the acceleration of the X-Guideway. \( \dot{Y}_L, \ddot{Y}_L \) are the velocity and the acceleration of the retro-reflector. \( \dot{Y}_c, \ddot{Y}_c \) and \( \dot{Y}_L, \ddot{Y}_L \) are respectively calculated from \( Y_c \) and \( Y_L \).

As the laser interferometer cannot be used in practical situations, an additional sensor for \( \dot{Y}_L, \ddot{Y}_L \) is necessary for eq.(3). We may consider eq.(4) assuming the damping exists only in \( Y_c \):

\[ Y_c - Y_L = a \dot{Y}_c + b \dot{Y}_c + d \]  
(4)

No extra sensor is needed in this equation, but eq.(4) could not estimate the deviations well. So, we used eq.(3) as the estimator of the deviations. These parameters are determined by applying the data to eq.(3).

In this case, \( a_c = -3.574e^{-4}[s^2] \), \( a_L = 4.041e^{-4}[s^2] \), \( b_c = 2.276e^{-2}[s] \), \( b_L = -2.277e^{-2}[s] \), \( d = -2.075e^{-4}[mm] \).

Figure 4 (d) shows the difference between the estimated deviations by eq.(3) and the actual deviations. Figure 4 (d) is better than Figure 4 (c). The deviation is improved from 0.045mm to 0.008mm.

Table 2 shows the results of applying these parameters to the other data, of which the maximum velocity is 70mm/s, 50mm/s and 30mm/s and the moving direction of the X-Guideway is the plus or the
Table 2 The results applying the parameters of eq.(3) to the other data

<table>
<thead>
<tr>
<th>Maximum Velocity [mm]</th>
<th>Moving Direction</th>
<th>(1) [mm]</th>
<th>(2) [mm]</th>
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</thead>
<tbody>
<tr>
<td>70</td>
<td>+</td>
<td>0.072</td>
<td>0.008</td>
</tr>
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<td>70</td>
<td>+</td>
<td>0.072</td>
<td>0.008</td>
</tr>
<tr>
<td>70</td>
<td>+</td>
<td>0.072</td>
<td>0.008</td>
</tr>
<tr>
<td>70</td>
<td>-</td>
<td>0.068</td>
<td>0.009</td>
</tr>
<tr>
<td>70</td>
<td>-</td>
<td>0.069</td>
<td>0.009</td>
</tr>
<tr>
<td>70</td>
<td>-</td>
<td>0.071</td>
<td>0.010</td>
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<tr>
<td>50</td>
<td>+</td>
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<td>0.009</td>
</tr>
<tr>
<td>50</td>
<td>+</td>
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<tr>
<td>30</td>
<td>-</td>
<td>0.068</td>
<td>0.011</td>
</tr>
</tbody>
</table>

(1) The deviation between the position of the X-Guideway and the retro-reflector
(2) The improved deviation in applying the parameters

minus direction of the y-axis. Table 2 shows the deviations can be also improved in different maximum velocities. As the improved deviation in 30mm/s is larger than in 70mm/s, Table 2 shows that the parameters should be determined in every maximum velocity.

Moreover, the deviations in different positions of the x-axis could not be improved by applying these parameters to eq.(3). The values of these parameters are dependent on the position of the Z-pinole, namely the x, z-coordinates in this kind of the CMM. Therefore it is necessary to investigate the relation between the parameters in eq.(3) and the x, z-coordinates of the CMM. In this research, we measured the deviations in the movement of the X-Guideway along the direction of the y-axis. For the practical use, it is also necessary to measure the deviations in the movement of the Z-pinole along the direction of the x-axis, but corrections can be applied in an analogue way.

Acknowledgements

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We wish to thank Renishaw Ltd. for supplying the laser interferometer.

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5. Conclusion

In this report, we analysed the deviations between the position of the X-Guideway measured by the y linear scale of the CMM and the position of the stylus measured by the laser interferometer, and then compensate these deviations in high speed movements and measurements. From this research, the following may be concluded:

(1) The deviations can be estimated without any extra sensors in high-speed movement from eq.(1).
(2) The additional sensor, which can measure $\ddot{Y}_L, \ddot{Y}_L$ in eq.(3) accurately, is necessary for estimating the deviations in high speed probing.

As the parameters in eq.(3) are dependent on the x, z-coordinates of the CMM, it is necessary to investigate the relation between the parameters in eq.(3) and the x, z-coordinates of the CMM.