A fine tool servo system for global position error compensation for a miniature ultra-precision lathe

Gan Sze-Wei, Lim Han-Seok, M. Rahman, Frank Watt

Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore
Department of Physics, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore

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Abstract

There is an increasing demand for single-point diamond turning to manufacture micro components as well as micro features on a large workpiece surface. In order to obtain high accuracy and a fine surface finish of the large area workpiece, position control of machine tool has become the main concern to achieve the high precision position control. A coarse-fine servo system is able to provide a cost-effective solution. This system can provide information on the entire guidance errors profile data and simultaneously compensate the error in real-time by using the fine position control technique. In this study, a piezoelectric actuator based fine tool servo (FTS) system has been developed and it has been incorporated with a miniature ultra-precision lathe. A cost-effective position sensitivity detector (PSD) is integrated in the FTS design, which is able to measure the global straightness error of the translational slide accurately. The detected error signals are compensated by the FTS during the turning process. For better tracking performance, a proportional-integral (PI) feedback controller has been implemented and tested in this study. Experimental results show that the developed FTS can effectively and successfully compensate the micro waviness error which is caused by the x-axis translational slide of the miniature ultra-precision lathe.

Keywords: Global measurement; Waviness compensation; Fine tool servo; Position sensitivity detector

1. Introduction

In recent years, ultra-precision machining techniques have been successfully implemented for the manufacture of computer memory discs, photoreceptor components, micro lenses, and optical components. These high performance surfaces are most effectively manufactured by single-point diamond turning using ultra-precision diamond turning machines, as compared to multiple processes such as grinding and polishing. However, the geometric behavior of such machines has become the main concern in manufacturing the sub-micrometer accuracy components. Geometric behavior of a machine tool is referred to the form and position error of movement of machine tool parts such as translational slides and spindle systems. Subsequently, the non-linearity of linear slide, error of lead screw, and others mechanical errors in a translational slide will influence the accuracy of a machined surface of the workpiece. In order to compensate the effects from these errors, one of the approaches in diamond turning is to control the diamond tool movement as a function of spindle and axis position to compensate the small error during turning process. This can be done with a tool servo which is mounted on the translational slide of the machine tool.

Diamond turning using a tool with fine tool servo (FTS) or fast tool servo is one of the more popular techniques in micro/nano-machining because of its shorter machining time, better repeatability, and easy setup. In this study, a FTS which was mounted on a miniature ultra-precision lathe was developed. By implementing this system, the diamond tool tip can be driven and moved in 4.6 μm effective working stroke with resolution of 30 nm during turning. Therefore, an actuator with high resolution and high stiffness is needed to drive the FTS in the required range. Some researchers have used the piezoelectric actuator...
driving concept to develop a fast tool servo system with high stiffness and high frequency response. Patterson and Magrab [1] designed a fast tool servo for diamond turning with 2.5 μm stroke and 660 Hz bandwidth. Hara et al. [2] developed a micro-cutting device with piezoelectric actuator and parallel spring guidance which was able to achieve stiffness of 80 N/μm and stroke of 3.7 μm. Woronko et al. [3] developed a piezo-based fast tool servo with a 38 μm stroke and 3200 Hz natural frequency. Cattino et al. [4] developed a fast tool servo with long stroke of 100 μm and bandwidth of 100 Hz by using a piezoelectric stack 13 cm long and 70 N/μm in stiffness. In summary, the piezoelectric actuator is becoming the most popular choice in the FTS driving system, due to its high stiffness, high bandwidth and nanometer resolution positioning.

Another design concern is the positioning measurement for FTS feedback system implementation. Two common techniques that are used to measure the tool position error in real-time are available; one is local position-measurement and the other is global position-measurement. In local position-measurement, a sensor is directly installed and aligned with the cutting tool in the FTS device. The measurement is taken by measuring the deflection of the tool against the workpiece during turning. Most of the developed FTS have used the high resolution capacitance gap sensor to measure the submicrometer displacement which is created by the diamond tool tip during machining [1–4]. This type of position-measurement technique is very suitable for machining the fine features of free-form surface on the workpiece during turning. However, it is unable to measure the entire machining profile on the workpiece surface.

On the other hand, global position-measurement in FTS utilizes an optical technique such as laser interferometer to measure the entire position of the workpiece along the translational slide. This technique is able to provide the information on straightness error of translational slide during turning process. Pahk et al. [5] developed the dual-information on straightness error of translational slide. This technique is able to provide the entire position of the workpiece along the translational slide; and the FTS is to compensate this error on-line during the turning process.

In this study, a unique FTS system has been developed by using a piezoelectric actuator as a driving element and a PSD as a position measurement sensor. A small-sized flexure body has been designed based on the translational slide of a miniature ultra-precision lathe. The design of the FTS mechanical structure has become easier since the PSD is small in size and the laser light source also can be easily placed on the machine. The prototype of the FTS was mounted and tested on the x-axis translational slide of the miniature ultra-precision lathe. The developed FTS can move several micrometers in the z-axis direction. It is also able to compensate the straightness errors of the translational slide in real-time. The cost-effective PSD is used as a feedback position error measurement sensor in the closed-loop FTS system. In order to obtain an optimal performance of the system, a closed-loop control system with proportion-integral (PI) analogue controller is implemented and tested. From the experimental results, the FTS system using the global position-measurement method is found to be effectively compensating the waviness on the machined surface during face turning process.

2. Fine tool servo (FTS) system

The developed FTS is divided into three main parts: (1) a main moving body including a tool holder and a PSD with cover; (2) a fixed body base; and (3) a piezoelectric actuator as shown in Fig. 1. A multilayer-type piezoelectric actuator of 10 × 10 × 20 mm in size and effective stroke of 12.3 μm is placed at the center of the FTS. The piezoelectric actuator
which can actuate forward and backward with high resolution is the main driving element of the FTS system in the z-axis direction of the machine. It actuates the moving flexure body and allows the single-point diamond tool tip to move in the desired distance. The load produced by the piezoelectric actuator acts against the moving flexure body and produces 4.6 \mu m effective working stroke of the FTS. This working stroke is sufficient to compensate the error created in x-axis translational slide of the machine.

2.1. Mechanical flexure structure

The translation of the piezoelectric actuator is guided by a flexure mechanism element. In micro-precision machinery, a flexure mechanism that has some notched hinges is always a good choice in designing a micro-positioner system. One effective system is a parallel and symmetric design as shown in Fig. 2. The force generated from piezoelectric actuator pushes the guiding system and moves in a straight path in the z-axis direction. The merit of the design is to minimize the undesirable parasitic motions.

In this study, a flexure mechanical body was designed by using eight circular notch-type hinges which have no backlash properties and no non-linear friction. These circular notch-type hinges are arranged in a parallel and symmetric manner which is indicated in Fig. 3. The dimensions of the parallel notch hinges are determined through the formulae of bending stiffness $K_B$ and axial stiffness $K_S$ of the notch hinge given by Paros and Weisbord [9] as follows:

$$K_B = \frac{2Ed^{3/2}}{9\pi R^{1/2}},$$

$$K_S = \frac{Ed}{\pi(r/t)^{1/2} - 2.57},$$

$$K_x = \frac{8K_B}{(L_1 - L_2)^2 + 4K_S \left(1 - \frac{L_1 - L_2}{\sqrt{x^2 + (L_1 - L_2)^2}}\right)},$$

where $R$ is the notch radius, $t$ is the thickness, $d$ is the width of the notch hinge, $E$ is the Young’s Modulus of flexure materials and $K_x$ is the stiffness of the flexure structure.

A high modulus material, carbon steel, was used as the structural material for this device. The static stiffness of the FTS, which is estimated from theoretical calculation, is almost identical to the experimental value measured which is 4.29 N/\mu m. The damping coefficient of the structure is determined through an impact test on the structure and using the following equation:

$$D = 2\zeta \sqrt{K_x \cdot M},$$

where $M$ is mass of flexure structure and $\zeta$ is damping ratio which is given by $\zeta = 1/2\pi \ln(x_1/x_2)$. $x_i$ and $x_j$ is the amplitude from the impact response graph. The characteristics such as mass, spring constant and damping coefficient of the developed flexure structure are given in Table 1.

2.2. Position sensitivity detector (PSD)

A cost-effective PSD is used as a global position error measurement sensor for the translational slide. The PSD is a common substrate of photodiodes divided into either two or four segments. It can measure the light spot position all the way to the edge of the sensor, and is independent of the light spot profile and intensity distribution that affects the position reading in the segmented diodes. Fig. 4(a) shows the sensing circuit to determine the position of the light emitted from laser diode. The intensity of laser light is measured by detecting the electrical current signal from detectors which are converted to voltage signals. Both

<table>
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<th>Characteristic of flexure structure and piezoelectric actuator</th>
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<tr>
<td><strong>Flexure structure</strong></td>
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<tr>
<td>Mass (kg)</td>
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<td>Stiffness (N/\mu m)</td>
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<td>Damping coefficient (N/ms(^{-1}))</td>
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<td><strong>Piezoelectric actuator</strong></td>
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<td>Size (mm)</td>
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<td>Displacement (\mu m)</td>
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<td>Generated force (N)</td>
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signals from element left (L) and right (R) are compared and amplified to achieve 1 V equal to 1 μm as presented in Fig. 4(b).

The PSD is aligned with the tool holder in the FTS design, thus the measurement can be made without any significant errors such as Abbe error. In order to measure the overall travel length of x-axis translational slide, the laser light source is aligned parallel with the linear guide in the machine as shown in Fig. 5. When the FTS is moving along the translational slide, the emitted laser light is continuously detected by the PSD and the overall error profile is directly measured. However, the output signal from the sensing circuit becomes very sensitive to the environmental changes such as air flow and ambient light after the output signal from the PSD is amplified. Due to this sensitivity problem, the PSD and the laser light source were properly covered by a shroud. This can help to isolate the emitted laser light source from the influence of environment. Thereby, it is found that the output signal noises were reduced significantly and the system could be easily controlled.

3. Experimental setup and procedures

Fig. 6 shows the schematic diagram of the FTS system on a miniature ultra-precision lathe. The machine model used is Mikrotools Miniature Ultra-Precision Lathe (UPL-2020) which is a two-axes T-base diamond-turning machine. The coarse slides are the z- and x-axis translational slides. These slides are controlled by the machine control unit (MCU) of the machine. However, the developed FTS is acting as a fine slide which can move the tool and compensate the submicron error created in the x-axis translational slide. The control architecture of the coarse slides and FTS are independent of each other. The closed-loop control system is implemented and tested in the FTS system. For this miniature ultra-precision lathe, the workpiece is mounted on the spindle in the z-axis slide and the diamond tool is placed on the x-axis slide. When the turning process is ongoing, the PSD is measuring the position error along the x-translational slide in on-line manner. Meanwhile, this output is feedback to the system and is compared with the reference input. The determined error between actual output and reference input is controlled by an analogue PI controller. Hence, the FTS is driven by the piezoelectric actuator by according to the amplified signal that is sent from the high voltage amplifier. The completed experimental setup of this FTS system is shown in Fig. 7.

In the experiment, a single-point diamond insert was used, and the workpieces used for the experiment were of non-ferrous materials; these were brass and aluminum. The purpose of this experiment was to investigate the FTS performance for the global position error compensation during machining process. Hence, the face turning was chosen as the machining profile so that the reference signal is equal to zero. In order to understand the straightness error profile of the x-axis translational slide before the start of the machining experiment, the FTS was controlled to move along the slide and the error position was measured by the PSD. For the machining experiment, the cutting conditions that were used in machining aluminum and brass were 1500 rpm cutting speed, 5 mm/min feed rate, and 1 μm depth of cut. The error profile measured by the PSD was recorded during machining for with and without the FTS compensation. The machined workpieces were measured by a stylus-type surface measurement instrument. The average surface roughness and average waviness were the analysis parameters in this study. Two types of samples were used in this investigation; these were with the
Fig. 6. Schematic diagram of fine tool servo system implementation.

Fig. 7. Experimental setup of fine tool servo system. (a) Detail of system setup; (b) Photograph of system setup.
FTS implementation, and without the FTS implementa-

4. Experimental results and discussion

4.1. Tracking performance of FTS

The performance of the FTS is investigated in terms of frequency response and tracking performance. Fig. 8 shows the frequency response plot of the FTS in open-loop system. The response is flat up to approximately 25 Hz and starts to decrease above this frequency. However, the frequency response of the closed-loop FTS system is 2 Hz only. Since a slow feed rate is used in this study, this frequency response range is considered sufficient for the application. For better tracking performance, manual tuning of the analogue PI controller is implemented in this study. A sine wave signal is input to the system as a reference signal. Both proportional action and integral action are introduced by increasing the values of the gains, respectively. By comparing the actual position output and the reference input, the tracking performance of the FTS can be determined until the acceptable settle time and error are achieved. Fig. 9 shows the sine wave signal input and output from the analogue PI controller of the FTS system. The remaining maximum error of about 30 nm is found after implementing the analogue PI controller system. This remaining error is considered acceptable in this experiment, and further development on the controller design and implementation of FTS will be done in the future.

4.2. Global position error profile output

The horizontal straightness error of the $x$-axis translational slide of the miniature ultra-precision lathe has been measured by the PSD as shown in Fig. 10. It is found that

Fig. 10. Measured horizontal straightness errors of the $x$-axis translational slide of ultra-precision lathe.

Fig. 11. Machining profile of aluminum and brass workpieces with and without fine tool servo compensation during face turning: (a) aluminum; (b) brass.
the \( x \)-slide is tilted in a certain angle and the measured peak-to-valley of sinusoidal form error without machining is approximately 0.08 \( \mu \text{m} \). This error resulted from the slide’s mechanical design error and coupling errors between the ball screws of the miniature ultra-precision lathe. Since it is impossible to correct this error by using machine controller, compensation of this error by implementing the FTS system is needed.

The machining experiment has been carried out to analyze the FTS performance. When the FTS system is implemented, this error profile is feedback to the system and compensated during the machining process. Fig. 11(a) shows the comparison of waviness error profile between with the FTS and without the FTS implementation of brass workpiece during machining process. From the result, it can be observed that the error profile is completely compensated by the FTS. This is identical in the case of the aluminum workpiece as shown in Fig. 11(b) where the measured peak-to-valley of sinusoidal form errors before the FTS compensation of brass and aluminum are approximately 0.13 and 0.18 \( \mu \text{m} \), respectively.

The error profiles in Figs. 11(a) and (b) are lifted up to 0.3 \( \mu \text{m} \) as compared to the error profile without the machining process. During the machining process, the thrust force on the workpiece acting against the diamond tool tip is pushing the whole moving body of the FTS in axial direction. The results indicate that the FTS system is able to compensate the minor displacement error on diamond tool tip which is believed to be created by the thrust force during the machining process.

### 4.3. Face turning output

For the purpose of investigating the performance of the developed FTS system, average waviness and surface roughness of the machined workpieces are measured by using stylus-type measurement instrument in this study. For these measurements, the same cut-off lengths are used for different samples and are used for comparison. Fig. 12 shows the average waviness on an aluminum workpiece machined with/without the FTS. The peak-to-valley waviness is about 0.90 \( \mu \text{m} \) when the FTS is not implemented. However, there is a significant reduction in waviness when the FTS system is implemented. It is found that waviness of 0.18 \( \mu \text{m} \) is found to remain on the aluminum workpiece, although the measured output error from PSD is almost zero as shown in Fig. 13(b). This is due to the imperfect cutting mechanism and thermal changes in environment. Meanwhile, this is also due to the limited ability of the analogue PI controller that has been implemented and tested in this FTS system. In the case of the brass workpiece, Fig. 13 shows the average waviness of the machined workpiece before and after implementation.

![Waviness measurement of brass material with and without fine tool servo compensation during face turning](image-url)

Fig. 13. Waviness measurement of brass material with and without fine tool servo compensation during face turning: (a) \( W_a = 0.1233 \text{ mm} \); (b) \( W_a = 0.0638 \text{ mm} \).
of the FTS. The reduction of average waviness of the brass workpiece after using the FTS is only half of the waviness without the FTS.

Fig. 14 depicts the average surface roughness on the aluminum workpiece machined with/without the FTS. It can be observed that there is no significant improvement in surface roughness. This case has also occurred in machining of the brass workpiece as shown in Fig. 15. It is most probably due to the imperfect cutting conditions between the interface of the diamond tool and the workpiece such as material properties and tool wear. Additionally, it may possibly create the cutting vibration between the workpiece and the diamond during the machining process and this may affect the machined surface. Fig. 16 shows the photograph of the machined workpiece of aluminum and brass materials after the FTS implementation.

5. Conclusions

The error created in translational slide of a turning machine will directly influences the accuracy and surface finish of a workpiece. If an ultra-precision part is required to be manufactured, the error compensation technique needs to be introduced in the machine. In this study, a piezoelectric actuator based fine tool servo (FTS) has been developed to achieve the fine motion with 4.6 μm working stroke. This system has been installed on a miniature ultra-precision lathe, comprising a global position error measurement system. The measured position signal is feedback to the FTS system for on-line error compensation. From this study, following conclusions have been drawn:

1. The cost-effective position sensitivity detector (PSD) has replaced the laser interferometer measurement method in this system. The PSD is detecting an emitted laser light and measuring the position change of laser light. By aligning the laser light parallel to the translational slide, the PSD is capable of measuring the entire
straightness error profile of the slide on miniature ultra-precision lathe effectively.

2. The closed-loop FTS system has not only compensated the error created in translational slide, but it has also compensated the minor displacement error of the diamond tool tip which is created by the thrust force during the machining process. From the machined surface measurement, it can be concluded that the FTS has successfully compensated the average waviness on the workpiece. Due to the imperfect cutting conditions, the surface roughness of the machined workpieces did not show any significant improvement.

References