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Single Axis Error Compensation of Ultra Precision Lathe Using Dual Servo Actuation

Aravind Raghavendra M R.

Manufacturing Division, Department of Mechanical Engineering, Faculty of Engineering, NUS, Singapore

Senthil Kumar A.

Department of Mechanical Engineering, Faculty of Engineering, NUS, Singapore

Abstract

Steady increase in the precision requirement of today's manufacturing industries is the driving force for the development of new and innovative precision machines. The accuracy of the machined workpiece depends widely upon the accuracy of the machine tool and its individual component and sub-assemblies. In the current work, we have put forward a dual servo error compensation mechanism for an ultra-precision lathe to compensate the tool positioning error along Z-axis due to the Z-axis following error caused by the machine's servo and X-axis form error along the Z direction. A monolithic single axis piezo-actuated flexure based mechanism is designed to compensate the micro-metric positioning error of the lathe to provide nanometric level machine accuracy. Experiments have been conducted to verify the machine's performance characteristics with and without the fine tool servo (FTS) compensation using a high resolution capacitance sensor. The surface roughness of 9nm has been achieved using the following error compensation mechanism alone with a primary profile height P_t *of 1.285μm. The results were evident that the surface roughness has been improved tremendously with the Z-axis following error compensation mechanism. Further experiments have been carried out in order to improve the primary profile of the machined surface by studying the errors along the Z axis and formulate controller logic in order to compensate the cumulative error along the Z axis in real-time. The surface roughness of 4nm and profile height of 0.3μm has been achieved using the compensation system. Further studies are also being carried out in order to study the form error of the machine and actively compensate all the errors along Z axis cumulatively in real-time*

Keywords*: Flexure based stage, Following error compensation, Piezo-actuator, Ultra precision Lathe*

1 Introduction

Ultra high precision components demand mirror surface finish with sub-nanometric level surface roughness R_a. Practical difficulty in achieving such high quality demands by conventional machining forces us to capitalize the advantage of the precision machining technology [1–3]. Various errors affect the accuracy of such high precision machines. Geometric error accounts for the major part of inaccuracy in machine tools [4]. The geometric error is caused mainly by the geometric tolerances and friction between moving parts like the lead screw or moving slides. The use of linear motion guideways for machine axes has served to greatly reduce the friction at the slide/base interface and eliminate problems like deformation of the low friction liners used in conventional slide designs [5]. In the case of ultra high precision machines such as the diamond turning machine, achieving nanometric level accuracy will be more challenging even after using sophisticated linear motors, guideways etc., The easier and effective way to meet such high demands is to allow for the error to happen and proactively compensate the same using an external mechanism in real-time with a faster response time.

2 Literature review

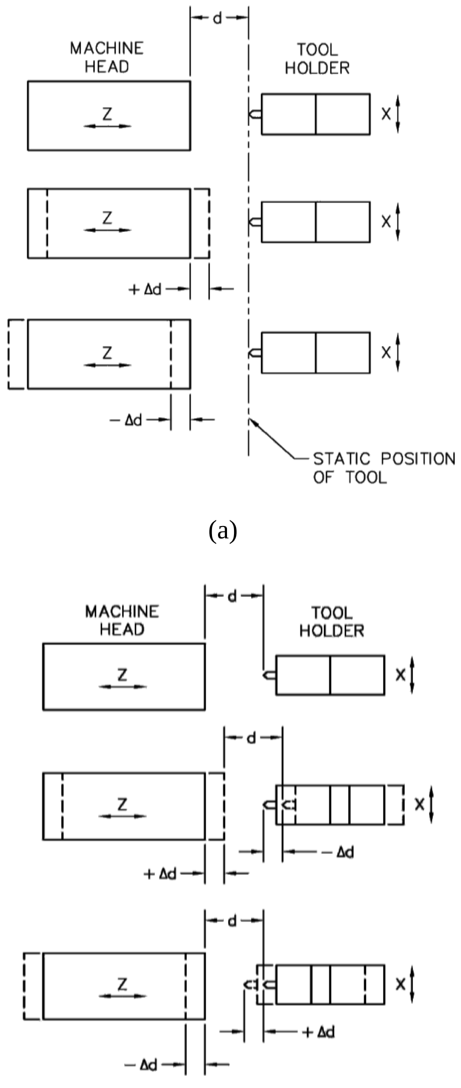
A recent approach made in diamond turning is to incorporate fine tool servo (FTS) to improve machining accuracy by reducing the surface-normal tool position errors. FTSs refer to an auxiliary servo that is specially adopted to activate the diamond tool using the piezo-actuator with fine resolution, high stiffness and fast dynamic response. FTSs were mounted to diamond turning machines to fabricate non-rotationally symmetric surfaces by rapid actuation of tools with a sufficiently high bandwidth. FTS can also be an effective means for the fabrication of large aspheric off-axis mirrors in diamond turning machines. In FTS, besides the controllers and sensors, flexure hinges play a major role in obtaining precise, accurate and faster response. Flexure-based piezoelectric-actuated nanopositioners have emerged as an important technological advancement in hi-tech applications, including scanning probe microscopy, lithography, nano-metrology, beam steering for optical communication systems, fabrication, and assembly of nanostructures [6]. These nano-positioning stages typically have high positioning accuracy and high travel speeds of several hundred hertz which provides faster response to compensate the error in real-time.

Gan Sze-Wei et al. [7] developed a piezoelectric actuator based fine tool servo (FTS) system that has been developed to compensate the form error of the lathe using an external position sensitivity detector (PSD) to measure the global straightness error of the translational slide accurately. They achieved a surface roughness R_a of 181nm. Elfizt at al. [8] have designed the "Dual stage feed drive" DSFDs for machine tools using the combination of linear motor for coarser movement and a PZT actuator for the finer motion. They have designed single and dual axis serial type mechanisms to overcome tracking error of a milling machine. The linear motors' limitation such as the stick-slip friction, force ripple and quantization error are overcome by the high frequency, force and unlimited resolution of Piezo-actuators.

The objective of this paper is to develop a dual servo compensation mechanism using a flexure based piezo-actuated stage to compensate the following error (FE) using the data from the machine's controller. PLC logic has been developed to maintain the same depth of cut "d" throughout the machining process and control of servo interrupt between the dual servo-loop. The designed stage is fabricated and tested by both static and machining experiments in order to achieve nanometric surface roughness using a diamond turning machine.

3 Working Principle

3.1 *Following error compensation*



(a)

(b)

Figure 1: (a) FE motion of Z axis
(b) PZT compensation to maintain Depth of cut "d"

Figure 1(a) represents the following error of Z axis of the lathe and Figure 1(b) represents the error compensation mechanism. To compensate the positioning error along the Z axis, we have designed a monolithic single axis piezo-actuated flexure based mechanism which compensates the micrometric positioning error of the lathe to provide nanometric level machine accuracy. The dual compensation is achieved by using the machine's servo as the primary compensation mechanism (coarser) and a secondary compensation using a Piezo actuated servo loop (finer < 2µm) with the machine's linear encoder as the error input. Elaborate machining experiments using single point diamond tool have been performed and the surface characteristics of the machined work-piece were studied. The surface roughness of 9nm has been achieved using the following error compensation mechanism. The results indicated that the machine's performance improved tremendously with the Z-axis following error compensation mechanism. Further extension of the current compensation mechanism were carried out and presented in the following sections.

3.2 *Combined following error & Form error compensation*

As an extension of the current research, in addition to the following error compensation along Z axis, the form error in the X axis of the lathe which causes the waviness/profile error in the surface of the machined workpiece is measured and compensated both off-line and on-line. Figure 2 represents the schematic of the experimental setup.

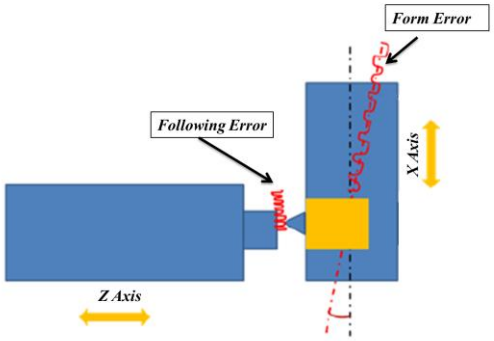


Figure 2: Proposed cumulative error compensation along Z axis

The form error values are measured and recorded using a high resolution capacitance sensor. The measured error values are compensated off-line using the machine servo's compensation table. A PLC logic is framed in order to compute the cumulative effect of both Z-axis following error (Z-axis encoder) and the X-axis form error (Capacitance sensor) along the Z axis. Computed value is fed as an input voltage to the Piezo-actuator through the machine's controller which in turn actuates the designed single axis FTS to compensate the error along Z-axis. Figure 3 shows the schematic of the dual servo compensation system. An elaborate experimentation of error compensation is being carried out and results will be discussed.

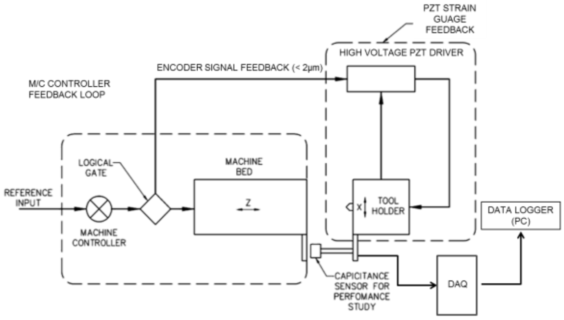


Figure 3: Schematic of Dual servo Control system

4 Experiments & Results

For the experiment, the ultra precision lathe (UPL-4040) from Mikrotools is used (Figure 4). The main spindle of the precision lathe has an aerostatic bearing mounted on a built-in type DC motor and operated above 6 bar air pressure. The slideways are made up of high precision needle bearings mounted on the precise V guideways with a travel of 40mm. The body of the machine is a granite bed with passive isolators. Air bearing and slideways are mounted on the granite bed in order to isolate high frequency environmental vibration and to keep them in the assembly parallel. A PZT actuated flexure stage is designed to provide submicron depth of cut. This machine is operated in a thermostatic room because machine components, particularly the air bearing spindle, guideways and the workpiece, are very sensitive to temperature in ultraprecision cutting.

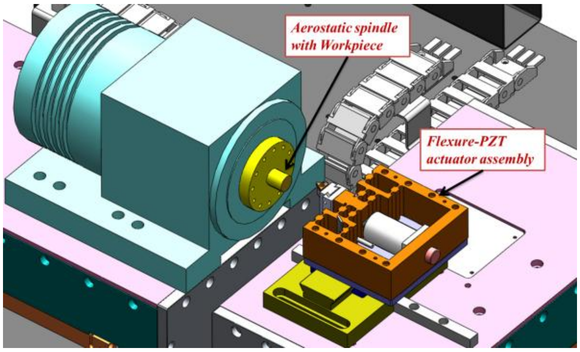


Figure 4: UPL 4040 Machine with PZT actuated flexure assembly

4.1 *Flexure Stage Calibration*

The designed flexure stage is designed with notch type flexure hinges which are fabricated as a monolithic design using wire-cut process. The design incorporates accurate locating for the PZT actuator in order to maintain the perpendicularity between the PZT actuator and flexure mechanism. The flexure stages' displacement is calibrated by varying the input voltage to the PZT actuator using the machine's controller. The stage displacement is measured using a high resolution (5nm) capacitance sensor as shown in Figure 5. Voltage versus displacement is plotted in Figure 6. The maximum displacement achieved for an input of 10V to the PZT actuator is 16.6µm. The performance of the flexure stage with servo being activated is accurate and repeatable with no overshoot and vibration of the flexure stage.

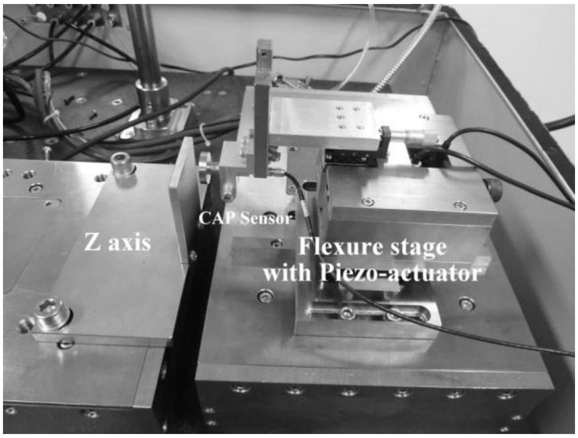


Figure 5: PZT actuated Flexure stage with CAP sensor assembly

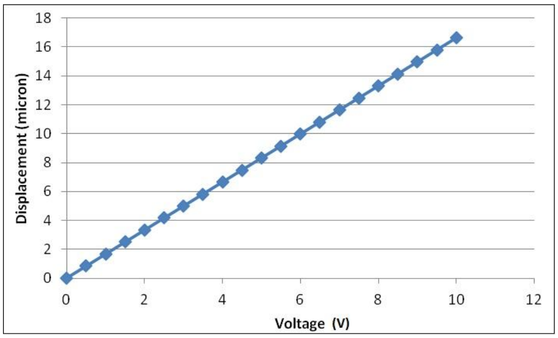


Figure 6: Flexure stage calibration chart

4.2 *Static following error Measurement*

The stage is measured for static following error with and without the compensation mechanism. The following error is measured using the capacitance sensor 1 as shown in Figure 5. The following error is measured to be around 200 nm at static position when the machine servo alone is activated without the following error compensation in place. In the dual servo mode, the machine's encoder is feedback as an input to flexure based PZT actuator in order to compensate the following error. The following error is reduced to 20nm due to the compensating motion of the FTS. The effect of the compensation is seen clearly in Figure 7 where except the intermittent environmental noise, following error remains consistent around 20nm.

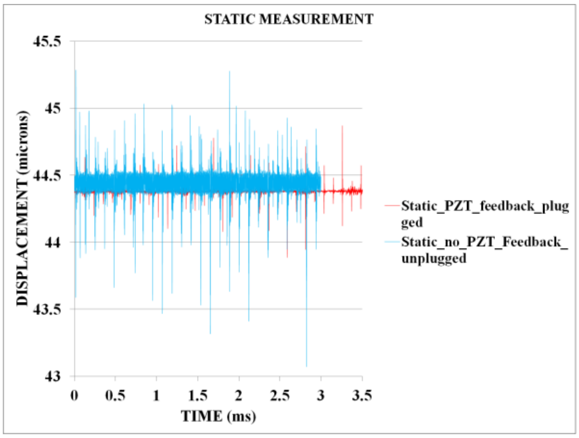


Figure 7: Static following error measurement with and without PZT compensation

4.3 *X axis straightness error measurement*

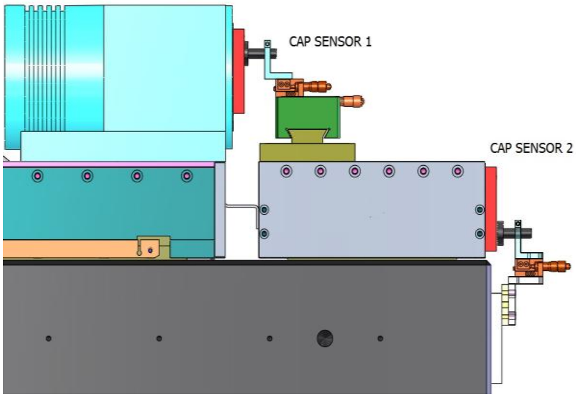


Figure 8: Capacitance sensor assembly for simultaneous X axis straightness with respect spindle face

Following the Z axis following error measurement and compensation, the X axis straightness error with respect to the Z axis is measured (Figure 8). Since the profile error on the machine depends on the perpendicularity of the X axis and spindle face, the straightness error is measured directly on the spindle face as the straightness between the two axes is more important than the straightness of the X axis alone. The first time measurement of the straightness error is measured using the high resolution (5nm) non-contact type capacitance sensor. Care has been taken in parallel alignment of the sensor face and target measurement face during the measurement.

In the initial experimental setup, the capacitance sensor 2 was used to measure the deviation of the X axis along its travel (0-40mm) with respect to the machine's granite base. Proper precautions were taken in order to align the capacitance sensor face to be orthogonal to the target plate. The straightness error of the X stage with respect to spindle face was measured to be around 12µm for the whole travel length of 40mm (Figure 9). The profile is linear and with less noise disturbances from the machine servo due to the damping effect of the large granite base. In order to capture the more realistic error which is transmitted from the tool axis to the workpiece, the perpendicularity between the spindle face and the X axis is measured using the capacitance sensor 1. The perpendicularity between the flexure stage and the spindle appears to differ from the error measured using the capacitance sensor 2 (Figure 10). The error value obtained by the sensor 1 is around 10µm and has a profile similar to that of a machined workpiece. The measurement is directly obtained with respect to the spindle face and this data provides the information of the following error of Z axis and also the profile error of the X axis.

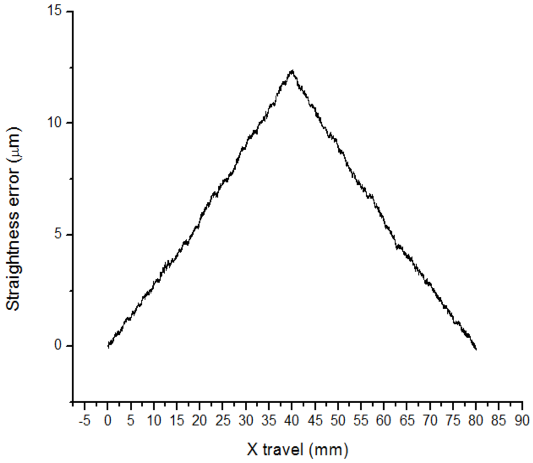


Figure 9: X axis straightness error with respect machine table (CAP sensor 2)

Since the influence of the straightness error with respect to the machine's table is less on the workpiece profile, this data (Figure 9) is omitted in the compensation procedure.

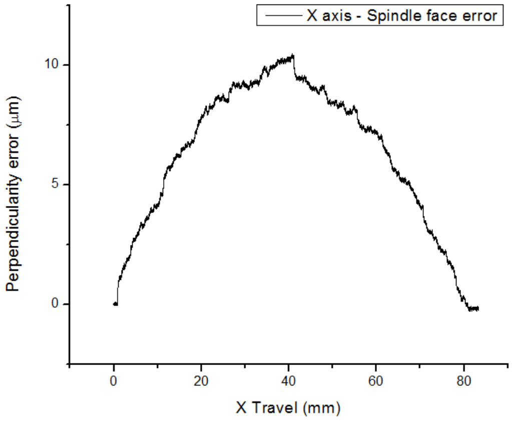


Figure 10: X axis straightness error with respect spindle face (CAP sensor 1)

The following error of the Z axis is computed in real time using the Z axis position encoder, the raw data recorded using the capacitance sensor is filtered to reduce the low frequency noise and a curve is plotted to fit the filtered data. The equation obtained from this fit curve is a function of X axis location and the corresponding error. This equation is fed to the machine's controller and using this data a curve is fitted in order to find the form error of the X axis as shown in Figure 11. The experiment has been repeated a few times in order to find the repeatability of the measurement value. Since the PZT actuation is a negated Z axis displacement, equation (1) satisfies the compensation motion by the PZT actuated flexure mechanism.

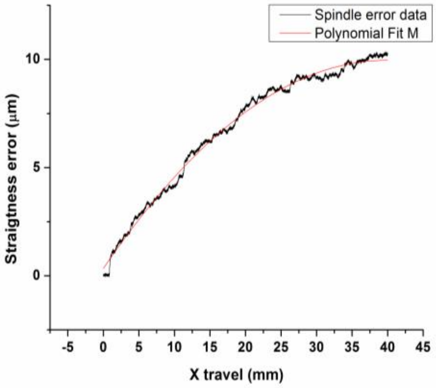


Figure 11: CAP sensor assembly for simultaneous X axis straightness with respect spindle

$$y = 0.3389 + (0.48246 * x) + (-0.00605 * x^2) \qquad (1)$$

Where,

y – PZT displacement value (micron)

x – X axis location captured from machine's controller in real-time (mm)

4.4 *Error Compensation Measurement*

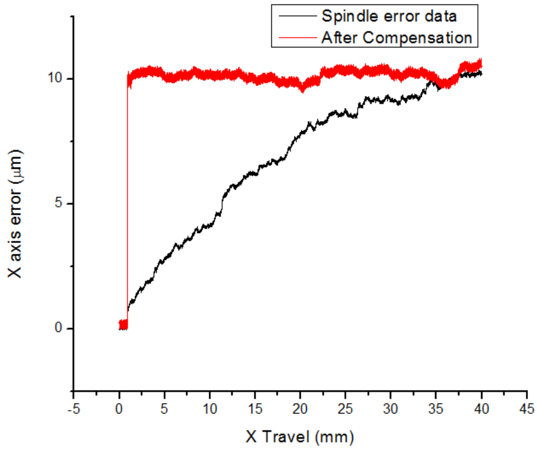
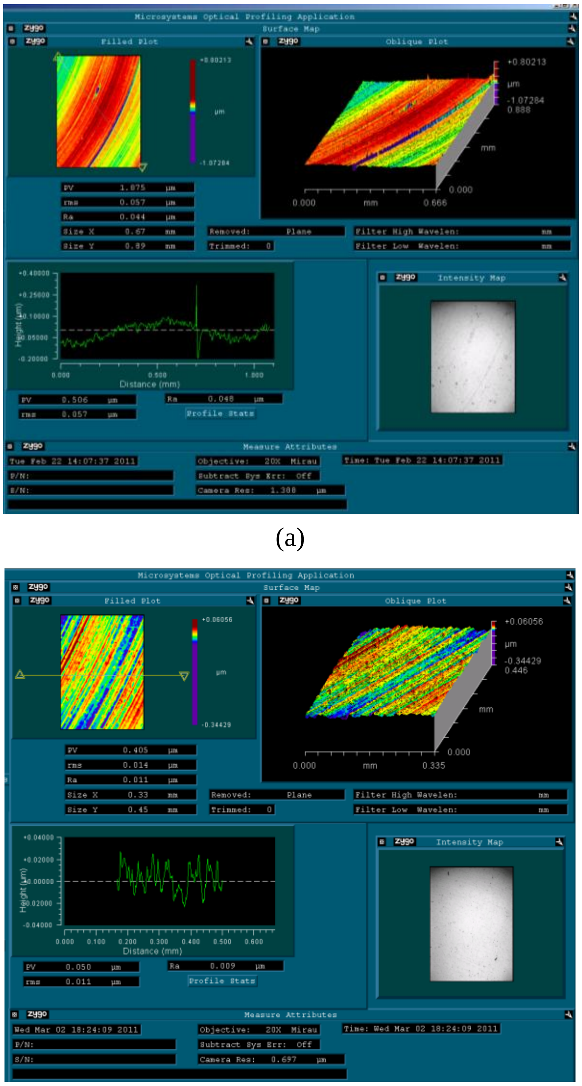


Figure 12: CAP sensor measurement with & without error compensation

The equation of the compensation data is stored in the machine's controller and the measurements are recorded in order to verify the effect of the compensation using the PZT actuated flexure stage. Figure 12 shows the error before and after compensation using the PZT flexure mechanism. The result shows the error reduced to sub-micron range.

In the machining experiments, two sets of experiments were performed. Firstly, an experiment with only following error compensation was initiated. In the following error compensation experiment, the surface roughness Ra achieved using the real-time compensation using the following error data from the machine's controller had a significant improvement. The surface profile and roughness is measured using ZYGO^{TM} white light interferometer. A surface roughness Ra 48nm was achieved without the compensation (Figure 13a) with a wavy surface profile. With the following error compensation mechanism, the surface roughness Ra achieved was 9nm (Figure 13b) with smoother, mirror surface.

In the second set of experiment, both the following error compensation and the straightness error compensation were initiated and both the surface profile and roughness seemed to be improved.



PV 1.075 µm
rms 0.057 µm
Ra 0.044 µm
Size X 0.67 mm
Size Y 0.89 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: mm
Filter Low Wavelen: mm
PV 0.506 µm
rms 0.057 µm
Ra 0.048 µm
Tue Feb 22 14:07:37 2011
P/N:
S/N:
Objective: 20X Mirau
Subtract Sys Err: Off
Camera Res: 1.308 µm
Time: Tue Feb 22 14:07:37 2011

(a)

PV 0.405 µm
rms 0.014 µm
Ra 0.011 µm
Size X 0.33 mm
Size Y 0.45 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: mm
Filter Low Wavelen: mm
PV 0.050 µm
rms 0.011 µm
Ra 0.009 µm
Wed Mar 02 18:24:09 2011
P/N:
S/N:
Objective: 20X Mirau
Subtract Sys Err: Off
Camera Res: 0.697 µm
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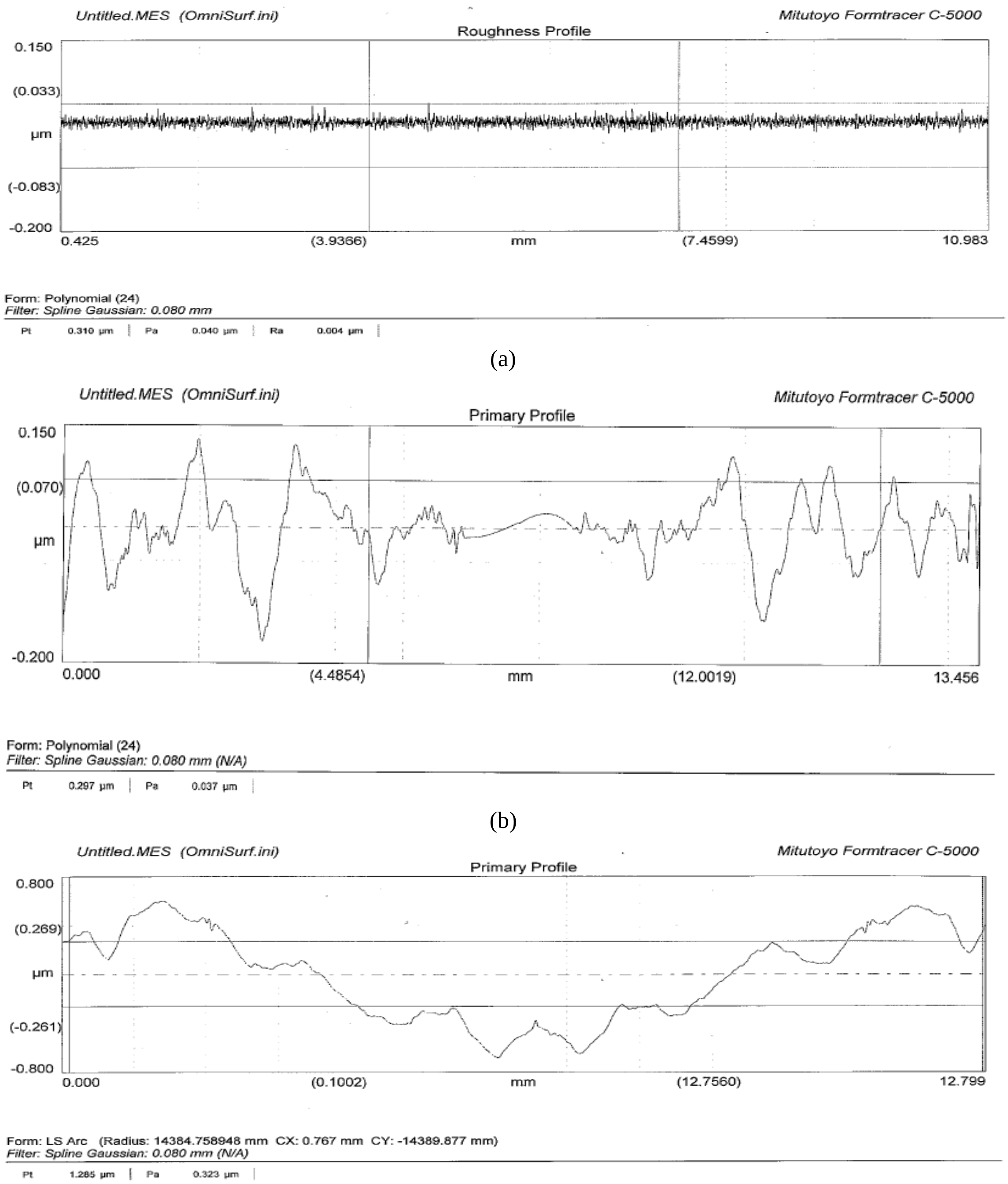
(b)

Figure 13: (a) Without compensation Ra 48nm (b) With compensation Ra 9nm

With both the following error and straightness error compensation is in place, the surface roughness and the primary profile of the machined surface is measured using a Mitutoyo Formtracer surface profiler. Surface roughness Ra of 4nm (Figure 14 a) with a total height of the primary profile P_t reduced to 0.3µm (Figure 14b) compared to the P_t value of 1.285µm (Figure 14c) while the following error and straightness error compensation are not incorporated while machining. The results also shows that the large difference in the profile height data between the capacitance sensor measurement and the actual machining experiments is due to the “contact damping” created at the tool-workpiece interface, still following the same profile as that of the capacitance sensor measured data.



(a)

(b)

(c)

Figure 14: Surface roughness (a) & Primary profile measurement with (b) and without (c) dual error compensation

5 Conclusions

The dual servo error compensation mechanism for an ultra-precision lathe to compensate the tool positioning error along the Z-axis due to the Z-axis following error and X-axis form error along the X travel has been successfully implemented. Experiments have been conducted to verify the machine’s performance characteristics with and without the fine tool servo (FTS) compensation using high resolution capacitance sensor. The surface roughness of 9nm and a primary profile height P_t of 1.285µm has been achieved while the following error compensation mechanism alone is incorporated. The results were evident that the surface roughness has been improved tremendously with the Z-axis following error compensation mechanism using the machine’s Z-axis encoder as input. Further, in order to improve the primary profile of the machined surface, the perpendicularity between the X axis and the spindle face is measured and compensation has been formulated using the error data. A surface roughness of 4nm and profile height of 0.3µm has been achieved using this compensation system. Further studies are also being carried out in order to study the form error of the machine and actively compensate all the errors along Z axis cumulatively in real-time.

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