Experimental Study on Dynamic Accuracy Behavior of a High-speed CNC Machine Tool with Semi-closed and Fully-closed Feedback Control

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INTRODUCTION

The electromechanical feed drive system, with ball screw transmission elements, has a dynamic effect on the positioning accuracy of a CNC machine tool system, which is directly associated with the accuracy of a product machined. There are many error sources such as pitch error of the screw, backlash, elasticity, thermal deformation error, etc. If the errors are repeatable and constant, the compensation by software is possible in a position feedback control loop. As a matter of fact the current controllers are mostly using this quasi-static compensation technique. The thermal induced error in a ball screw feed drive system, however, is the most critical and also difficult to compensate since it behaves unpredictable and unrepeatable. In recent high-speed machine tool systems, compared to the conventional machine tool systems, more heat is generated between the screw and the nut during a high acceleration and deceleration motion, which results in dynamic and random behavior of the longitudinal thermal deformation of a ball-screw. Because of this dynamic behavior, the rotational angle readings of an encoder can not be used to precisely calculate the exact position of the worktable, thus leading to the position control accuracy deterioration of a CNC machine tool system. One solution for reducing the thermal expansion is to cool the screw system by water circulation in the hollow screw. But this methodology is difficult to maintain a reliable operation and costly compared to the conventional system. In recent years, some of high-speed machines, especially linear motor machines, are being equipped with a linear encoder system. But for a ball screw feed drive system, the effectiveness of linear encoder against the ball screw thermal deformation has not been well studied (1).

Therefore, the goal of this research is to investigate the positioning error behavior of the high-speed horizontal machining center with the ball screw and rotary encoder feedback, and to eventually build a high-speed horizontal machining center equipped with a switchable rotary and linear encoder motion control system. The main focus of the paper is on investigating the difference of motion control feedback behavior between a rotary encoder and a linear encoder feedback, and to discuss the effectiveness of the linear encoder based motion control. The experimental results measured by the rotary encoder from two types of high-speed machining centers are presented.

EXPERIMENTAL PROCEDURE

The system diagram for measuring the position of worktable is shown in Figure 1. Two horizontal machining centers were used in the experiments. The specifications are given in Table 1. A linear scale (VM182, Heidenhain) with a measurement range of 520mm was used for detecting the position of the spindle head. The data processing software (ACCOM Measurement Version 2.01) with Interface Card (VM121, Heidenhain) was installed in a computer. The experiments were designed and performed by following the standard procedures defined in ISO-230 (2). Figure 2 shows the parameters to define the traverse motion used to operating the machine tool. The parameters to define the motion are as follows:

- Target points (Test range): The distance between two target points defines the test range.
- Bi-directional measurement (Lead distance): Two additional distances adjacent to the both ends of test range defines the lead distance for getting rid of reversal error during the tests

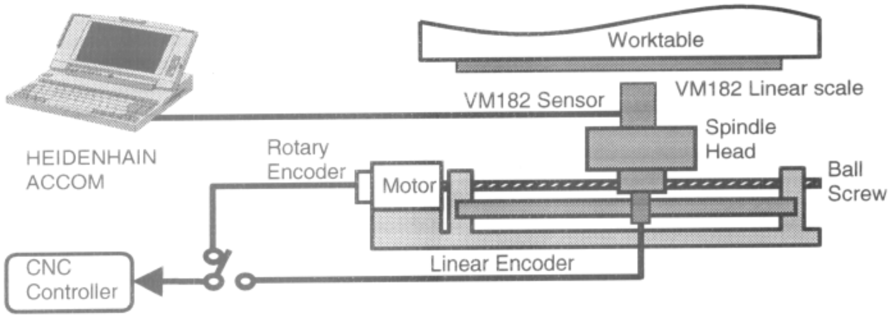


Figure 1. Measurement System Diagram

Table 1. Specification of Machine Tools

SPECIFICATIONS		MAKINO A55-A40	MORI SEIKI SH-
Travel	X-axis Stroke (mm)	560	840
	Y-axis Stroke (mm)	560	760
	Z-axis Stroke (mm)	560	840
Feedrate	Max Rapid Traverse Rate (mm/min)	24000	32000
Spindle	Max. Spindle Speed (mm^{-1})	12000	15000
	Spindle Bearing Inner Diameter (mm)	85	100
ATC	Type of Tool Shank	BT-40	HSK A100
	Tool Storage Capacity	40	60
APC	Number of Pallets	2	2
Motors	Feed Motors (X, Y, Z) (kW)	3.5, 3.5, 3.5	5.0, 7.3, 5.0
	Spindle Drive Motor (30min./continuous rating) (kW)	22 / 18.5	30 / 25

Table 2. Measurement Conditions

Machine Tool	MAKINO A55-A40	MORI SEIKI SH-630
Measurement System	HEIDENHAIN VM182 (Max. Measure Length 520mm)	HEIDENHAIN VM182 (Max. Measure Length 520mm)
Feedback Method	Rotary Encoder (YASKAWA)	Linear Encoder (HEIDENHAIN) and Rotary Encoder (FANUC)
Target Positions (Pisition A & B)	X axis: 15mm and 415mm away from machine home position Y axis: 20mm and 300mm away from machine home position	X axis: 300mm and 700mm away from machine home position Y axis: 20mm and 420mm away from machine home position
Dt: Distance between Target Positions	X axis: 400 mm Y axis: 280 mm	X axis: 400 mm Y axis: 400 mm
Dr: Distance between Target Position and Reversal Position	X axis: 15 mm Y axis: 19 mm	X axis: 20 mm Y axis: 20 mm
Traverse rate	Rapid Traverse rate (approximately 24000 mm/min)	1000, 5000, 10000, and 16000 mm/min
Dwell Time	3 sec.	3 sec.
Measurement Cycle (times / min.)	999 cycles / approximately 270 min.	up to 999 cycles / approximately 215 min.
Rest Time	At least 4 hours (240 min)	At least 4 hours (240 min)

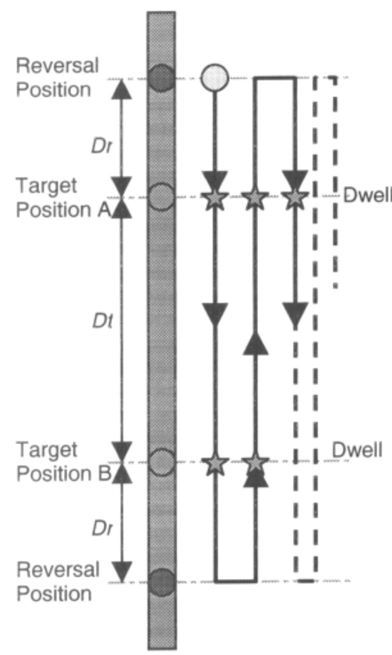


Figure 2. Motion Parameters

- Traverse Rate (Speed)
- Dwell time for holding the measurement point: A shorter dwell time may not be able to measure the point data because of the machine may not be stopping at the point completely (may have a vibration). A longer

dwell time may need to take a long time to get the thermal deformation error, because of the ball screw may be cool down during the dwell time.

- Measurement Cycles (Time): The ACCOM software, which is used in this test, can measure the data up to 999 cycles (single or bi-directional) for the linear motion test. The different traverse speed gives the different cycle time.
- Rest Time: During the rest time, machine tool will cool down.

MEASUREMENT RESULTS of THERMAL GROWTH

The measurement conditions in X and Y-axis direction for machine A55 is given in Table 2. The measured results are shown in Figure 3. From this figure, it is found that with the increase of the running time, the ball screw has a big thermal growth in both X and Y-axis. In the first two hours running, the thermal expansion increases rapidly. For example, the thermal growth reaches a value of 0.035mm for X and Y-axis. After that, the ball screw gradually expands. It was found that from these measurement results the thermal growth is remarkable. It can be deduced that there is a big difference between the position information reflected by the rotary encoder and the actual position measured directly by linear scale and therefore this will deteriorate the machined part accuracy. The machine SH-630 is different from the machine A55 in that SH-630 is equipped with both rotary encoder and linear scale position reading system. Figure 4 shows an example of measured results in the condition of feedrate of 16m/min (Y-axis direction). It is found that the linear encoder feedback has the small positioning error in comparison with the error by the rotary encoder feedback. Figure 5 show the change trends of the thermal growth in various motion conditions for SH-630 by the rotary encoder and linear scale feedback, respectively. The results show that with the increase of the feedrate, the positioning error increases and with the increase of the cycle number, the positioning

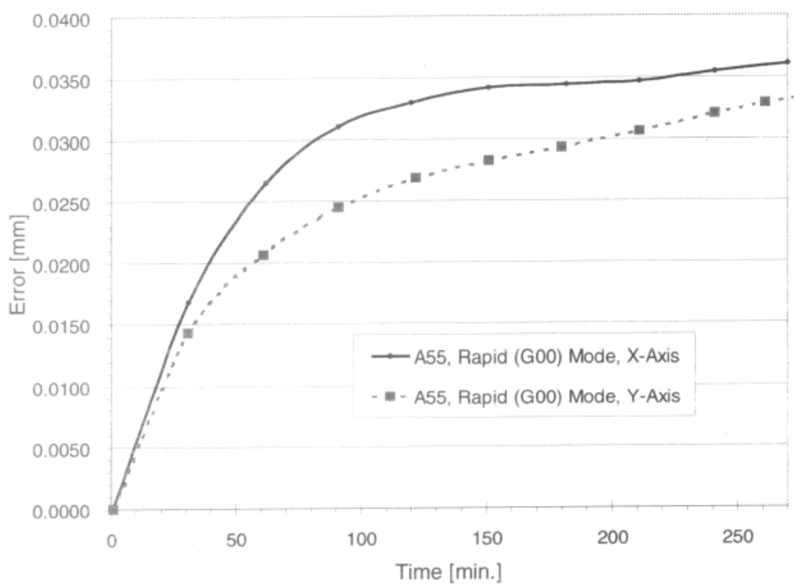
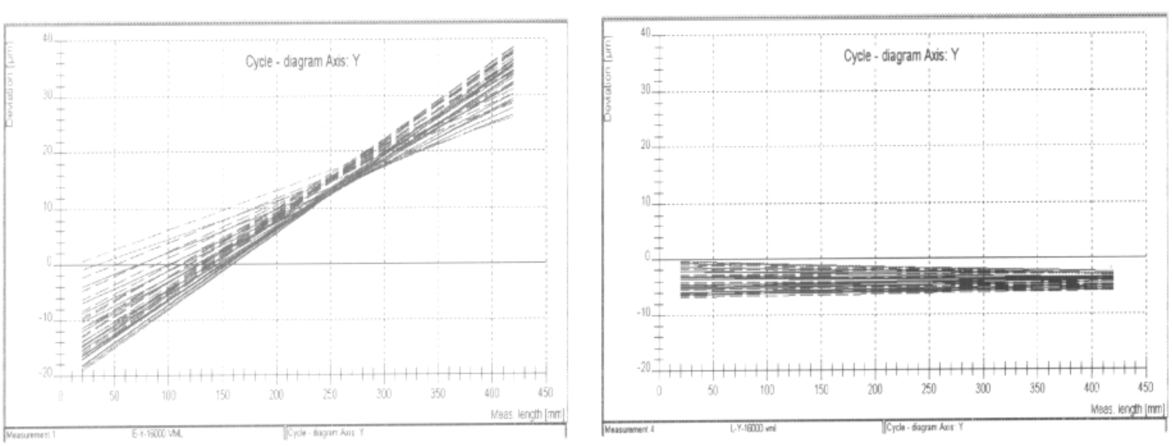


Figure 3 Positioning Error by Rotary Encoder Feedback (A55)



(a) Rotary Encoder Feedback (b) Linear Encoder Feedback

Figure 4. Measurement Results (SH-630, Y-Axis, Feedrate: 16 m/min)

error increases in the case of encoder feedback control. However, in the case of linear scale feedback case, the positioning error almost does not change either for an increase of cycle number or feedrate.

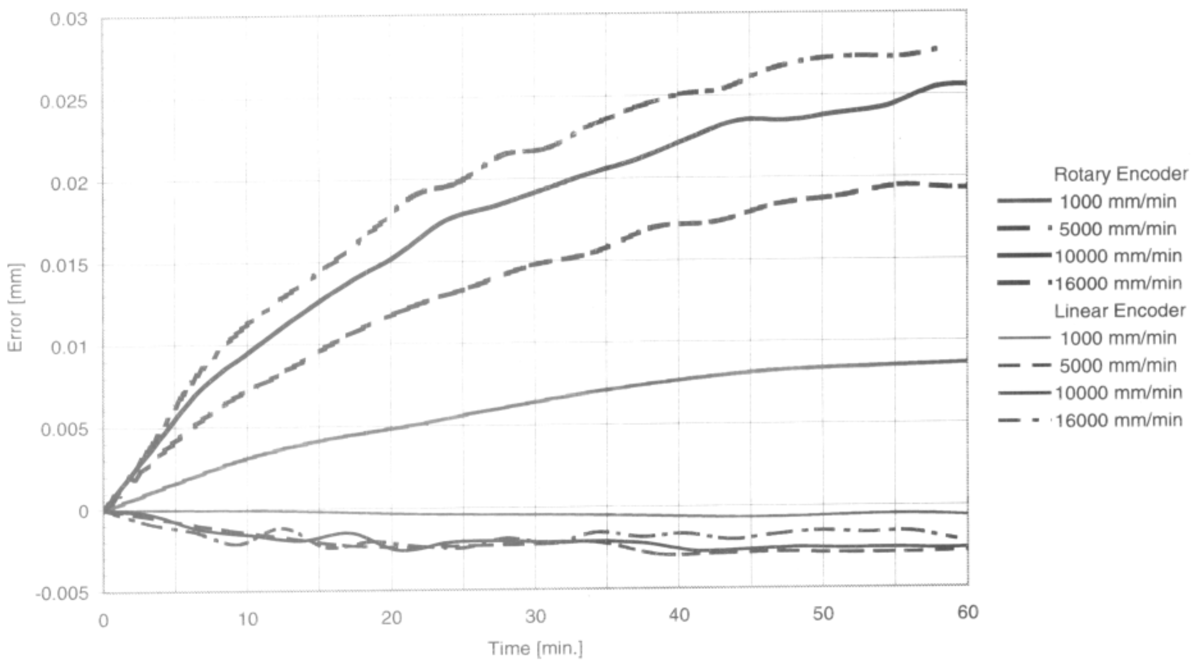


Figure 5. Positioning Error measured from Linear Encoder and Rotary Encoder Feedback in Y-axis (SH-630)

SUMMARY

The positioning performance using the rotary encoder and linear scale feedback system for the ball screw drive systems was investigated. When the rotary encoder feedback is used for relatively high speed repetitive traverse motion of the table, a thermal expansion of the ball screw causes positioning error in the magnitude of 0.04 mm when the machine running time is one to two hours in terms of the traverse speeds. In the case of linear scale feedback system, the thermal error can be dynamically monitored and the motion error of the worktable is greatly enhanced. In this research, the motion accuracy difference between the rotary encoder and the linear encoder control feedback was also examined in conjunction with the possible error causes including the measurement method of the errors. The next goal of this experimental study is to investigate the motion error due to the thermal growth in a circular motion.

REFERENCES

1. Braasch J., "Position Measurement on Machine Tools — By Linear Encoder or Ball screw and Rotary Encoder", Technical Article on the World Wide Web, HEIDEINHAIN (http://www.heidenhain.com)

2. ISO/TC 39/SC 2 - Draft International Standard ISO/DIS 230-3 "Test code for machine tools -Part 3: Determination of thermal effects"