Development and Evaluation of a High-Precision Machining Center with Friction-Less Drives

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Abstract

In order to realize high-speed and high-precision machining, the enhancement of the motion accuracy of NC machine tools is required. It is effective to minimize the friction forces imposed on drive systems to enhance the motion accuracy. From this viewpoint, we developed a high precision machining center using linear motors and hydrostatic guideways for its drive system. The disturbance forces on the developed machining center are measured to evaluate the fundamental motion characteristics. Contouring error trajectories in high-speed circular motions of small radii are also measured for the evaluation of roundness.

1 Introduction

For high-speed and high-precision machining with a small diameter endmill, the enhancement of the motion accuracy of NC machine tools and the compensation of machining errors caused by tool deflection are required to realize sub-micron-order geometrical and dimensional accuracy under high-speed machining. Because of the friction imposed on drive systems, it is generally difficult to enhance the motion accuracy to less than 1μm on the conventional machine tools using ball screws and rolling guideways. For sub-micon-order machining, machine tools with friction-less drive systems are promising. For example, a X-Y-θ table using linear motors and aerostatic guideways has been developed for a compact nano-machine tool [1]. However, aerostatic guideways do not have enough stiffness for the cutting of high hardness material with economical speed.

In order to solve this problem, we developed a high precision machining center using linear motors and hydrostatic guideways for its drive systems. Minimizing the friction force on the drive system enables higher motion accuracy in small and high-speed motions.

This paper presents the fundamental motion characteristics of the developed machining center. The disturbance forces on the developed machining center are measured and compared with friction forces imposed on the conventional ball screw drives. Furthermore, contouring error trajectories in high-speed circular motions of small radii are measured by using the cross grid encoder for the evaluation of roundness.

2 Developed machining center

2.1 Machine structure

Figure 1 shows the structure of the developed machining center. Table 1 shows the basic specifications. Since the machining center was developed to machine small-size and high-precision dies, the axis travels are set as 250-300mm. As high feedrates are not necessary for such short travels, the maximum feedrate is hold to 20m/s. The acceleration rate is set to 0.8G for shortening positioning times with less vibration.

Linear motors and hydrostatic guideways are selected for the drive systems to minimize the friction force. High-gain control using linear motors also enables higher motion accuracy in high-speed motions. At the same time, it is possible to obtain higher stiffness as well as fine surface roughness by using hydrostatic guideways.

Two motors are employed in each axis so that the motors can cancel the attraction forces. To reduce the table's angular motion (yawing motion), the guideways are located outsides of linear motors of each axis, which compose wide guideway systems. The struture of the machining center is the vertical type with a lower center of gravity, which can realize high stiffness and reduce complex vibration modes.

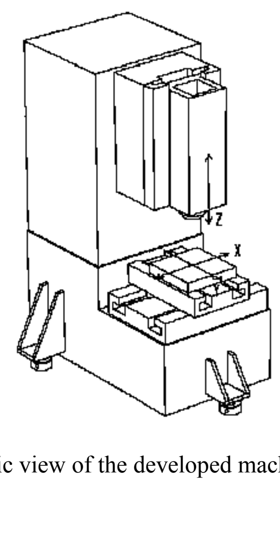

Fig.1 Schematic view of the developed machining center

Table 1 Specifications of the developed machining center

X-axis travel	300mm
Y-axis travel	250mm
Z-axis travel	250mm
Rapid traverse rate	20000mm/min
Feedrate	10000mm/min
Drive motor	Linear motor
Guideway	Hydrostatic guideway
Scale resolution	7.8nm
Spindle speed	150-30000min^{-1}
Spindle nose taper	NT No.30
Spindle bearing	TAC bearing

2.2 Control system

Figure 2 shows the block diagram of the drive system. The requirement of the motion accuracy of this machining center is 0.1-0.5μm. In order to meet this accuracy requirement in high-speed motions, nano-order resolution of position command and detection is necessary. Therfore, the position command is interpolated with 1nm step. The scale resolution is 7.8nm.

A digital filter(IIR filter) is installed in the current feedback loop, so that wider bandwidth of the servo loop can be obtained by reducing the resonance by the filter to set the servo gain higher.

On the machine structure mentioned in the previous section and the control system, the position loop gain can be set as high as Kp=140s^{-1}. The feedforward gain FFp is set to 1.

3 Measurement of the disturbance force on the drive system

Since the drive systems of the developed machining center are noncontact drive systems, the friction force imposed on the drive systems should be 0N ideally. However, sources of disturbance force such as those from covers to protect the drive system and cableveyors to support cables exist. To evaluate them, the disturbance forces are measured when the table is driven along linear trajectories under a constant feedrate and a vortex trajectory under a variable feedrate. The motor currents are measured to evaluate disturbance forces. The driving forces of the motors are calculated by multiplying measured motor currents by the force constant of each linear motor. These driving forces are regarded as the disturbance forces on the drive systems in linear motions at constant feedrates. In a vortex motion, disturbance forces are calculated by subtracting estimated inertial forces from the driving forces.

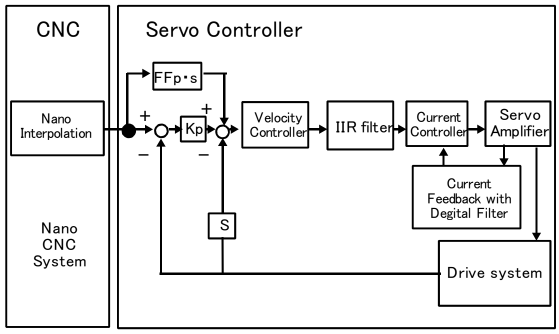

Fig.2 Block diagram of the drive system

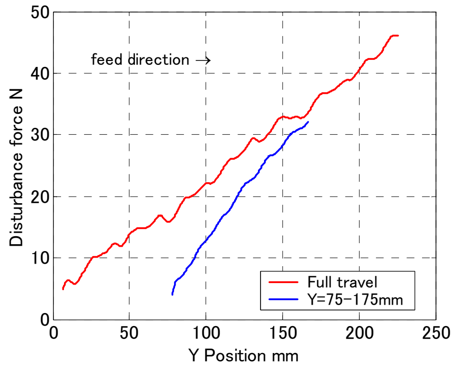

Fig.3 Relationship between disturbance force and table position

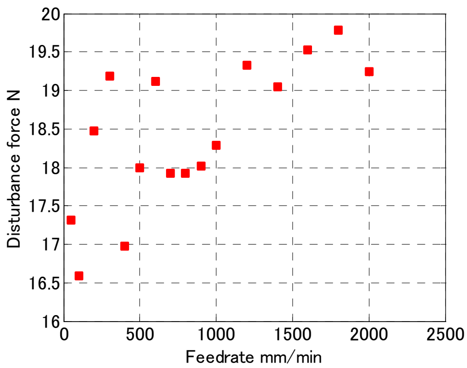

Fig.4 Relationship between disturbance force and feedrate

3.1 Disturbance force under linear motions at constant feedrates

First, the disturbance force when the Y-axis is driven over the full travel (Y=10-240mm) at 1500mm/min is measured. The solid line in Figure 3 shows the result of the measurement. It can be seen that the disturbance force increases gradualy from 5N to 45N.

Second, we investigate whether the fluctuation of the disturbance force depends on the table position or not. The disturbance force when the Y-axis is driven between Y=75-175mm at the same feedrate (1500mm/min) is measured.

The dashed line in Figure 3 shows the result. In the result at Y=75-175mm, it can be seen that the disturbance force increases gradualy from 5N to 32N. As shown in Figure 3, the fluctuation of the disturbance force depends on the table position, but it is not only factor to determine the disturbance force.

Finally, we investigate whether the disturbance force changes at different feedrates. Figure 4 shows the mean values of the disturbance force measured at each feedrate when the table is driven between Y=75-175mm at various feedrates from 50mm/min to 2000mm/min. As shown in Figure 4, the mean value of the disturbance force varies within 3N, but the influence of the feedrate to the disturbance force is small.

3.2 Disturbance force under a vortex motion with variable feedrate

Figure 5 shows the tool center trajectory used in the measurement. In this figure, the start point is inside the vortex, and the vortex motion has 22 cycles. The stationary area and the transient area are defined as shown in the figure. While the tool center is in the stationary area, the feedrate is constant. While it is in the transient area, the radius and the feedrate gradually change to the values in the following stationary area. The feedrate changes from 3800mm/min to 1000mm/min, and the radius changes from 2.2mm to 8.7mm. These conditions are decided from the typical cutting conditions for dies and molds.

The estimated inertial force is calculated by multiplying the acceleration rate and the mass of the driven object for each axis. The acceleration rate is obtained by taking the second derivative of the position feedback signal. The mass is calculatad from the design information of the machine.

Figure 6 shows the driving force of the motor and the inertial force in the X-axis drive. Figure 7 shows the disturbance force in the X-axis drive. Compared with the inertial force, the disturbance force is quite small. However, the disturbance force varies from 0N to 70N. As shown in Figure 7, the disturbance force decreases in the first 13 cycles and increases in the next 6 cycles and reaches stationary cycles after that.

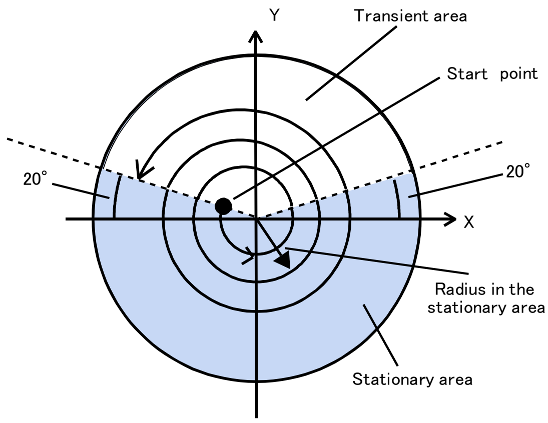

Fig.5 Vortex trajectory used in the meausrement

For comparison, Figure 8 shows the disturbance force measured on a conventional machining center (medium-size machine) using ballscrews and rolling guideways. The pattern of the disturbance fluctuation shown in Figure 7 is different from that shown in Figure 8. This implies that the

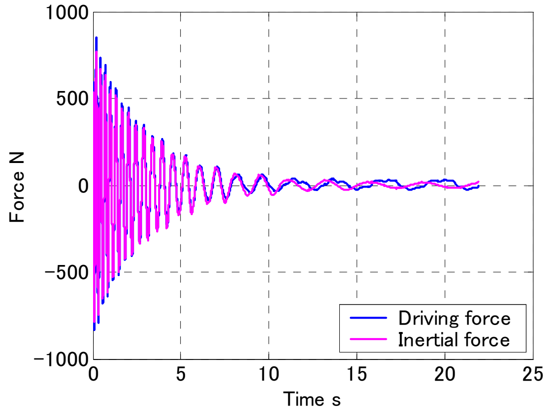

Fig.6 Driving force and estimated inertial force in the vortex motion

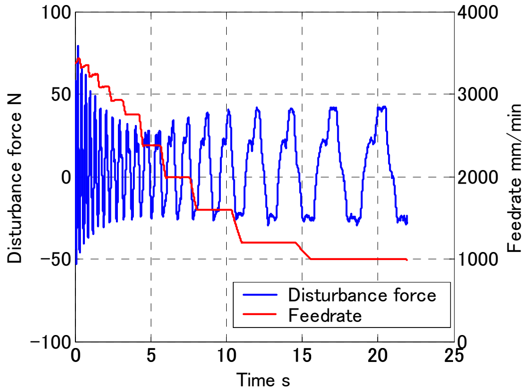

Fig.7 Disturbance force and feedrate in the vortex motion

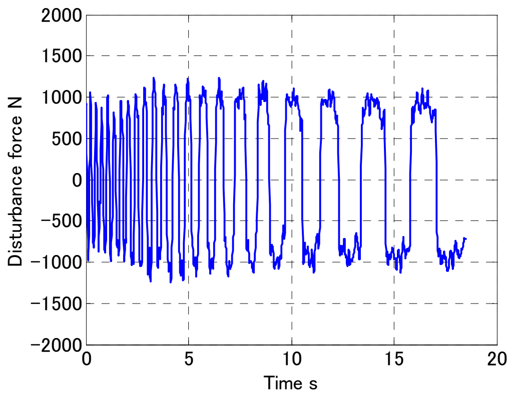

Fig.8 Disturbance force in the conventional ballscrew drives

disturbance force observed on the developed machine is not completely caused by the Coulomb friction.

Two possible reasons are considered to explain this difference. The first reason is that the identification error of the mass of the driven object may generate the estimation error of disturbance forces. The second reason is that the cableveyors and/or the covers may disturb table motion.

4 Measurement of the motion accuracy

As the disturbanse forces in circular motion in the developed drive systems are estimated less than 50N and positon loop gain is 140 s^{-1}, we can expect higher contouring accuracy in high speed motions. In order to evaluate the motion accuracy, high-speed circular motion tests in the X-Y plane with small radii are conducted. The measurement instruments is the cross grid encoder (KGM181 made by HEIDENHAIN). The nominal measurement accuracy of KGM181 is ± 2μm/140mm, which is enough for circular motion tests with small radii. The measuremant conditions are shown in Table 3. In each measurement condition, the drive table rotates three times clockwise. The measured trajectory data at the second cycle for each conditon is selected as its feedrate is stationary. The measured X-Y data is transferred to r-θ coordinate, and avearge radius is calculeted for radius compensation. By radius compensation, the roundness change due to the feed change is investigated.

Table 3 Measurement conditions

Radius mm	Feedrate mm/min
0.6	465, 657, 805, 930, 1039
2.5	949, 1342, 1643, 1897, 2121
6.4	1518, 2147, 2629, 3036, 3394

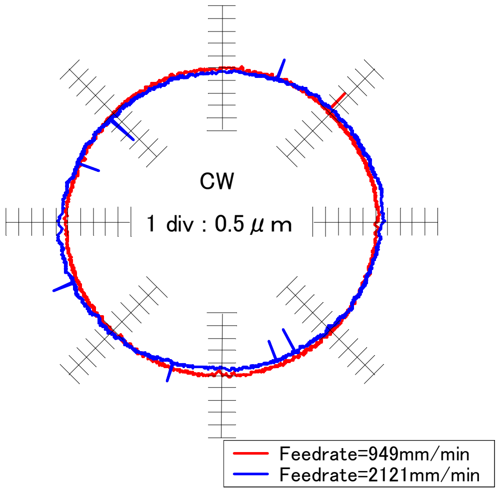

Fig.10 Motion error traces (radius is 2.5mm)

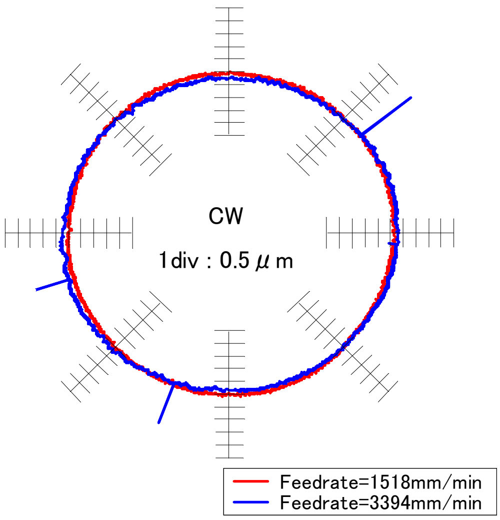

Fig.11 Motion error traces (radius is 6.4mm)

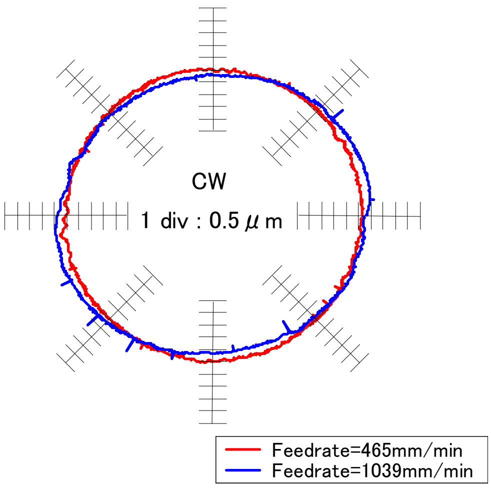

Fig.9 Motion error traces (radius is 0.6mm)

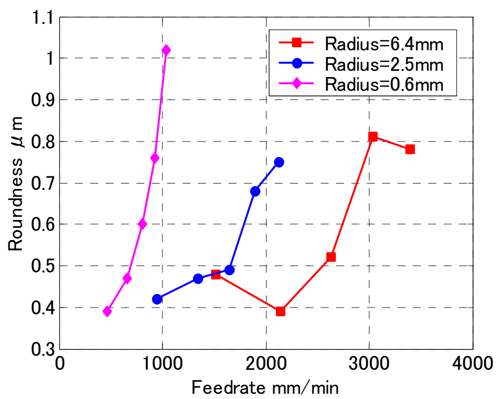

Fig.12 Relationship between feedrate and roundness

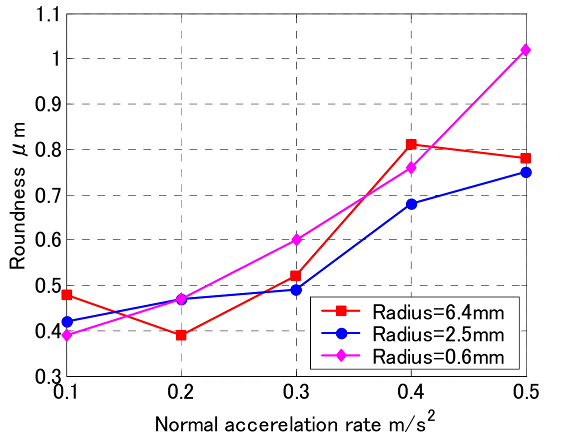

Fig.13 Relationship between normal accelelation rate and roundness

Figures 9, 10, and 11 show measured roundness in different radii. Stick motion errors at the quadrant changes are not observed in each result. The spike type errors are seen in several results, but these are due to the noise in the measurement system. This noise is not considered in the following consideration. As the feedrate is getting faster, the roundness is getting larger due to the ellipse-type distortion in each radius condition. Directions of the major lines of the ellipses seem to be same.

Figure 12 shows the roundness change due to the variation of the feedrate. The roundness is less than about 1μm in all conditions and increases in parabolic curve in each radius condition. Figure 13 shows the relationship between the normal acceleration rate and roundness. As shown in this figure, roundness depends on the normal acceleration rate, which suggests dynamic difference between X and Y drives [2].

5 Conclusions

A high-precsion machining center using linear moters and hydrostatic guideways for its drive systems was developed. From the measurement results of the disturbance force and the roundness in high-speed circular motions on X-Y plane, the following conclusions are obtained.

1. Disturbance forces less than 70N exits in the machine drive.
2. Roundness in the circular motion is less than about 1.0μm.
3. Roundness of the motion trajectories depends on the normal acceleration rate, which suggests dynamic difference between X and Y drives.

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