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PERFORMANCE ENHANCEMENT OF INTEGRATED MACHINE TOOL THROUGH USE OF DIRECT DRIVE MOTOR

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ABSTRACT

A built-in-motor spindle system eliminates the necessity of mechanical transmission components such as belts, reduction gears, etc, resulting in reduced vibration and noise. Therefore, built-in-motors have been widely used in advanced machine tools in order to achieve high speed and accuracy. A rotary table is conventionally driven by a worm gear or other mechanical mechanisms with disadvantages such as limited rotation speed and backlash existence. Direct drive for rotary motion is gradually being adopted. Using direct drive motor for rotation axis motion has been considered to be crucial technology in enhancing the performance of an integrated machine tool. Many studies have been conducted for the application of direct drive in rotary table motion, but not for the application of direct drive in rotary axis as of yet. In this study, a direct drive motor used for driving a rotation axis in an integrated machine has been developed.

INTRODUCTION

A newly developed high-speed, high accuracy direct drive motor (DD motor) has been successfully integrated on a horizontal machining center to drive a rotary table. By applying a DD motor to drive a rotation axis in a machine tool, the vibration, the backlash, and the noise resulting from gear transmission can be significantly reduced. Furthermore, the DD motor is directly connected to the rotating component; there is no need to have a speed reducer mechanism. As a result, a higher speed, higher accuracy rotary drive can be achieved in comparison with other drive mechanisms such as worm gear drives. This study will present the design of a DD motor embedded to drive a rotation axis of a tool spindle in an integrated machine tool, and its effectiveness of a DD motor with respect to the machining productivity and accuracy. On an integrated machine tool, it is required that the tool spindle (B-axis) rotate in synchrony with other linear axes in order to perform contour machining (such an operation is required for machining a cam, for example). In other words, a rotary axis (B-axis) driven by a DD motor will be used not only as an indexing drive for angular positioning, but also as a continuous motion drive for contouring. In addition, the DD motor is required to exhibit high torque and high output even in a high speed range in order to realize a high acceleration and high speed motion drive. The paper presents the design of a DD motor to meet such demands, and the performance evaluation of the designed DD motor. In this paper, a permanent magnet synchronous motor is considered.

1 - INTEGRATION OF DD MOTOR ON INTEGRATED MACHINE TOOL

Based on the DCG (Drive at the Centre of Gravity) technology, X- and Z-axis drives on the integrated machine shown in Fig. 1 are designed. Through driving the object at its center of gravity using two ball screws, the vibration occurring during the acceleration process is restrained and highly accurate machining can be achieved without sacrificing the speed. As depicted in Fig.1, the saddle is supported and driven symmetrically at the top and bottom by two ball screws, which are mounted in a vertical box-in-box structure. Consequently, the distortion of the saddle can be significantly reduced. For the Y-axis, a ram with an octagonal shape is used as shown in Figure 2. The rotary axis for the tool spindle is called the B-axis, whose rotary drive mechanism is embedded into the ram. With a clamped tool installed in the B-axis, a turning operation can be performed by rotating the workpiece using the main spindle. In the case of hole making and facing milling in an inclined machining plane, the workpiece is held by the main spindle; the tool spindle (B-axis) needs to be indexed to an arbitrary angular position, where tool spindle performs required milling operations. When machining a blade or impeller or other part with a free-form geometric shape, B-axis included synchronous motion is necessary for simultaneous 5 axis machining. Therefore, B-axis rotation is required to have high speed and accuracy for both indexing and continuous contouring to obtain a better smooth machined surface.

Conventionally, a servomotor connected to a speed reducer mechanism such as a worm-gear system is used to drive B-axis rotation. Due to the existence of backlash and vibration in the gear transmission mechanism, the surface finish is degraded and the feed speed is limited. To counter this, we adopt a DD motor to directly drive the B-axis, aiming to achieve a high accuracy, high speed machining. Traditionally, the rotor of the DD motor is shrink-fit onto the rotation axis shaft. However, it is not feasible to fit a DD motor used for the tool spindle into the ram structure. Therefore, in this research, we design a DD motor such that its rotor and the rotation axis is unified to meet the limited space requirement and output the necessary torque. The developed motor structure is shown in Figure 2. Table 1 shows the performance comparison between the developed DD motor drive and a conventional worm-gear drive for an integrated machine tool. From Table 1, the DD motor drive can rotate 4 times quicker than the worm-gear drive. For an angular rotation of 240 degrees, DD motor's indexing time is 0.9 second shorter than the worm-gear drive.

2 - COMPARISON IN STATIC REGIDITY THROUGH SIMULATION

First, the static rigidity of the DD motor-embedded tool spindle unit and worm-gear drive unit is enumerated through the FEM simulation. It is predicted that the DD motor driven unit has a higher rigidity since it does not have serial mechanical components such as a worm and a worm wheel, which often cause the deterioration of the rigidity, or the backlash. The static deformation of the tool tip is calculated under the load of 3000N and 5000N imposed at the tool tip. Figure 3(left side) shows the simulated deformation of the DD motor driven unit. It is found that the deformation is negligible. Figure 3(right side) shows the simulated deformation of the worm-gear driven unit, where the red colour represents the largest magnitude of the deformation. It is found that there is a considerable deformation.

Furthermore, for a worm-gear driven unit, it is also important to evaluate the backlash. Figure 4 shows the backlash displacement of the worm-gear unit, where the symbols are defined as follows.

R_1 : Distance between the rotation centre of the B-axis and tool tip
R_2 : Worm-wheel radius
Y : Backlash amount
C : Angular displacement of tool tip due to load (simulated by FEM analysis)
D : Angular displacement due to backlash
X_1 : Displacement of tool tip due to load
X_2 : Displacement of tool tip due to backlash

Thus, the angular displacement due to backlash can be

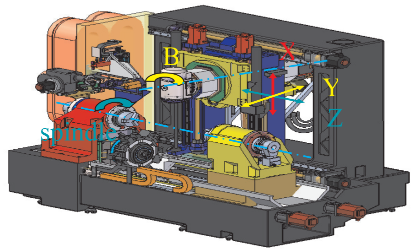


Figure 1: Integrated machine's structure

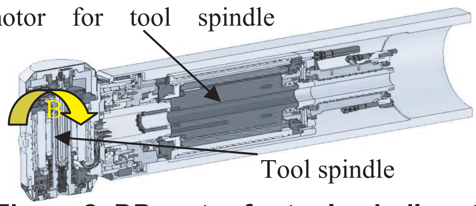


Figure 2: DD motor for tool spindle rotation

	DD motor system	Worm-gear system
Maximum Speed	100min^{-1}	27min^{-1}
Index Time	0.58s/120deg. 0.78s/240deg.	0.93s/120deg. 1.68s/240deg.

Table 1: Performance comparison between DD motor and worm-gear

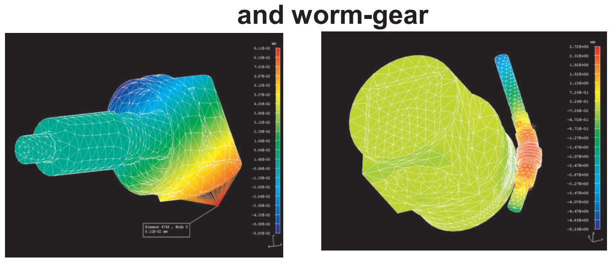


Figure 3: Deformation analysis results of DD motor drive and worm-gear drive

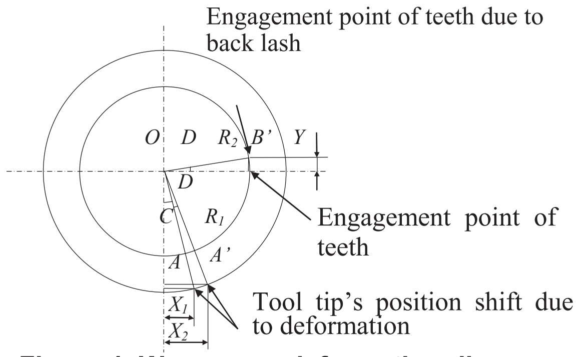


Figure 4: Worm-gear deformation diagram

calculated using Eq. (1), when R_2 and Y are given.

$$D = \sin^{-1}(Y / R_2) \qquad \text{Equation (1)}$$

Table 2 shows the calculated results under the conditions that R_1 and R_2 are 210mm and 125mm, respectively. It is assumed that the backlash Y is 15μm, a typical level in actual machine setting. It is found that the static rigidity of the DD motor driven unit is 1.5 ~ 2.2 times higher than that of the worm gear driven unit.

At last, Table 3 shows the comparison of part count between the two drives. By replacing a worm-gear with a DD motor, the part count of the drive system decreases by about 50%.

3 - COMPARISON IN STATIC AND DYNAMIC MOTION ACCURACIES

The static and dynamic angular positioning accuracies of an integrated machine tool with a DD motor driven B-axis are investigated. First, the static angular positioning accuracy of the B-axis is measured using an autocollimator conforming to the ISO230-2 standard. Measurements are made at a 30 degree interval in the clockwise direction, followed by measurements at that interval in the counter clockwise direction. 5 measurements are carried out. Table 4 lists the averaged results of the measured data. From Table 4, the positioning accuracy is 3.05arcsec for the DD motor driven B-axis, and 7.66arcsec for the worm-gear driven B-axis; the repetitive accuracy is 2.51arcsec for the former, and 6.88arcsec for the latter. From these results, it can be seen that the DD motor unit has better positioning accuracy and repeatability when compared to the worm-gear unit.

As previously mentioned, for an integrated machine tool, the synchronous motion accuracy between the tool spindle and other linear axes to perform simultaneous 5 axis contouring machining is important, just as the static positioning accuracy of each linear and rotary axis. To measure the dynamic synchronous motion accuracy of the B-axis and linear axes in a simple, quick manner, this paper proposes a method by using the DBB (Double Ball Bar) device. A DBB is very commonly used to measure the contouring motion accuracy between two linear axes. This paper will introduce the extension of the DBB measurement to measure the dynamic motion error between two linear axes and a rotary axis.

In particular, we consider the synchronous motion between X-axis, Z-axis and B-axis. In this case, the tool tip's positioning error can be decomposed to two components as shown in Fig. 5; 1) the component in the tangential direction of B-axis rotation (dr_t) and 2) the component in the radial direction of B-axis rotation (dr_r). The radial error, dr_r, is not affected by the angular motion error of B-axis, dB, and directly correlates with the positioning errors of X-axis and Z-axis, dx and dz. To measure dr_r, set up the DBB device as illustrated in Fig. 6(a) (Measurement 1); two balls are mounted on the main spindle and tool spindle respectively and connected with a bar. The B-axis, X-axis and Z-axis positions are simultaneously interpolated to rotate the assembly around the center of the ball mounted at the main spindle. On the other hand, the tangential error, dr_t, is mainly affected by the angular motion error of B-axis, dB, in addition to dx and dz. To measure it, the following two measurements are carried out. As illustrated in Fig. 6(b), the bar stays in X-axis direction and the simultaneous interpolation is carried out to rotate the assembly around the ball mounted to the tool spindle (Measurement 2). The extension of bar (dr_1) is measured with respect to angle C. Similarly, the assembly is set up such that the bar stays in Z-axis direction as shown in Fig. 6(c), and a similar operation is carried out to measure the extension of the bar, dr_2 (Measurement 3).The tangential error, dr_t, can be calculated using Eq. (2)

	3,000(N)		5,000(N)	
	DD	Worm	DD	Worm
Distance between B axis rotation center and tool tip(mm)	247	210	247	210
Deformation angle of tool tip due to the load(deg)	0.006	0.006	0.011	0.010
Deformation angle of tool tip due to back lash(deg)	0	0.007	0	0.007
Deformation angle of tool tip due to load and back lash(deg)	0.006	0.013	0.011	0.017
Static stiffness(N/deg)	500e3	231e3	455e3	294e3
	2.2 times		1.5 times	

Table 2: Static stiffness

	DD motor	Worm-gear
Main component's number	15	30

Table 3: Component's number of B axis assembly

	DD	Worm
Position accuracy(arcsec)	3.05	7.66
Repeatible position accuracy(arcsec)	2.51	6.88

Table 4: Positioning accuracy comparison

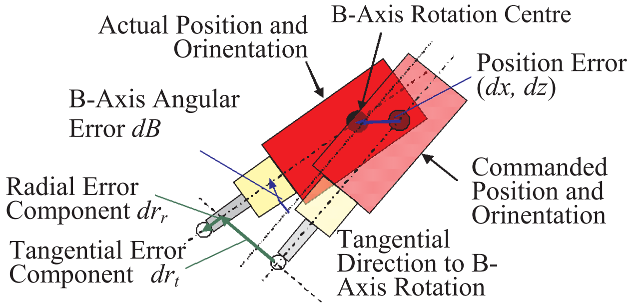
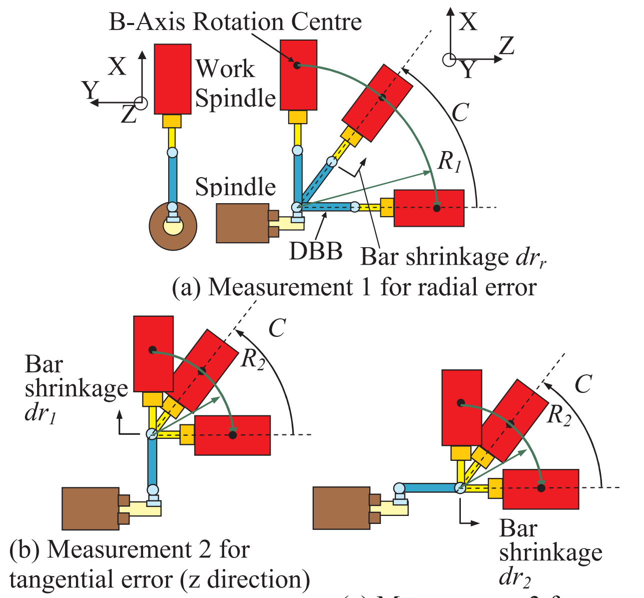


Figure 5: Positioning error components at tool tip



(a) Measurement 1 for radial error

(b) Measurement 2 for tangential error (z direction)

(c) Measurement 3 for tangential error (x direction)

Figure 6: DBB measurement setups

$$dr_t = dr_1 \cos C + dr_2 \sin C \qquad \text{Equation (2)}$$

For the conventional integrated machine with a tool spindle axis driven by a worm-gear (referred to as the worm-gear driven machine hereafter), Figure 7(a) and (b) show dr_t and dr_r estimated from Measurements 1 to 3. The feedrate was 500 mm/min in all tests. When the tool is in X direction orientation, B-axis=0 deg. When the tool is in Z direction orientation the B-axis= -90 deg. It can be seen that the tangential error (dr_t), which closely correlates to the B-axis accuracy, is much larger than the radial error (dr_r), which closely correlates to the motion error in X and Z directions. The B-axis of this machine has a worm-gear of 108 teeth. This causes the gear teeth engagement between the wheel and worm-gear every 360 deg/108=3.3 deg. From Fig. 7(a) it can be observed that there is a high frequency motion error component, with a magnitude of about 0.007 mm, corresponding to this engagement cycle. Since the rotation radius R_2 in Measurements 2 and 3 is 379.782 mm, this error corresponds to the rotation angle of B axis of approximately 0.0011 deg. When the feedrate was 2000mm/min, this error magnitude was 0.017mm. The higher the feed rate is, the larger the error caused by the gear engagement is.

Figure 8 (a) and (b) show the measured results of dr_t and dr_r on the new integrated machine with a spindle axis driven by the DD motor (referred to as the DD motor driven machine). The feedrate was 500 mm/min. It can be seen from Fig. 8(a) that the magnitude of the high frequency component in the tangential error (dr_t) is about 0.0001 mm, which is much smaller than the machine with a worm-gear driven spindle axis. Even when the feedrate increases to 2000 mm/min, the motion error almost has no change. On an integrated machine tool, due to longer distance between the tool tip and the rotation center of B-axis, the B-axis rotation error results in a larger motion error at the tool tip. For the machine used in the experiments above, the B-axis rotation error of an amplitude of 0.001deg results in the error of an amplitude of 630 * sin(0.001) = 0.011 mm at the tool tip, when a tool of the allowable maximum length (630mm) is installed. With this tool, on the worm-gear driven machine, the amplitude of tool tip vibration will be 0.028 mm when the feedrate is 2000 mm/min. These results lead us to the conclusion that it is difficult to obtain satisfactory surface finish by multi-axis contouring on this machine. The DD motor driven spindle axis can almost completely eliminate this vibration.

4 - MACHINING CYCLE TIME COMPARISON

The cycle time for machining an impeller using two integrated machine tools equipped with a DD motor drive unit and a worm-gear drive unit is compared. In the machining of an impeller, it is often required to drive a tool in the normal direction to the machined surface. On a surface where its gradient rapidly changes, the velocity and the acceleration of the spindle axis' rotation significantly affect the machining time. Under the same feedrate of 10,000mm/min, the machining time is 8 hours 26mintues for the DD motor driven machine and 12 hour 25 minutes for the worm-gear driven machine. Figure 9 shows the surface finish of a blade machined using two types of drive. It is noticed that there exists a stripped pattern on the machined surface for worm-gear drive. A better machine surface can be obtained using DD motor drive.

CONCLUSIONS

By unifying a DD motor's rotor into a spindle unit, it becomes feasible to adopt a DD motor in a restricted space as a rotation axis to drive a tool spindle. Using a DD motor to drive the tool spindle greatly enhances the rotation speed, acceleration speed, rigidity, accuracy and repeatability.

REFERENCE

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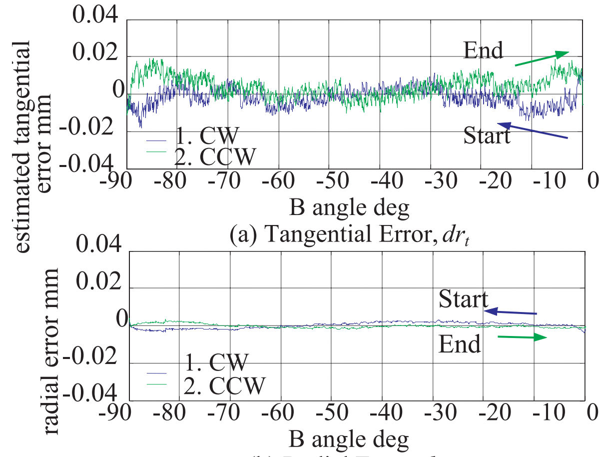
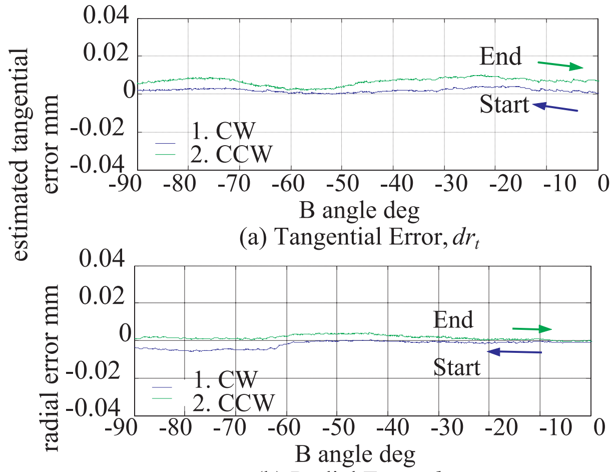


(a) Tangential Error, dr_t

(b) Radial Error, dr_r

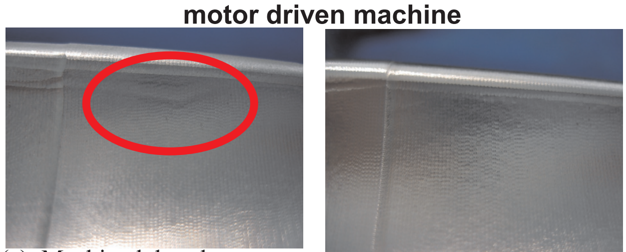
Figure 7: Estimated motion error at tool tip on the worm-gear driven machine



(a) Tangential Error, dr_t

(b) Radial Error, dr_r

Figure 8: Estimated motion error at tool tip on the DD motor driven machine



(a) Machined by the worm-gear driven machine

(b) Machined by the DD motor driven machine

Figure 9: Comparison in machined surface of the blade

