XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

MOTION ACCURCY MEASUREMENT DEVICE BY USING PARALLEL MECHANISM FOR MULTI-AXIS MACHINING CENTERS

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Abstract: The main purpose of this study is to develop a measuring device by parallel kinematics for measuring a motion accuracy of multi-axis machining centers. The initially developed measuring device had three displacement sensors and it could measure only position of the spindle because it had only 3 DOF. Optical linear encoders were used for the displacement detecting sensors, while the steel balls and permanent magnets were used for the joints of parallel mechanism. With the 3 DOF device the motion accuracy of machine tools with three-axis was measured. Since the mechanism of the joint was smooth and the sensor resolution was small enough, the measured result showed that the measuring device had an enough performance for the machining centers in normal accuracy. Then the 6 DOF measuring device was developed. It had six displacement censors and it could measure both position and posture angle of the main spindle. In spite of the adoption of parallel kinematics, the forward kinematics calculation was possible due to the sophisticated arrangement of sensors, thus the hi-speed data acquisition could be possible.

Keywords: motion accuracy, parallel kinematics, machining centers, posture angle of the spindle

1. INTRODUCTION

There is a growing demand of multi-axis machining centers because of its possibility of flexible machining. Multi-axis machining center's main spindle can be controlled position and posture angle in order to obtain a better cutting condition to the work piece.

Since normal cutting tools are used by revolving the spindle attached, rotation angle of spindle can be neglected and five DOF should be considered, however, sometimes special cutting tools are used without revolving the spindle such as hale cutting, in this case six DOF should be considered.

Motion accuracy measurement methods or devices of machining centers are established on ISO 230 [1], 10791 [2] and so on. Most test methods or devices are designed to measure only one axis (1 DOF) movement. It is in some sense very reasonable, because measuring devices (sensors) for one DOF are very accurate and easy to handle. However, actual machining process is normally complicated and multiple axes' motion should be measured at the same time. Thus, some measurement devices were already proposed and adopted to the standards. One is a ball bar, shown in Fig. 1, which has only one displacement sensor with a very limited stroke, but it can measure a hemispherical positional deviation. Another is a grid encoder, shown in Fig. 2, which has two displacement sensors and can measure arbitral 2 DOF positional deviation of a plane. The other devices are also found on the standard for measuring industrial robots.

Fig. 1. Ball Bar Device

Fig. 2. Grid Encoder

2. MEASUREMENT DEVICES WITH PARALLEL MECHANISM ALREADY PROPOSED

2.1. Parallel Mechanism for 3 DOF measurement

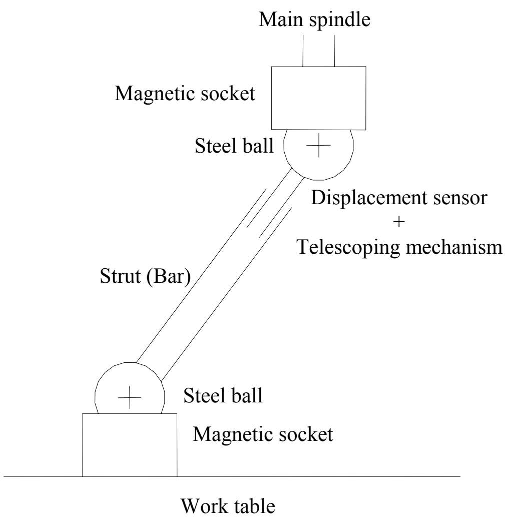
Some measuring devices of 3 DOF were already proposed by using parallel mechanism [3, 4]. It is called as "Laser Ball Bar". The concept of the device is to obtain more flexibility than Ball Bar as shown in Fig. 1.

The original Ball Bar device has permanent magnets and steel balls as spherical joints. One device has two balls (joints). First attempt for the improvement of the Ball Bar was that a linear encoder was used as a displacement sensor instead of LVDT, because of the development of digital technology. In case linear encoder is used, either optical scale or laser interferometer, it can measure the longer displacement than LVDT, so that the reachable area is wider. The limit of the bar length of Ball Bar will be the magnetic force for support the bar weight. The telescoping mechanism without twisting the bar shaft also had to be developed.

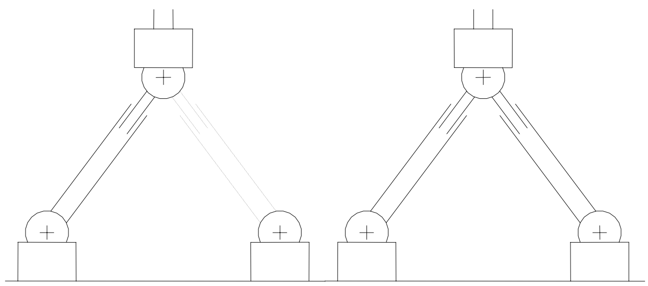
Second attempt for the improvement of the Ball Bar was to prepare plural sockets on the work table side. The measurement could be performed in between many sockets, that is, the total measurable range was wider. Of course, the positions of the plural sockets have to be calibrated and they are known before the measurement sequence. This concept was come from the artifact for calibrating the CMM.

Then the third attempt was that it uses multiple displacement sensors. In this case, spindle side ball was common to use and interference occurred between multiple magnet sockets. This was a disadvantage of the single spindle side joint mechanism. There is an advantage of single joint mechanism that the calculation of position is simpler, because both forward and inverse kinematics are solved analytically. The other attempt of multiple displacement sensor system with multiple spindle side joint was also reported [5].

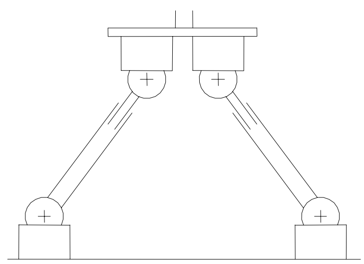
Figure 3 shows the summery of the integration of Ball Bar type motion accuracy measurement device with parallel mechanism.



(a) Mechanism of normal ball bar device



(b) Plural socket **(c) Multiple struts (sensors)**



(d) Multiple spindle side joint with multiple struts

Fig. 3. Configuration of ball bar sensors

2.2. Other device without parallel kinematics

Recently, the substituting test devices, which do not have parallel kinematics have been proposed. One is R-test [6], which has three displacement sensors but sensors are fixed and there are no joints (Fig. 4). The tip of the displacement censor that has a small steel ball traces the sphere of larger size ball. If the diameter of the ball is known, it is not so difficult to calculate the actual ball center position from three displacement sensors' output, because sensors are always fixed such that their axes cross at one position. Figure 5 shows the other device proposed by FIDIA with almost same structure as R-test. Only the fixed angles are different. The above-mentioned devices have three sensors and they can measure position only. Other devices with more than 3 DOF are proposed but they do not have parallel kinematics.

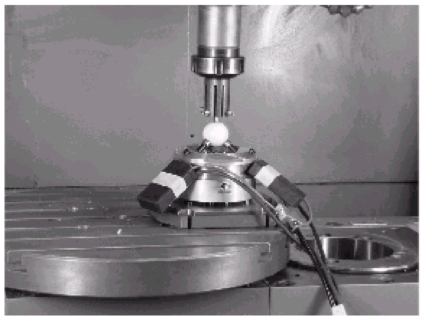


Fig. 4 R-test device

Fig. 5. Device by FIDIA

3. DESIGN OF MEASUREMENT DEVICES WITH PARALLEL MECHANISM AND 6 SENSORS

In order to measure the machine spindle's position and posture angle, at least 6 sensors are necessary. Moreover, the easy calculation is desired for obtaining fast and high precision. The most well known structure for 6 DOF is Stewart Platform. Stewart Platform has already been adopted as milling machine. As an actuator, it has little problem because the inverse kinematics calculation is not so difficult. However, when it uses as a sensing device, forward kinematics calculation is necessary and it needs convergence calculation with Jacobi matrix.

In this study, the motion accuracy measurement device using parallel kinematics, with which both position and posture angle were analytically calculated with forward kinematics, was designed.

3.1. Specifications of the device

The device is used for the measurement of metal cutting machine such as machining center, so that the device size itself is as small as possible. The measuring range will cover by means of placing and setup in the other position.

The spherical joints on the work table side consisted of the same magnet socket as commercial Ball Bar device shown in Fig. 1. The diameter of balls was 18 mm. Since the measuring device could be also used as 3 DOF measurement, 3 magnetic sockets (A, B, C) were located as an equilateral triangle, the length of whose side was almost same as the length of strut. The fourth (D) and fifth (E) sockets were located at the position that the center point of triangle ABC (O), D and E were an equilateral triangle. The sixth socket (F) was located at the position that the points O, E, F construct as an equilateral triangle. Figure 6 shows the 3D model of the base plate that the six sockets positions are expressed.

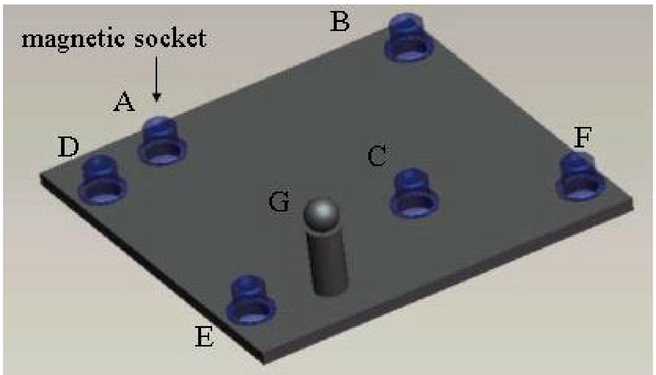


Fig. 6. 3D model of base plate and magnetic sockets

Each strut consisted of the displacement sensor, sensor case, steel ball with 18 mm size and a small magnetic socket. The small magnetic socket is shown in Fig. 7. It consisted of rare earth magnet with 4 mm diameter and 3 small steel balls with 4 mm diameter. Since the magnet was made of Samarium-Cobalt, the magnet socket had enough force to support the head of the strut.

On the machine spindle side, six sensor tips have to be received. The spindle side joints consisted of the steel ball with 25.4 mm diameter. There were three balls named as P, Q and R. Ball P received three sensor tip A, B and C. Ball Q received two sensor tip D and E. Ball R received sensor tip F. Distances PQ and PR were designed such that they were almost same as strut length. These three balls were fixed by the steel plate as shown in Fig. 8 and named as "End plate".

Fig. 7. Small magnetic socket on the sensor tip

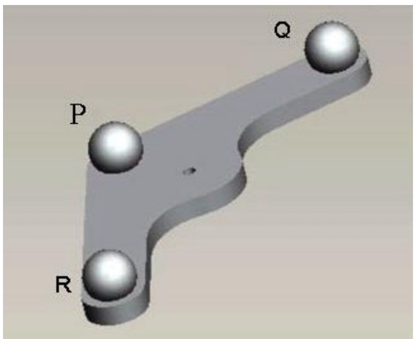


Fig. 8. Location of spindle side joint (End plate)

Optical linear encoder was used as the displacement sensor. The stroke was 12 mm and minimum resolution was 0.05 μm. Since the sensor had no reference point, it had to be calibrated before the assembly of the measuring device. In Fig. 6 one steel ball G is found on the base plate. Calibration of the sensor was done by connecting ball G and socket A then set the initial sensor value. The initial value was designed about 170mm.

3.2. Calculation of the position and posture angle

The purpose of this section is to show how to calculate the position and posture angles of the work spindle. The position calculation strategies are as follows.

(i) Each ball position is calculated by the length of three struts and three positions. The coordinates of the base plate joints are defined as $A(u_1, v_1, w_1)$, $B(u_2, v_2, w_2)$, $C(u_3, v_3, w_3)$, $D(u_4, v_4, w_4)$, $E(u_5, v_5, w_5)$, $F(u_6, v_6, w_6)$, while the lengths of six struts are $L_1, L_2, L_3, L_4, L_5, L_6$. These six struts are connected between AP, BP, CP, DQ, EQ, FR, simultaneously.

(ii) Machine's main spindle position and posture angle are calculated by the position of three balls P, Q and R. That is, coordinates of point $P(x_1, y_1, z_1)$, $Q(x_2, y_2, z_2)$, and $R\ (x_3, y_3, z_3)$ are to be obtained.

Equations for the above-mentioned calculations are as follows.

$$(x_1-u_1)^2+(y_1-v_1)^2+(z_1-w_1)^2=L_1^2 \quad (1\text{-}1)$$
$$(x_1-u_2)^2+(y_1-v_2)^2+(z_1-w_2)^2=L_2^2 \quad (1\text{-}2)$$
$$(x_1-u_3)^2+(y_1-v_3)^2+(z_1-w_3)^2=L_3^2 \quad (1\text{-}3)$$
$$(x_2-u_4)^2+(y_2-v_4)^2+(z_2-w_4)^2=L_4^2 \quad (2\text{-}1)$$
$$(x_2-u_5)^2+(y_2-v_5)^2+(z_2-w_5)^2=L_5^2 \quad (2\text{-}2)$$
$$(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2=PQ^2 \quad (2\text{-}3)$$
$$(x_3-u_6)^2+(y_3-v_6)^2+(z_3-w_6)^2=L_6^2 \quad (3\text{-}1)$$
$$(x_3-x_1)^2+(y_3-y_1)^2+(z_3-z_1)^2=PR^2 \quad (3\text{-}2)$$
$$(x_3-x_2)^2+(y_3-y_2)^2+(z_3-z_2)^2=QR^2 \quad (3\text{-}3)$$

The reference of machine spindle position can be defined at any position such as point P, Q, R or $S(x_4, y_4, z_4)$, while S is the center of gravity of triangle PQR. The posture angles are calculated between reference point and S by the following equations. The angles are defined in Fig. 9.

$$\alpha = \tan^{-1}\left(\frac{z_4 - z_1}{y_4 - y_1}\right) \quad (4\text{-}1)$$

$$\beta = \tan^{-1}\left(\frac{x_4 - x_1}{z_4 - z_1}\right) \quad (4\text{-}2)$$

$$\gamma = \tan^{-1}\left(\frac{y_4 - y_1}{x_4 - x_1}\right) \quad (4\text{-}3)$$

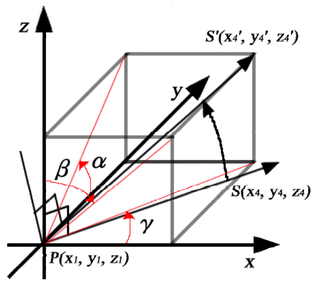


Fig. 9. Posture angle definition

4. MEASUREMENT EXAMPLE

Measurement was done on the 5-axis controlled machining center as a case study. Figure 10 shows the measuring device installed on the measured machining center.

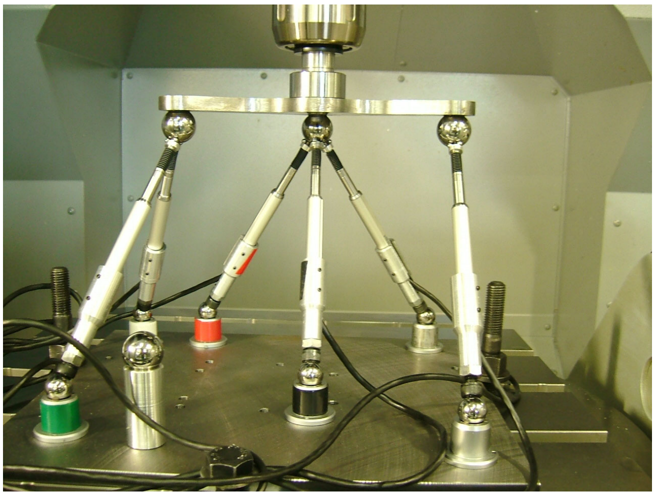


Fig. 10. Developed measuring device on the machine tool

4.1. Straight motion test

Only one linear axis of the machine was moved in a uniform velocity. Figure 11 shows the *Y* direction deviation while *Z*-axis was gone 10 mm up and down 5 times. A concave curves are found, however, the amplitude is less than 0.5 µm. Ten lines are drawn in the figure and the repeatability seems to be small as 0.5 µm. From this result the developed measuring device had an enough accuracy to measure the metal cutting machine. However, in order to measure the machine with higher accuracy, this device had insufficient accuracy. Joint mechanism or sensor resolution has to be improved.

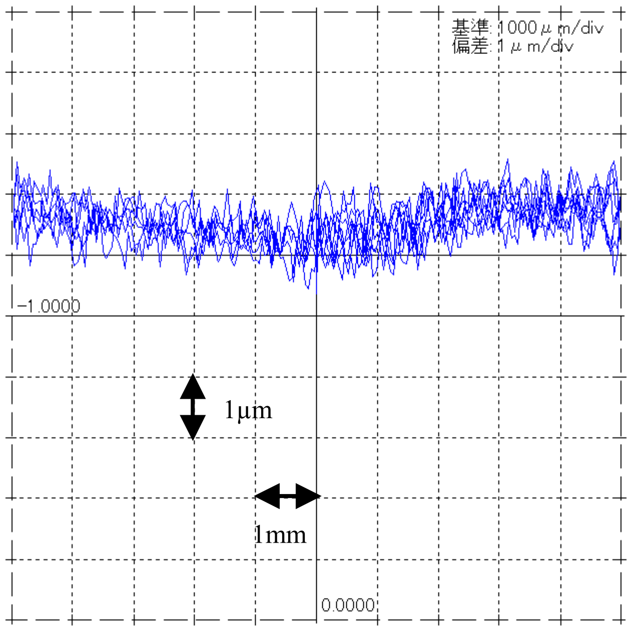


Fig. 11. Measured result with straight line

4.2. Circular motion test

Circular interpolation motion test was done on the same machine. On this test, two linear axis of the machine was moved simultaneously and trace a 3mm radius circle. With the developed device, arbitral two axes can be chosen, such as X-Y or Z-X without changing setup. This is a great advantage of this measurement device. With the other measuring device commercially available, if the plane is changed, the setup has to be changed. Figure 12 shows an example of the measured result. There are two lines in the figure, one is CW and the other is CCW. Since lines are very close both the motion of the machine and measuring device were with high accuracy.

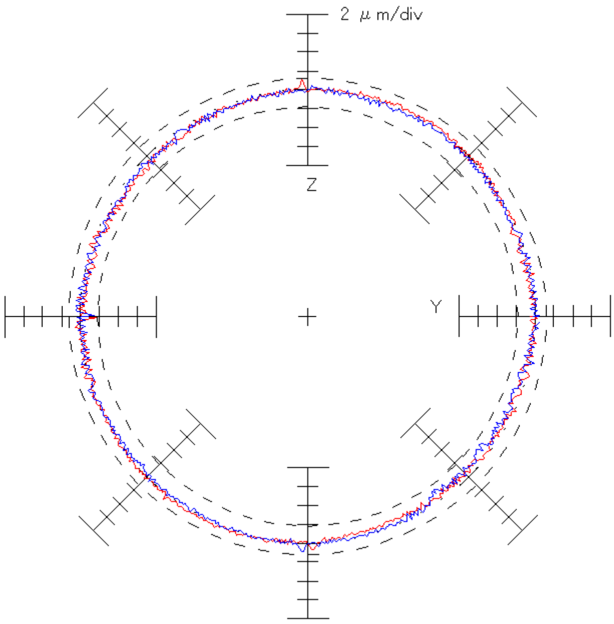


Fig. 12. Measured result with circular interpolation motion

4.3. Measurement of posture angle

Although the measuring range of posture angle with the developed device were such a small range as ±8° around X direction and ±5° around Y direction, the measurement accuracy was good. Figure 13 shows the angle measurement result around X axis while the machine's A-axis was moving ±2° up und down in a uniform angle velocity.

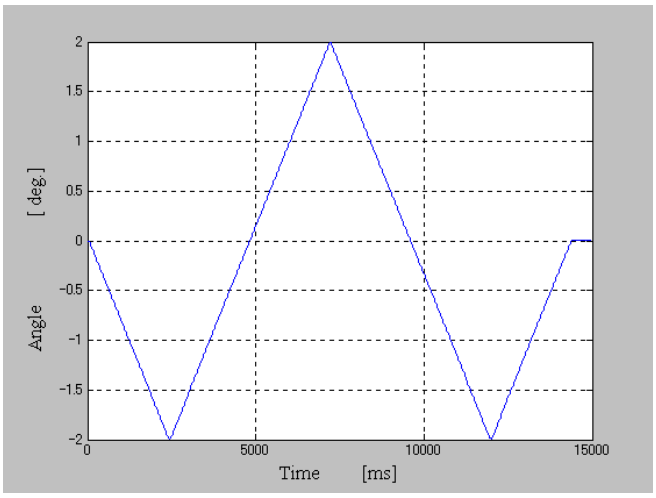


Fig. 13. Measured result with circular interpolation motion

5. CONCLUSION

The 6 DOF motion accuracy measurement device using parallel mechanism was developed. The calculation for obtaining position and orientation was easy, and the accuracy was high enough.

ACKNOWLEDGMENTS

This study is done by the Grant-in-aid for scientific research No. 17560108 by Japan Society for the Promotion of Science. The authors also thank Mazak Foundation for financial support in 2005.

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