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Evaluation of linear axis motion error of machine tools using an R-test device

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Abstract

The existing accuracy test standard for machining centers (ISO10791) is being revised in order to add a test method for five-axis machining centers. In the revised part of the standard (ISO10791-6), simultaneous three-axis interpolation motion accuracy tests for two linear axes and one rotary axis are proposed as an interpolation accuracy test for five-axis machining centers. These tests enable the measurement of the motion error in three directions, e.g., X, Y, and Z. Two devices can be used as the measurement instrument in these tests. One is a ball bar device, and the other is a combination of a ball and a displacement sensor. An R-test device that incorporates three displacement sensors has been designed for the latter. Using the ball bar device, measurement in three directions can be performed independently, and the radii of circular interpolations for each measurement are different. Using the R-test device, time is shortened by measuring three measurement directions at once, and the acquired data can be analyzed in various ways. The original goal of the measurement method using the R-test device was to measure the dynamic accuracy of the rotary axes. In the present study, the R-test device was actually prototyped and several machines were measured. In addition to the dynamic error of the rotary axes, incorrect pitch error compensation settings for the numerical controller, straightness, or squareness of the linear axes can be well detected.

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Keywords: Machining center; Motion accuracy; Test standard; R-test

1. Introduction

Recent machining centers (MCs) require highly precise processing, which in turn requires further technical development. The demand for five-axis controlled machines, which have two additional rotary axes (AB or BC or AC) compared to the conventional three-axis (X, Y, Z) controlled machine, is increasing.

The R-test device is a measurement instrument with three displacement sensors that is shown in ISO/DIS10791-6:2012. However, the standard is still under development and so the test results by using it are not well known. In the present study, a prototype R-test device was constructed. In addition, several machines were examined, and the test results were considered.

2. ISO10791-6

ISO10791-6:1998 is the current standard, which deals with feed speed, spindle speed, and motion accuracy testing for machining centers (MCs). ISO/DIS10791-6:2012 [1], which is currently being revised in order to be applicable to the five-axis MC. Tests for five-axis MCs are prescribed in the normative annex of the revised standard. In the revised standard, five-axis MCs are classified into three groups: 1) machines that have two rotary axes on the spindle (type-A), 2) machines that have two rotary axes on the table (type-B), and 3) machines that have one rotary axis on the spindle and one rotary axis on the table (type-C).

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3. R-test Device

3.1. Development of the R-test device structure

The measurement device is comprised of three displacement sensors and a master ball. Normally, the directions of the three displacement sensors are approximately toward the center of the master ball. The three-dimensional position of the master ball is calculated based on the outputs of the displacement sensors. Basically, the device measures the dynamic accuracy of the rotary axis of the machine. The device can simultaneously collect far more information than the ball bar measurement system. FIDIA Company (Italy) and ETH Zurich [2,3,4] (Switzerland) announced the development of measurement devices at approximately the same time. Moreover, a measurement device by IBS Precision Engineering (Netherlands) [5] is only just becoming available on the market.

3.2. Setting method

There are two methods for placing the R-test device on the machine that is to be measured. One method is to fix the device to the workpiece table, and the other is to fix the device to the machine spindle.

Figures 1 and 2, respectively, show the E-setting and Es-setting setups of the prototype device considered in the present study.

In E-setting, the sensors are attached to the workpiece table, in the same manner as in the FIDIA and ETH Zurich devices. The outputs of the displacement sensors are geometrically transformed to the (X, Y, Z) coordinate system of the machine tool.

In Es-setting, the sensors are attached to the machine spindle in the same manner as the device sold by IBS Precision Engineering. As in the case of E-setting, the outputs of the displacement sensors are geometrically transformed into the workpiece coordinate system.

Other settings, in which the sensors are set parallel to the linear axes of the machine, are also possible. [6] In such cases, geometrical operations, such as those required for E-setting, are not necessary without minute adjustments.

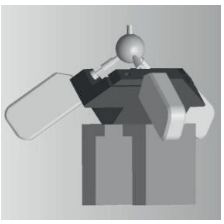

Fig. 1. E-setting.

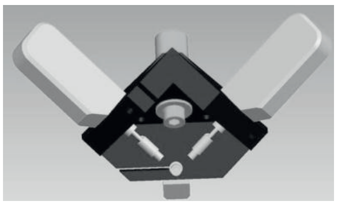

Fig. 2. Es-setting.

The prototype device is composed of three contact-type displacement sensors (MT1281, HEIDENHAIN) with a measurement range of 12 mm and a system accuracy of ±0.2 µm. The tips of the displacement sensors used for the probes are flat. EIB741 (HEIDENHAIN) is used as an interface to transfer sensor data to a personal computer. The master ball used in this case is a steel ball having a diameter of 1 inch and a sphericity of 0.13 µm or less. The master ball is attached by a stick of stainless steel with adhesive.

Abrasion of the master ball by the sensor probes was observed after a few measurements. Figure 3 shows the surface of the master ball after 20 measurements with a pressure of approximately 0.6 N applied by the probe. Figure 4 shows the surface of the probe tip. Since the sphericity of the master ball deteriorates after numerous measurements, the master ball must be refurbished often.

Fig. 3. Scratch made by the master ball.

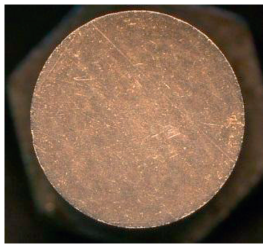

Fig. 4. Surface of the probe.

4. Orientation error of the measurement device

In E-setting and Es-setting, three displacement sensors must be aligned along the linear axes of the machine tool by means of coordinate transformation.

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\varphi & 0 & -\sin\varphi \\ 0 & 1 & 0 \\ \sin\varphi & 0 & \cos\varphi \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\omega & \sin\omega \\ 0 & -\sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

In the expended equations,

$$U = u\cos\theta\cos\varphi + v\cos\omega\cos\varphi\sin\theta + w\sin\omega\cos\varphi\sin\theta + v\sin\omega\sin\varphi - w\cos\omega\sin\varphi \quad (1)$$

$$V = -u\sin\theta + v\cos\omega\cos\theta + w\sin\omega\cos\theta \quad (2)$$

$$W = u\sin\varphi\cos\theta + v\cos\omega\sin\varphi\sin\theta + w\sin\omega\sin\varphi\sin\theta - v\sin\omega\cos\varphi + w\cos\omega\cos\varphi \quad (3)$$

where X, Y, and Z are the coordinates of the machine tool, U, V, and W are the coordinates of the sensors, u, v, and w are the displacements output by the sensor axes and ω, φ, θ is the rotation angles of the sensor axis. The order of the coordinate transformation shall be the U-axis, the W-axis, and the V-axis.

In a typical setup, one of the sensors overlaps the +X-axis when the device is viewed from the direction of the +Z-axis of the machine tool. In this case, the rotation angles for which the coordinate system of the sensor agree with the coordinate system of the machine tool with no error, are $\omega = 135°$, $\varphi = -35.264°$, and $\theta = 0°$.

$$U_X = u\cos(-35.264°) + v\sin(135°)\sin(-35.264°) - w\cos(135°)\sin(-35.264) \quad (4)$$

$$V_Y = v\cos(135°) + w\sin(135°) \quad (5)$$

$$W_Z = u\sin(-35.264°) - v\sin(135°)\cos(-35.264°) + w\cos(135°)\cos(-35.264°) \quad (6)$$

Adjust the setting error to appear at the time of fixing the device on the table. Here, ω_1, φ_1, and θ_1 are the angles of rotation of the U_X, V_Y, and W_Z axes, respectively. The Taylor's expansion is used because the setting error is small.

$$X = U_X + V_Y\theta_1 + W_Z\omega_1\theta_1 + V_Y\omega_1\varphi_1 - W_Z\varphi_1 \quad (7)$$

$$Y = -U_X\theta_1 + V_Y + W_Z\omega_1 \quad (8)$$

$$Z = U_X\varphi_1 + V_Y\varphi_1\theta_1 + W_Z\omega_1\varphi_1\theta_1 - V_Y\omega_1 + W_Z \quad (9)$$

In case of the Es-setting, acquired data must be transformed to the workpiece coordinate system in order to compare these data with the data obtained through other methods. For example, coordinate transformation around the *Z*-axis shall be performed for data measured by the BK2 test corresponding to the rotary axis *C*, as follows:

$$X' = X\cos C + Y\sin C \quad (10)$$

$$Y' = -X\sin C + Y\cos C \quad (11)$$

5. Method of experiment

5.1. Machine to be tested

Two five-axis MCs were tested. Machine A has two rotary axes (B, C) on the table, and Machine B has two rotary axes (A, B) on the table.

Following the description of ISO/DIS10791-6, the BK1 and BK2 tests were performed. The BK1 test checks three-axis simultaneous control motion for the Y, Z, and A axes. The BK2 test checks three-axis simultaneous control motion for the X, Y, and C axes. In Machine A, ZXB three-axis control motion was equivalent to the motion prescribed in the BK1 test.

5.2. Measurement direction

The measurement direction also followed ISO/DIS 10791-6. In case of the BK1 test (three-axis control ZXB test), the three measurement directions were the X-axis (tangential) direction, the Y-axis (axial) direction, and the Z-axis (radial) direction, as shown in Fig. 5. In the case of the BK2 test (three-axis control XYC test), the three measurement directions were the X-axis (radial) direction, the Y-axis (tangential) direction, and the Z-axis (axial) direction, as shown in Fig. 6. However, the radial and tangential directions are exchanged according to the mounting position of the measuring device.

Generally, the radial direction error primarily indicates the accuracy of the circular interpolation of the straight axis and the rotation accuracy of the rotary axis. The axial direction error is primarily associated with the parallelism between the straight axis and the table. The tangential direction error is due primarily to the synchronous speed mismatch between the spindle and the table.

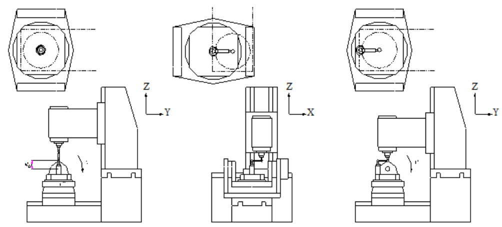

Fig. 5 Measurement direction for BK1

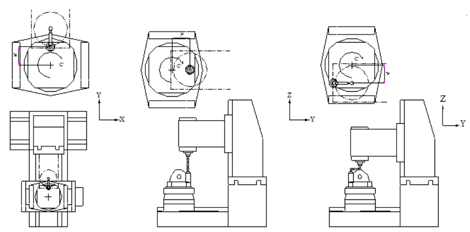

Fig. 6. Measurement direction for BK2

During the measurement, the sensor outputs were acquired every 0.2° of circular arc based on the actual feed speed. However, in the case of three-axis interpolation motion with two linear axes and a rotary axis, the actual feed speed is different from the programmed feed speed (F value of the NC code). The actual feed speed F' is obtained by the following equation:

$$F' = F \times (1 + (180/\pi R)^2)^{1/2} \quad (12)$$

where R is the radius of circular interpolation, and F is the programmed feed rate.

6. Consideration of the interference between the spindle and the table

The interference between the master ball and the sensor tips of R-test device was considered in a previous study. [7] In the present study, the interference between the machine spindle and the workpiece table is considered.

Here, H [mm] is the height of the measurement device and the jig (Fig. 7), W [mm] is the width from the top view (Fig. 8), D_s [mm] is the diameter of the machine spindle, D_t [mm] is the diameter of rotary table, L [mm] is the shaft length from jig to the center of master ball, and T [mm] is the length of the jig for fixing the ball (Figs. 9 and 10).

Figure 9 shows the measurement device installed on the rotary table rotated 90°. When $D_s/2 \geq H$, the condition required in order to avoid the interference should be $L + T > D_t/2$. However, when $D_s/2 < H$, $L + T$ can be much smaller than $D_t/2$, but $L > W/2$ is required in order to avoid interference between the measurement device and the tool holder.

Figure 10 shows the measurement device installed on the spindle and the table rotated to 90°. For the case in which $D_s/2 \geq L$, the required condition should be $H \geq D_t/2$, which is the same as Fig. 9 and $L > W/2$. Finally, when $D_s/2 \leq L$, the condition $H \leq D_t/2$ should be satisfied.

When the length of shaft L is larger, the shaft can be bent by its own weight or due to the sensor pressure.

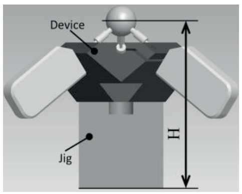

Fig. 7. Height of the device

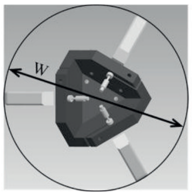

Fig. 8. Width of the device

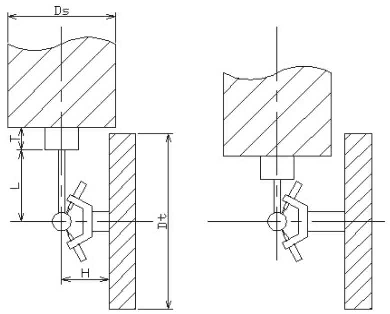

Fig. 9. Interference in E-setting

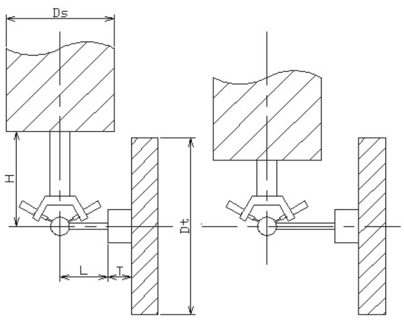

Fig. 10. Interference in Es-setting

In the case of the dimensions of machine A, which is primarily used in the present study, the spindle size D_s is 290 mm and the table size D_t is 500 mm. If the diameter of the shaft that supports the master ball is larger, it will interfere with the sensor tip. When the shaft is longer, it will bend significantly due to the pressure exerted by the sensor. In the present study, the diameter of the master ball is 25.4 mm, and the diameter of the sensor tip is 5 mm. The sensor pressure is 0.6 N. When $L + T > D_t/2$, the thickness of the support shaft should increase with the taper shape in order to avoid bending, or the length of supporting jig T should be increased as L decreases.

In the case of the measurement using the R-test device, the master ball should be exactly centered by obtaining an exact circular interpolation radius. As such, the location of the master ball should be easily positioned by machine operation. In case of testing a machine for which two rotary axes are located on the table, such as Machine A or Machine B in the present study, the master ball should be installed on the spindle. In other words, E-setting is better than Es-setting.

7. Experimental results

7.1. Machine A

Figures 11 and 12 show the measurement results for the XYC simultaneous interpolation test (BK2 test). A number of steps can be observed as motion error, as indicated by the marked circle in the figures. In order to identify the error source of the steps, a two conventional linear axes (XY) test and a rotary axis (C) radial error test were carried out using the ball bar device. The results are shown in Figs. 13 and 14, respectively.

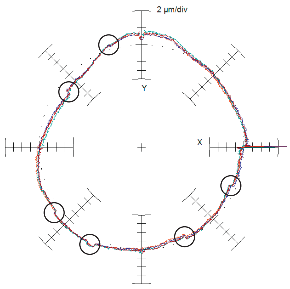

Fig. 11. Radial direction

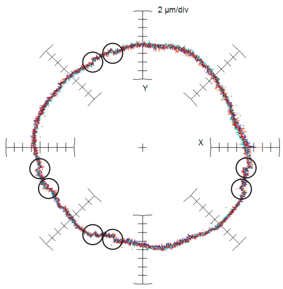

Fig. 12. Tangential direction

The shape in Fig. 13 is very similar to that shown in Fig. 11. On the other hand, there are no steps in Fig. 14, which means that the step shape error was due to the motion error of linear axes.

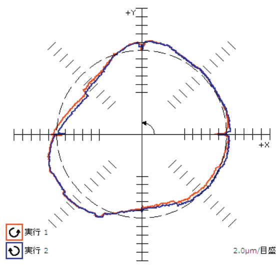

Fig. 13. Circular interpolation

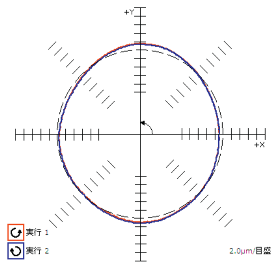

Fig. 14. Rotation motion

In the R-test for the five-axis machine, the sensitivity of each linear axis changes during radial and tangential direction measurement. Thus, measured data are converted by a geometrical operation similar to that given by Equations (10) and (11), because the sensitivity of each linear axis is always constant. Figure 15 shows the converted data for the X-axis sensitivity constant, and Fig. 16 shows the converted data for Y-axis sensitivity constant.

In these figures, steps symmetrical to the X-axis (Fig. 15) and the Y-axis (Fig. 16) can be clearly observed. These steps occurred as a result of the motion error caused by the pitch error compensation by the numerical controller. The measured machine tool was equipped with ball screws and a linear scale for linear axes. As a result, the compensated motion for the positioning error of the linear scale by NC exhibited step shape traces.

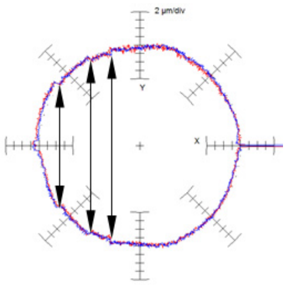

Fig. 15. X-axis direction

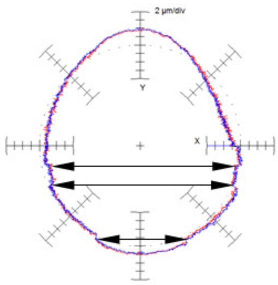

Fig. 16. Y-axis direction

7.2. Machine B

Figure 17 shows the radial direction measurement results of the YZA simultaneous interpolation test. Figure 18 shows the axial direction measurement results of the XYA simultaneous interpolation test, which are similar to the results shown in Fig. 17, but measurement plane was changed to the XY plane by rotating the B-axis by 90°.

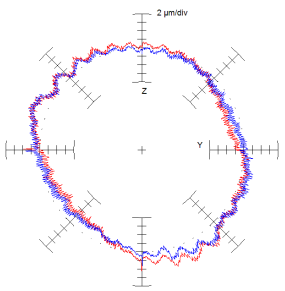

Fig. 17. Radial direction

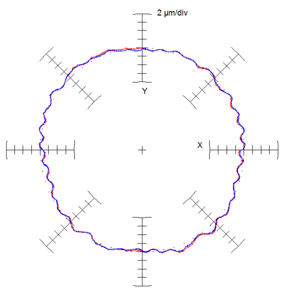

Fig. 18 Axial direction

The results in Fig. 17 exhibit an elliptical shape oriented -45°, which is caused by the squareness error between the Y-axis and the Z-axis. The results in Fig. 17 exhibit a cyclic shape in the second and fourth quadrants and a similar shape is observed in Fig. 18. These shapes are caused by the Z direction deviation accompanied by Y movement, i.e., the straightness error of the Y-axis motion. These cyclic errors can be detected by ball bar measurement. However, these errors can be detected more clearly by the R-test, because the R-test device has three displacement sensors, whereas the ball bar has only one sensor.

8. Conclusion

In the present study, the three-axis interpolation motion accuracy with two linear axes and one rotary axis of five-axis MCs was measured using a prototype R-test device that can be set up flexibly. The main conclusions of the present study are as follows:

- There are interference problems between the measured machine and the R-test device. These problems can be avoided by placing the R-test device on the workpiece table or the machine spindle. In the case of a five-axis MC with two rotary axes placed on the table, it is better to place the R-test device on the workpiece table.
- The R-test device has three displacement sensors. As such, more information about the motion error of the machine can be obtained, as compared to the ball bar device. Moreover, the deviation obtained by three sensors can be processed easily for different directions based on a linear axis, such as the X-, Y-, or Z-axis, or a rotary axis (radial, axial, tangential) because deviations are obtained at the same time.
- The R-test device is expected to detect primarily the motion error of the rotary axes in five-axis MC. However, since the motion error of a rotary axis is very small, the R-test device detects primarily the motion error of the linear axis, such as straightness, squareness and pitch error compensation, as in the case of the measurement using a two-dimensional linear scale. Based on this result, the R-test device is expected to be used for the motion accuracy measurement of lathes or turning machines because the spindles of these types of machines have good rotational motion accuracy.

Acknowledgements

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