Interpolation accuracy measurement on turning centre with three linear axes

N. Hamabata, M. Yamaji, Y. Ihara
Department of Mechanical Engineering, Osaka Institute of Technology, Japan
yukitoshi.ihara@oit.ac.jp

Abstract

Turning centres that have an additional milling spindle with a usual lathe are widespread. There is a test standard for interpolation motion (ISO/DIS 13041-5:2013) in the NC lathe and the turning centre. In the test standard three axis simultaneous interpolation motion measurement of two linear axes and one rotary axis proposed referring to the interpolation motion test (ISO 10791-6:2014) for five-axis machining centre is described clearly. A ball bar that can detect the displacement in one direction, a KGM (two-dimensional digital scale) that can read two-dimensional position, an R-test device that can detect the displacements of three directions, are also listed as standard measuring devices. Up to now, there are few reports that deal with the interpolation motion accuracy of lathe type machine tools. In this report, the circular interpolation motion measurement of two linear axes by ball bar and KGM, and three-axis simultaneous interpolation motion measurement by ball bar and R-test are performed. By comparing these results, the utility of R-test device was examined. Moreover, the motion error of the tested machine was verified.

1 Introduction

A turning center is a machine of the usual lathe that is added to a milling spindle for the milling process. Moreover, machines that have additional linear axes, have recently been developed. The demand of such machines is increasing because they can do both turning and milling processes. Recently, the multi-tasking machine tools that have a tilting milling spindle with turning center have also become popular. That is, the motion accuracy of turning centers has not been neglected.

The test standard of interpolation accuracy of turning centers is being revised at the moment in order to be adapted to various types of machines. However, reports of accuracy test results on turning machines are very few compared to milling machines.

This paper deals with the report of the motion accuracy of a turning center by referring to the ISO standard of interpolation test. Target motion accuracies are the simultaneous three-axis interpolation of two linear axes and a rotary axis. Moreover, this report deals with the usefulness of R-test by comparing the test results of KGM and ball bar.

2 Draft standard of turning centers

ISO 13041-5:2006 is a current standard for accuracy of feed rate, spindle speed, interpolation motion of turning center and NC lathes. Since the demand of multi-tasking machines has been increasing, the standard is going to be revised and then ISO/DIS 13041-5:2013 [1] have been currently proposed.

In the new standard, NC lathes are classified into three groups, that is:

1) machines that have a horizontal workholding spindle (type-A)
2) machines that have a vertical workholding spindle (type-B)
3) machines that have a inverted workholding spindles (type-C).

In the revised draft standard, motion accuracy of the simultaneous three-axis interpolation of two linear axes and a rotary axis, that is referred to the newly revised test conditions of 5-axis machining center (ISO 10791-6:2014 BK2 [2]), is described.

As measuring instruments, ball bar or two-dimensional digital scale (KGM) are shown for circular interpolation of two linear axes (AK4), while precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar are shown for the simultaneous three-axis interpolation of two linear axes and a rotary axis.

3 Measurement device

3.1 Ball bar

A ball bar is a measuring instrument that consists of two precision balls and a bar with a displacement sensor that detects the deviation of two balls. In this report, QC20-W (made by RENISHAW) was used. Figure 1 shows the setup of the device.

3.2 Two-dimensional digital scale

A KGM182 made by HEIDENHAIN was used in this report. It consists of a cross grid plate and a scanning head, so the non-contacting measurement can be performed. The parallelism between the surface of the cross grid plate and scanning head should be less than 0.02mm. In the case of the measuring the milling machine, the tolerance is satisfied by locating the plate on the machine table. However, in the case of the lathe type machine, a special jig for attaching the plate to the turning spindle is needed. Figure 2 shows the setup of the device. The measurement range depends on the size of the cross grid plate. Because the diameter of the largest cross grid plate currently available is 230mm, larger range measurement cannot be performed.

The results measured by KGM is evaluated by ACCOM software made by HEIDENHAIN. Although it only shows the radial direction deviation based on ISO 230-4 [3], the other deviations, such as X axis or Y axis, can also be calculated because the measured data has two dimensions.

3.3 R-test

The measurement device is comprised of three displacement sensors and a master ball [4][5][6]. Normally, the directions of the three displacement sensors are approximately facing 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 (Switzerland) announced the development of measurement devices at approximately the same time. Moreover, a measurement device by IBS Precision Engineering (Netherlands) [7] is the only device available on the market.

The original R-test device used in this report is shown in Fig. 3. It is composed of three contact-type displacement sensors (MT1281, made by 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 narrow pole of stainless steel with adhesive.

In the ISO test standard, the displacement sensors should be installed on the workpiece side. However, similar results can be obtained by coordinate transformation from the sensors data installed on the tool side [8].

Figure 1: Ball bar

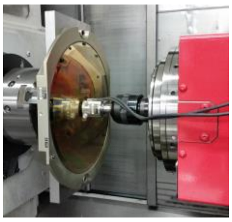


Figure 2: KGM

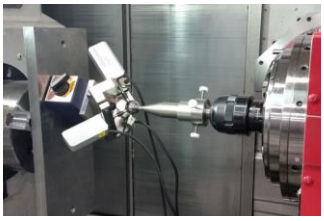


Figure 3: R-test

4 Method of experiment

4.1 Tested machine

In this report, the machine measured was a turning center on which rotary axis was C-axis of the workholding spindle and linear axes were X, Y, Z-axes of the milling spindle side. Although it also had a rotary axis (B-axis) on the milling spindle side, it was fixed to -90° (parallel to C-axis). Figure 4 shows the structure of the machine tool and Table 1 shows the moving range of each axis.

Following the description of ISO/DIS13041-5:2013, the AK4 and AK6 tests were performed. The AK4 test checks circular interpolation of two linear axes (X, Y axis). The AK6 test checks three-axis simultaneous control motion for the X, Y, and C axes.

The measurements in this report were done just after shipping and installing the machine before the fine tuning for observing larger size motion errors.

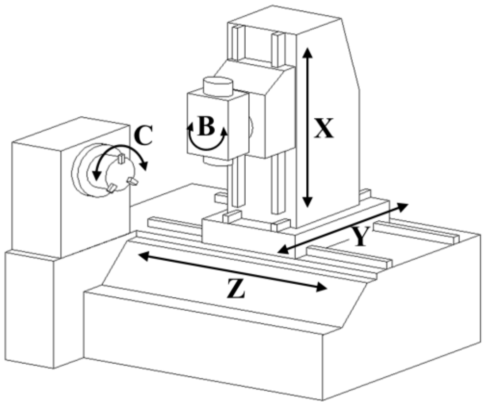


Figure 4: Tested machine [w C’ b Z Y X B (C) t]

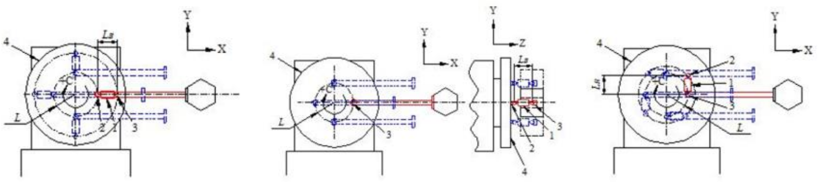
Table 1: Moving range

X-axis	380mm
Y-axis	± 105mm
Z-axis	460mm
C-axis	360°

4.2 Measurement direction

The measurement direction was also followed on ISO/DIS13041-5:2013. In the AK6 test (three-axis control XYC test), the three measurement directions were the radial direction, the tangential direction, and the Z-axis (axial) direction, as shown in Fig. 5.

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



(a) Radial direction (b) Axial direction (c) Tangential direction

Figure 5: Measurement direction of AK6

4.3 Centering method and location of measurements

The center coordinates of the rotary axis shifts with a time change. Therefore, centering just before measurement is necessary.

In order to align the center of C-axis with the master ball center that was attached to the milling spindle, a dial indicator is used as shown in Fig. 6. The sequence of centering is as follows. First, lock the milling spindle. Second, move the master ball along the XY plane to the center of C-axis while rotating C-axis.

In the case of KGM measurement on turning center, the jig to fix the grid plate to the workholding spindle is needed. The measurement position can be set arbitrarily depending on the design of the jig. Because the moving range of Y-axis of the tested machine is 200mm as shown in Table 1, the maximum radius of the circle in XY plane is limited to 100mm. Moreover, because the moving range of X axis downward is limited to 50 mm from the center of the workholding spindle, when the milling spindle is faced toward the workholding spindle on the tested machine, the circle radius is set to 50mm.

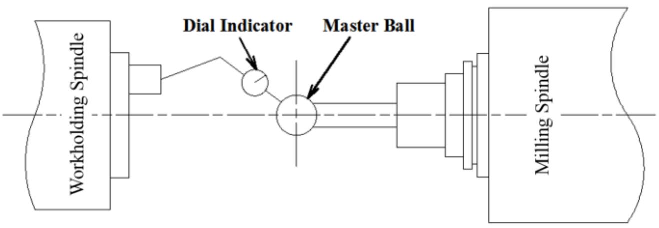


Figure 6: Centring method

5 Experimental results and considerations

5.1 Comparison between the R-test, ball bar and KGM

Basically the geometric accuracy of the rotation of the workholding spindle in turning centers is good because it is a critical factor to decide the machining accuracy and then direct drive motor or built-in type motor is adopted. To confirm the geometric accuracy of the rotation of the workholding spindle in the tested machine the measurement, as shown in Fig. 7, was done by using R-test device. The measurement result is shown in Fig. 8. It shows the motion error that can become a problem does not appear.

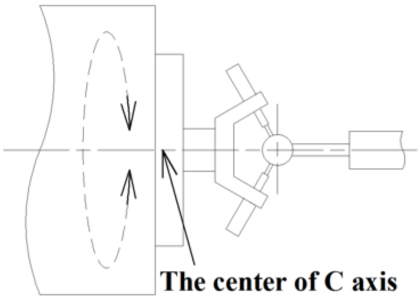
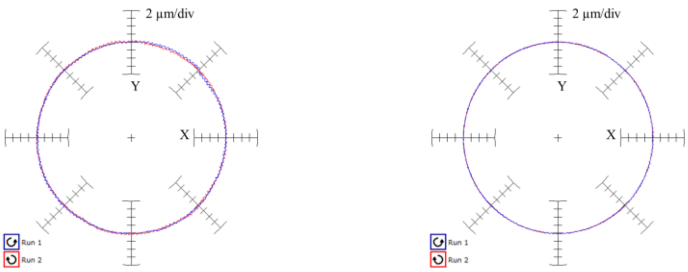


Figure 7: One rotary axis (C-axis) rotation test



(a) Radial direction (b) Axial direction

Figure 8: Test result of C-axis rotation

The circular interpolation motion in XY plane (AK4) was measured by using KGM, the result is shown in Fig. 9. Then there was a simultaneous three axes interpolation test of XYC axes (AK6) by using a ball bar. The result of axial direction is shown in Fig. 10. Moreover, there was a simultaneous three axes interpolation test of XYC axes (AK6) by using R-test, the result is shown in Fig. 11.

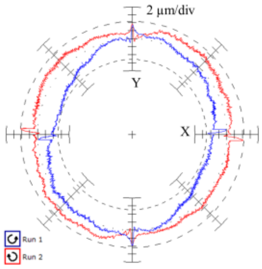


Figure 9: Radial direction by KGM

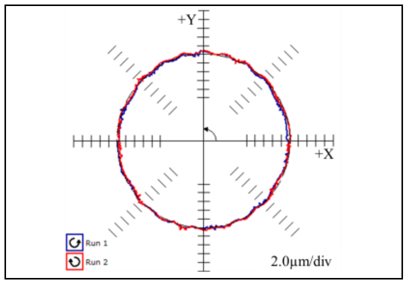
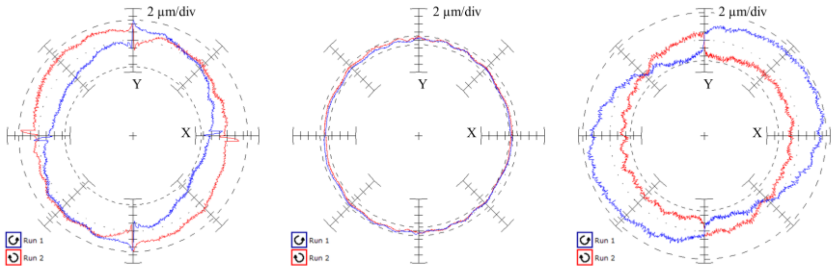


Figure 10: Axial direction by ball bar



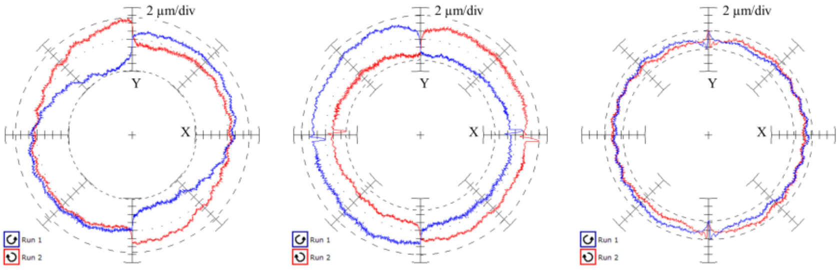
(a) Radial (b) Axial (c) Tangential

Figure 11: R-test measurement

In axial direction, few typical errors were found in Fig. 10 and Fig. 11 (b), which is the same as Fig. 8 (b). Although the offset of the center of the circle did not appear this time, often appears. The offset shows the squareness error between XY plane and C- axis, therefore, it is one of the motivations for doing this test by ball bar or R-test. When comparing the result of radial direction, at 45° and 225° two traces are separated in Fig. 9; however, they are overlapped in Fig. 11 (a). The reason is that the amount of reversal step in the Y axis is changed due to the machine's condition, because the measuring dates were different. In this machine, bi-directional repeatability of positioning differs very much on the condition of warming up time and room temperature. Considering this fact, the characteristics of traces are not different.

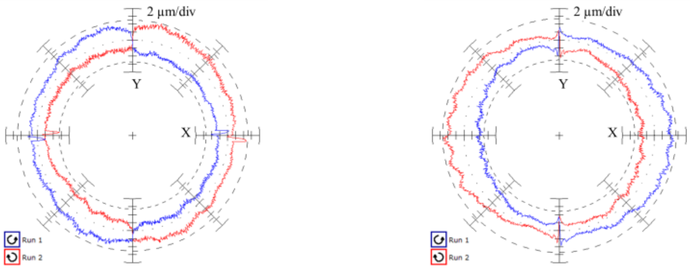
From the measured data obtained by KGM (Fig. 9), deviation of tangential direction (similar to the R-test result), deviation of X-axis direction and deviation of Y-axis deviation are calculated by coordinate transformation. The result is shown in Fig. 12.

In the case of the simultaneous three axes interpolation test by using R-test, the appeared deviation is transformed to the linear axes directions and evaluated when the error of the rotary axis is very small [9]. From the result shown in Fig. 11, the deviations are transformed to the X- and Y-direction by coordinate transformation. The result is shown in Fig. 13.



(a) Tangential (b) X-axis (c) Y-axis

Figure 12: Transformed result of KGM measurement



(a) X-axis direction (b) Y-axis direction

Figure 13: Transformed result of R-test measurement

By comparing Fig. 11(c) and Fig. 12(a), it can be observed that the characteristics of traces look very similar.

By comparing Fig. 12(b) and Fig. 13(a), it can be observed that the characteristics of traces also look very similar. The trace shows that there is a positive deviation when the Y-axis direction changes from the positive to negative direction; on the other hand, there is a negative deviation when the Y-axis direction changes from a negative to positive direction. There is an angular motion (pitching) in the Y-axis motion. By comparing Fig. 12(c) and Fig. 13(b), two traces are not separated in the result of the KGM measurement while they are separated in the result of the R-test measurement. It is because of the fact that the amount of reversal step in the Y axis is changed due to the machine's conditions that is observed more easily in these figures, as is already mentioned above.

The measurement result of circular motion by KGM is processed by ACCOM software normally provided by HEIDENHAIN. It only processes the data that shows the deviation of radial direction by ISO230-4; however, because the data has two-dimensional information, deviation of tangential direction (in addition to radial) can be obtained. Moreover, the deviation of X- and Y-direction can be obtained separately by coordinate transformation, similar to the result of R-test.

The size of the tested machine in this report was small. As mentioned above, because the rotational accuracy of the main spindle in the turning machine is normally good, circular interpolation motion larger than the plate size of KGM can be measured with the simultaneous three axes interpolation of two linear axes and a rotary axis by R-test device. For example, in the case of the machines with a vertical workholding spindle, the simultaneous three axes interpolation of two linear axes (X- and Y- axes) and a rotary axis (C-axis) is also prescribed as the BK6 test in ISO/DIS13041-5:2013. As far as the rotational accuracy of the table is good, this test by R-test can cover the weak point as the KGM measurement is limited by the size of the cross grid plate.

6 Conclusion

In this report, the interpolation motion error of the turning center was measured based on the draft test standard (ISO/DIS13041-5:2013) by various kind of measuring instruments such as KGM, R-test and ball bar. The typical results are as follows:

1) Typical motion errors found by R-test are the motion errors of the linear axes in the case of the machine that is the lathe type.
2) In the standard KGM measurement, the motion error is only processed for the radial error in ISO 230-4. However, because KGM obtains two dimensional position data, they can be processed by coordinate transformation and show much more information similar to R-test.
3) R-test has the possibility of the motion accuracy test of linear axes on larger size turning centers if it has good rotational motion accuracy.

Acknowledgement

We would like to express our gratitude to Machine Tools Technologies Research Foundation (MTTRF) for renting the machine tool used in the experiments.

References

[1] ISO/DIS 13041-5:2013, Machine tools — Test conditions for numerically controlled turning machines and turning centres – Part 5: Accuracy of speeds and interpolations.
[2] ISO 10791-6:2014, Machine tools — Test conditions for machining centres — Part 6: Accuracy of speeds and interpolations.
[3] ISO 230-4:2005, Test code for machine tools — Part4: Circular tests for numerically controlled machinetools.
[4] Weikert, S., Knapp, W., 2004, R-test: A New device for accuracy measurement on five axis machine tools, Annals of CIRP, Vol. 53, No. 1, pp. 429-432.
[5] Bringmann, B. Küng, A., 2005, A New Measuring Artifact for True 3D Machine Tool Testing and Calibration, Annals of the CIRP, Vol. 54, No. 1, pp. 471-474.
[6] Bringmann, B., Knapp, W., 2006, Model-based Chase-the-Ball Calibration of 5-Axes Machining Center, Annals of the CIRP, Vol. 55, No. 1, pp. 531-534.

[7] Florussen, G. H. J., Spaan, H. A. M., 2007, Static R-test: allocating the centerline of rotary axes of machine tools, *Laser Metrology and Machine Performance VIII* pp. 196-202, Bedford.

[8] Yamaji, M., Hamabata, N., Ihara, Y., 2014, Design of motion accuracy measurement device with three displacement sensors for machine tool and comparison of its setting method, *Bulletin of the JSME, Journal of Advanced Mechanical Design, Systems, and Manufacturing* Vol. 8, No. 4.

[9] Yamaji, M., Hamabata, N., Ihara, Y., 2014, Evaluation of linear axis motion error of machine tools using an R-test device, *Procedia CIRP* Vol. 14 (Elsevier) pp. 311-316.