New Measuring Method of Circular Movement of NC Machine Tools*

(Development of Alternative Method for Standardization)

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In this paper, we describe an alternative method based on a new idea for measuring the circular movement of machining centers. ISO has employed three methods for the acceptance tests of machine tools: the first is a rotating one-dimensional probe method, the second utilizes a two-dimensional probe and a master circular ring, and the third utilizes a kinematic ball bar. At present, it is necessary to develop an alternative method with no relation to the latter two methods because their patents are pending. We have developed an alternative method by improving the rotating one-dimensional probe method. The newly developed method is superior to the other two methods; the rotation angle can be detected and the rotation radius is variable. The effectiveness of the developed method is confirmed experimentally.

Key Words: Machine Tool, Numerical Control, Machining Center, Circular Movement, Alternative Method, Acceptance Test, Rotation Angle, Rotation Radius

1. Introduction

At present, for higher performance of numerical control (NC) machine tools, the significant tasks of improving the movement accuracy of the machines' linear axes and determining the appropriate values of the parameters to be set in the numerical controller are required. Conventionally, properties of NC machine tools have been tested with respect to geometrical, positioning and machining accuracy, according to the test methods specified by JIS (Japanese Industrial Standard)⁽¹⁾ or ISO (International Organization for Standardization)⁽²⁾. However, an NC machine tool, including the performance of the numerical controller, has not been evaluated in its entirety within those standards.

Recently, a circular contouring test which was carried out using special testing equipment was proposed as an acceptance test for NC machine tools,

and ISO has adopted the testing method as part of the test code category for NC machine tools⁽²⁾⁻⁽⁴⁾. The testing method, generally called the "circular movement test," is a new item among ISO standards and has superior characteristics in that not only the geometrical motion error of NC machines, but also the errors attributed to NC controllers and the errors which depend on the feed rate can be diagnosed without the inconvenience of actually cutting the workpiece⁽⁵⁾.

Several measuring devices for the circular movement test were previously developed⁽⁵⁾⁻⁽¹⁰⁾ and their usage is becoming widespread throughout the world⁽¹¹⁾. However, when these devices are adopted as part of the industrial standard, some difficulties arise. For example, some of them are not flexible in the measuring radius and some can evaluate only at a low feed rate due to the measuring principles. In addition, patents on the principles of these methods are pending^{(7),(9)} in Japan. From the point of view of standardization, it may not be fair to accept only patented methods.

In this paper, an alternative testing device, which can be produced easily and inexpensively, and a suit-

* Received 6th October, 1992. Paper No. 91-0776A

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able data sampling method are discussed. Furthermore, the effectiveness of the method utilizing this device is proven by comparing it with both the telescoping ball bar method⁽⁹⁾ and the circular test method⁽⁷⁾ proposed by Bryan and Knapp, respectively, which are already well-known methods for circular movement testing⁽¹²⁾.

2. Measurement Method of Circular Movement Test

2.1 Rotating one-dimensional probe

One of the aims of the circular movement test is to evaluate the deviation of an actual path from an ideal circular path drawn by an arbitrary point on the table of the machining center during 360-degree rotation with radius R in two simultaneously controlled axes. The three measuring devices and methods for this test, shown in Figs. 1, 2 and 3, have been adopted in ISO standards^{(2),(4)}.

The device shown in Fig. 1 is called the "rotating one-dimensional probe" in ISO standards⁽²⁾ and its measuring principle is well known. In this measuring device, an electric probe or a dial gage mounted on the rotary fixture rotates around the cylindrical bar fixed

Fig. 1 Rotating one-dimensional probe device

Fig. 2 Telescoping ball bar system

to the main spindle of the machining center and detects the relative displacement, ΔR in the figure, between the cylindrical bar and the rotary fixture. The rotary fixture can be rotated precisely around the axis, which is set at an arbitrary point on the work table. Either a contact or noncontact probe can be used as the detector of circular contouring error. However, the detection of the rotation angle is not considered in this method.

2.2 Telescoping ball bar method

In some cases, this method is called the "telescoping magnetic ball bar" (TMBB)⁽⁶⁾ or "double ball bar" (DBB)⁽⁹⁾ method. As shown in Fig. 2, the main structure of the system consists of two magnetic sockets which are designed to hold two precision balls and a telescoping bar inside a linear displacement sensor for TMBB or an optical scale as for DBB of which sensor detects the relative linear displacement in the radial direction between the two balls. The relative displacement detected by the sensor is conventionally transmitted through either an AD converter or a digital counter and stored in a personal computer. After the circularity and eccentricity are calculated, the results are recorded on an X-Y plotter using the polar coordinate system. The trajectory can be measured not only in the XY plane (360 degrees) but also in the YZ and ZX planes (180 degrees) without resetting the fixed socket. However, detection of the rotation angle is not considered in this method either.

2.3 Circular test method

The circular test method developed by Nakazawa⁽⁵⁾ and Knapp⁽⁷⁾ requires a circular master plate and a two-dimensional probe as shown in Fig. 3, and the error of the circular movement is directly plotted on an X-Y analog pen recorder without the aid of a computer. The 2-D probe is moved by the machining center on a circular contour relative to the master circular plate without rotating the probe. The relative displacements in the X and Y directions are independently detected by two LVDT transducers fixed on a

Fig. 3 Two-dimensional probe and master circular plate (Circular test method)

set of parallel leaf springs.

In principle, if there are several master plates of different diameters, the measuring radius R can be changed. Also, the 2-D probe can be used in the same way as cutting tools. However, owing to the friction between the stylus of the 2-D probe and the circular plate, there is a relatively large angular orientation between the clockwise and counterclockwise data plots⁽⁷⁾.

3. Newly Developed Measuring System

3.1 Outline of measuring system

In this research work, a new measuring system is developed through improvement of an existing system shown in Fig. 1 without infringing upon patent rights. A schematic view of the measuring system is illustrated in Fig. 4. In this advanced measuring system, the housed shaft can rotate with the arm such that the rotation angle can be detected by a rotary encoder directly connected to the end of the shaft. Also, the relative displacement between the spindle and the work table is detected by an LVDT transducer or a capacitance-type detector.

In the developed equipment, the radius R is variable from 0 mm to 150 mm and a larger measuring radius can be made available through use of a longer arm. In this system, a capacitance-type displacement sensor, which is a noncontact type, and an LVDT transducer, which is a contact type, are used. The signal from the displacement sensor is fed to a personal computer through the AD converter, which is synchronized with the pulse from the rotary encoder.

3.2 Data processing

As mentioned above, the data are digitally acquired; the procedure is illustrated in Fig. 4. The maximum number of data to be acquired is equal to

the number of pulses generated by the rotary encoder, of which the resolution of 2 500 pulses per revolution is adopted in the present system. Details of the procedure are as follows.

1) Determine the number of points N which describe an entire circle, and store the data with a personal computer. The maximum of N is limited by the resolution of the rotary encoder used, because of synchronization of data acquisition.

2) Create new data by calculating the mean value of the source data and by finding the difference between each source datum and the mean value in order to center the data within the coordinate system.

3) The component of eccentricity between the center of the measuring device and that of the circle described by an NC machine tool can be compensated by subtracting a 2π period term from the Fourier series of the data. In the developed system, the eccentricity up to about 100 μm can be compensated.

4) A polar coordinate system is adopted for displaying the results. At this time, an extra radius r , which should be a length appropriate for display, is added to each datum so that coordinates can be represented as $(r + r_n, \theta_n)$, where r_n is the n th datum. θ_n can be determined by the following equation.

$$\theta_n = \frac{360}{N}(n-1) \quad (n=1, 2, 3, \dots, N) \quad (1)$$

4. Performance of Developed System

4.1 Accuracy of developed system

The accuracy of the measuring system proposed in this paper depends on the circularity of the cylindrical test bar, which is the target of the displacement sensor, and the rotating accuracy of the arm. Hence, these effects are discussed in the following.

4.1.1 Effect of circularity of the test bar As shown in Fig. 4, the cylindrical test bar which is manufactured as one piece consists of three parts: the first is held by the collet chuck holder and attached to the spindle, the second is the target of the displacement sensor, and the third is inserted into the rectangular groove of the arm. The effects of these parts on the measured circular trajectory are analyzed. The following experiments were carried out on an X-Y stage with a CNC controller.

1) Effect of circularity of the target

The circularity of the target surface ground is 0.9 μm . This inaccuracy must be included in the inaccuracy of the eventual results from the circular movement test. Thus, the target surface must be carefully finished to obtain a sufficiently small circularity for a higher-precision test.

2) Effect of the inserted part of the test bar

The circularity of the third part of the bar, insert-

Fig. 4 Newly developed device and measuring system

ed into the groove, is $6\text{ }\mu\text{m}$. Since this part of the test bar is in contact with the side surfaces of the rectangular groove during rotation, circularity of this part leads to rotational error in the circumferential direction. The rotation of smaller radii is largely influenced by this kind of error. If we assume that the circularity $6\text{ }\mu\text{m}$ translates into rotational error in the circumferential direction with 22 mm radius, the amount of the angular error is 0.016 degrees. This amount can be neglected because it is much smaller than the resolution of the rotary encoder, 0.144 degrees. Since the amount of straightness deviation of the side surface is similar to that of the test bar, it is thought that the rotational accuracy in the circumferential direction is not influenced by these errors.

3) Effect of tilting of the test bar

If the test bar is tilted with respect to the measured plane, an elliptic component is contained in the measurement results. Through the tilting effect, the phase difference between the two sets of results can be found. We turned the test bar 90 degrees from its initial position without rotating the spindle, and measured the circular trajectory. However, the effect of tilting the test bar held by a collet chuck holder was not recognized in the measured results.

4) Clearance between the groove and the test bar

There is clearance between the groove of the arm and the test bar which enables the test bar to move in the radial direction smoothly. The clearance may produce two kinds of errors during measurement. One is that the actual starting point for measurement may be different in CW and CCW. The other is that extra pulses may be generated due to vibration which causes extra movement of the arm in the circumferential direction. The clearance in our study was approximately $80\text{ }\mu\text{m}$. If we assume that the displacement sensor is fixed correctly against the center axis of the target surface, the relative displacement of $0.7\text{ }\mu\text{m}$ in the radial direction is produced as the round target surface is shifted due to the clearance. In addition, if the measuring radius is less than 32 mm , the amount of clearance in the newly developed device becomes large enough that the encoder generates extra pulses. Thus, the gap should be considered in situations where the machine measured can generate vibration or a vertical plane is selected to be measured. Furthermore, the clearance, which is attributed to the dimensions of the groove, should be designed in consideration of the resolution of the rotary encoder and the measuring radius.

4.1.2 Rotational accuracy of the arm

Relative displacement of the arm to the rotational axis is measured using a reference surface located just under the arm as shown in Fig. 4, as the target of the

sensor which can be fixed under the arm. Repeatability of that measurement was excellent, with the result that maximum tracing error was $0.1\text{ }\mu\text{m}$. Similar to the case of the test bar, the parallelism between the center axis of the shaft and that of the test bar should be investigated. Accordingly, the accuracy of the circular interpolation of the X-Y stage was measured, with the direction of the housing changing 90 degrees. The result is shown in Fig. 5. In this figure, we see that the shape rotated in the same direction as the housing rotation. This indicates that the rotational axis of the shaft is slightly tilted. Therefore, the elliptic component in the experiment was compensated by calculation in the results from the newly developed device. It is necessary that the shaft and the test bar be constructed accurately so that the measurement can be carried out without this kind of compensation.

4.2 Effect of displacement sensor

Figure 6 shows the results of circular movement test with two kinds of displacement sensors. Figure 6

Fig. 5 Rotating accuracy of the arm

(a) shows the result for an LVDT transducer and Fig. 6(b) that for a capacitance-type sensor. As shown in the figures, large differences can be recognized in high-frequency components. The amplitude for the LVDT transducer is smaller than that for the capacitance-type sensor. Similarly, when the feed rate is 2 000 mm/min, which is four times as large as the feed rate shown in Fig. 6, the difference between the two sensors becomes clearer in the high-frequency components, as shown in Fig. 7, although their circular forms are almost the same. These results show that the frequency responses of the sensors used are quite different, and that the LVDT transducer has lower-frequency characteristics than the capacitance-type sensor. The LVDT transducer is not suitable for measurements in which a high-frequency phenomenon, such as an arrested motion at the changing point of the coordinate quadrant, is to be evaluated, although it is accurate enough to measure approximate values.

On the other hand, the measurement range of the capacitance-type sensor is generally too small to

allow smooth adjustment of the center of the measuring device to the center position of circular movement in the initial setting for the circular movement test, although the frequency response and resolution of the capacitance-type sensor are high. Thus, it can be concluded that a sensor having both high frequency response and high resolution is suitable for this kind of measurement.

4.3 Comparison with telescoping ball bar method

The precision of the developed measuring system, named the " $r\theta$ method," in measuring the accuracy of the circular interpolation was investigated by comparing it with the DBB method⁽⁹⁾. Since the measuring radius is usually 150 mm in the DBB method, the same radius is adopted in the $r\theta$ method for comparison. The trajectory obtained from the DBB method is shown in Fig. 8. Comparing Fig. 8 with Figs. 6(b) and 7(b), we see that the position at which the arrested motion occurs differs greatly, although the circular forms are in good accordance. With the $r\theta$ method, the arrested motion occurs at the X and Y axes in

(a) Linear variable differential transducer (LVDT)

(b) Capacitance-type displacement sensor

Fig. 6 Effect of displacement detector ($r\theta$ method)
(Feed rate $F=500$ mm/min, Radius $R=150$ mm)

(a) Linear variable differential transducer (LVDT)

(b) Capacitance-type displacement sensor

Fig. 7 Effect of displacement detector ($r\theta$ method)
(Feed rate $F=2\,000$ mm/min, Radius $R=150$ mm)

rectangular coordinates, while with the DBB method the measured results are rotated slightly in the circumferential direction. This inconvenience is attributed to the insufficient function of the detection of the rotation angle in the DBB system and to incompleteness of the data acquisition system construction.

Referring the data acquisition system in detail, in the DBB method, measurement is started by pushing the execution switch of the CNC controller and the trigger switch of the measuring system simultaneously. However, in the $r\theta$ method, measurement is started by pushing only the execution switch of the CNC controller; the first pulse generated by the rotary encoder invokes the measurement automatically. In addition, in the DBB data sampling method each datum is acquired on the basis of an internal time clock, which is calculated from the feed rate and the measuring radius; in the newly developed method, data sampling occurs in synchronization with the pulse generated by the rotary encoder at every given constant angle. Thus, the $r\theta$ method utilizing a rotary encoder is superior to the DBB method in terms of stable data acquisition.

(a) Feed rate $F=500$ mm/min

(b) Feed rate $F=2000$ mm/min

Fig. 8 Measured results of telescoping ball bar (DBB method)

4.4 Comparison with circular test method

In the circular test method, the measuring radius can be selected by means of an appropriate circular standard comparison from among several sizes⁽⁷⁾, while in the DBB method radius size is limited to 150 mm⁽⁹⁾. In particular, a small radius of 22 mm can be measured in the circular test method. In this section, the accuracy of circular interpolation with a radius of 22 mm is investigated. Figure 9 shows comparison of the circular test results with those of the $r\theta$ method. With respect to the magnitudes of the arrested motion and of high-frequency component, a difference can be seen clearly, although the overall circular configurations of the two sets of results are almost the same. This is due to the fact that the analog pen recorder used in this system has a considerably low frequency response as compared with the $r\theta$ method, which adopts a capacitance-type displacement sensor and a digital data acquisition system. In addition, the orientation of the plotted trajectory in the circumferential direction is apparently caused by contact friction between the stylus of the 2-D probe and the

(a) $r\theta$ method

(b) Circular test method

Fig. 9 Comparison of $r\theta$ method with circular test method (Feed rate $F=177$ mm/min, Radius $R=22$ mm)

measuring surface of the master circular plate. For the present measuring system, there is a shortage of error information. Therefore, it may be required that the data acquisition system be improved and that the friction be canceled by some means.

5. Conclusion

In this paper, a method named the " $r\theta$ method" was reported. Without infringing upon patent rights, this method improves upon one of the three methods of the circular movement test that has been adopted in ISO standards. The characteristics were compared with those of both the telescoping ball bar method and the circular test method. From the results, the following conclusions can be drawn.

(1) Since the circularity of the test bar and the rotational accuracy of the arm affect synthetic measurement accuracy, these elements should be manufactured accurately.

(2) Use of a rotary encoder as the detector of rotational angle makes it possible to start the measurement automatically and to obtain each datum at the correct position.

(3) In order to acquire error information more accurately, use of a capacitance-type displacement sensor is more favorable, although an LVDT transducer is also available.

In addition, the performance of the newly developed measuring system is found to be superior to the other methods by comparison and to be able to be sufficiently employable for the circular movement test.

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