Diagnosis and compensation of motion errors in NC machine tools by arbitrary shape contouring error measurement

S. Ibaraki[1], Y. Kakino[1], K. Lee[1], Y. Ihara[2], J. Braasch[3] & A. Eberherr[3]

[1]*Department of Precision Engineering, Kyoto University, Japan.*
E-mail: ibaraki@prec.kyoto-u.ac.jp, kakino@prec.kyoto-u.ac.jp, t60a0715@ip.media.kyoto-u.ac.jp
[2]*Department of Mechanical Engineering, Osaka Institute of Technology, Japan.*
E-mail: ihara@med.oit.ac.jp
[3]*Dr. Johannes Heidenhain GmbH, Germany*

Abstract

The DBB (double ball bar) method is widely accepted as a tool to measure the motion accuracy of NC (numerically controlled) machine tools and to diagnose their error sources. The DBB method can only perform circular tests due to its nature. Motion errors due to the mistuning of CNC servo control systems are, however, often easier to observe on non-circular paths. In this paper, we present an overview of a method to diagnose motion errors due to servo control systems by measuring the machine's motion accuracy in arbitrary shape contouring, and then to re-tune CNC servo control systems such that the optimal contouring performance can be obtained. The cross grid encoder method, or the KGM method, is used for two-dimensional contouring error measurement. By comparing with contouring error profiles of position feedback signal, motion errors due to mechanical structures and those due to CNC servo control systems can be both identified.

1 Introduction

The diagnosis methodology to identify motion error sources in NC (numerically controlled) machine tools based on the DBB (double ball bar) method was proposed about ten years ago, and is now widely accepted in today's industry [1]. Typical DBB devices consist of two high-precision balls connected by a telescoping bar, and the distance between two balls is measured by a linear scale installed on the telescoping bar. The DBB device is used to measure a contouring error profile as the machine is traversing along a circular trajectory.

Circular tests provide a quick and efficient way to measure the machine's contouring accuracies and then to diagnose its error sources. Circular tests are accepted in ISO [2]. However, today's market sometimes requires a motion accuracy test under the condition where the DBB test cannot be performed. For example, most DBB systems normally work with radii of $50 \sim 300$ mm, although some applications require the machine to perform a circular interpolation of smaller radius. Furthermore, the measurement accuracy of the DBB method is impaired at the feedrate higher than 10 m/min, due to the friction between the ball and the magnetic socket.

Another critical disadvantage of the DBB method is that it is restricted only to circular tests due to its nature. Motion error sources in NC machine tools can be roughly classified into two categories: 1) those due to mechanical structures, and 2) those due to CNC servo control systems. In particular, motion errors due to servo control systems are often easier to be identified on non-circular paths. For example, when the proportional gain of the position feedback loop controller does not match between two axes, one can observe a steady state contouring error from a straight-line reference trajectory inclined by 45 degree from one axis [3]. Another example is a contouring error due to the transient response of each axis. It is harder to observe on circular paths.

The diagnosis methodology based on the DBB measurement mainly focuses on motion errors due to mechanical structures. The diagnosis method presented in this paper focuses more on motion errors due to CNC servo control systems. Compared to motion errors due to mechanical structures, those due to CNC servo control systems are easier to compensate by properly re-tuning parameters in servo controllers. After the measurement and diagnosis of contouring errors, the present method automatically tunes servo parameters in order to reduce contouring errors. By using this method, tuning processes of servo control parameters are significantly facilitated in many situations where manual tuning is usually required, such as the testing of experimental machines, the setup of market machines, or their maintenance. The proposed tuning method is particularly effective for the applications where contouring accuracy is important.

For the measurement of two-dimensional contouring error, we employ the cross grid encoder method, or the KGM (Kreuz Gitter Meßsystem in German) method, developed by Heidenhain [4]. Since the KGM method is non-contact optical measurement, it is more suitable for high-speed and high-accuracy measurement. Most importantly, there are no restrictions on the motion to be measured due to a mechanical linkage, as in the DBB

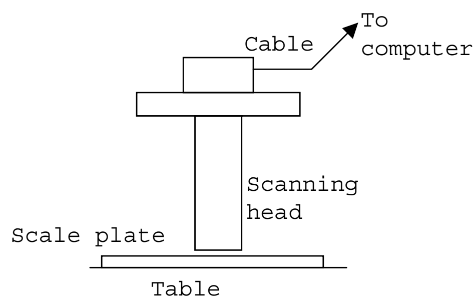

Figure 1: Schematic view of KGM device

method.

The remainder of this paper is organized as follows. Section 2 briefly reviews the KGM method. A contouring error measurement method using position feedback signal is also discussed. In Section 3, an overview of the diagnosis and compensation methodology of motion errors in NC machine tools is presented. Section 4 presents examples of contouring error measurement by using the KGM method and position feedback signal in order to illustrate the importance of properly tuning servo controller parameters.

2 Measurement of Motion Errors in Arbitrary Shape Contouring

2.1 Cross Grid Encoder Test

The cross grid encoder method [4], or the KGM method, is employed for two-dimensional motion accuracy tests in arbitrary shape contouring. Figure 1 shows a schematic view of the KGM device. On the scale plate, the grating of the interferometer's glass encoders is crossed perpendicularly so that the two-dimensional position of the scanning head can be measured by using the principle of diffracted light. More details about the KGM method can be found in [5]. An advantage of the KGM device is its ability to measure any move within a range of the scale, like two-dimensional coordinate measuring machines. The scanning head fixed on a spindle of a NC machine tool is moved according to the programmed path over the scale plate, which is fixed on the table of the machine.

Other methods to measure two-dimensional contouring errors include the laser ball bar method [6]. A single-aperture laser Doppler displacement meter measures the one-dimensional displacement of a table or spindle, where a flat mirror is attached as a target. For a two-dimensional motion accuracy test, two profiles measured in two directions perpendicular to each other must be combined. More discussion are needed to validate its measurement accuracy in multi-dimensional tests.

2.2 Contouring Error Profiles by Position Feedback Signal

Since servo control systems measure the position of the table (or the spindle) by using a linear or rotary encoder in all of three axes, contouring error profiles can be obtained by simply combining those feedback signal.

The KGM method observes the relative error between a spindle (a tool tip) and a table (a workpiece). Its contouring error profiles contain not only motion errors due to CNC servo control systems, but also those due to errors in mechanical structures of the machine. On the other hand, contouring error profiles of position feedback signal do not contain motion errors due to mechanical errors. Therefore, by comparing these two profiles, one can distinguish motion errors due to servo control systems from those due to mechanical structures. Many latest NC machine tools have a fast CPU and high-capacity memory, which makes it easy to sample position feedback signal in a fast rate. The sampling of position feedback signal requires no additional physical device if the NC machine tool has an additional memory to store sampled data.

In the full-closed loop type machines, the table position is measured by a linear scale attached on a table guideway. In the semi-closed loop type machines, it is measured by a rotary encoder installed on a servo motor. The position feedback signal measured by a rotary encoder does not contain errors in the ball-screw mechanical system, while that measured by a linear encoder does.

3 Diagnosis and compensation of motion error sources in NC machine tools

3.1 Classification of Motion Error Sources

Table 1 summarizes possible sources of motion errors in NC machine tools. The motion error sources can be roughly classified into two categories: 1) those due to mechanical structures and 2) those due to servo control systems. The DBB method mainly focuses on the diagnosis and identification of motion error sources in mechanical structures of NC machine tools. See [1] for the details of the diagnosis methodology based on the DBB measurement.

It is, however, generally hard to compensate such motion errors; it often requires to re-assemble parts of the machine. On the other hand, the motion errors due to servo control systems can be easily compensated by properly re-tuning parameters in servo controllers. Similarly, the motion errors that are caused by mechanical structures but can be compensated by servo control systems are classified in (1-3) of Table 1. For example, most of today's machining centers have a compensation algorithm in their servo control systems for the lost motion or the stick motion. However, it cannot perform effectively if its parameters are not properly set. In order to

Table 1: Motion error sources in NC machine tools

(1) Motion errors due to mechanical structures
(1-1) Errors in positioning mechanism
(a) Uniform expansion or contraction of the ball screw and linear scale
(b) Cyclic error of the ball screw, linear scale, etc.
(c) Noise in detectors
(d) Backlash
(1-2) Profile errors of guide way
(g) Squareness errors between two axes
(h) Straightness errors
(i) Rotational moment
(j) Parallelity error
(k) Collision of hose, friction of the sliding cover
(1-3) Errors that can be compensated by servo control systems
(l) Lost motion (step type, exponential type)
(m) Stick motion
(n) Stick slip
(o) Mistuning of pitch error compensation
(2) Motion errors due to servo control systems
(2-1) Mismatching of position loop gains
(2-2) Radius reduction in circular interpolation due to response lag
(2-3) Response lag or overshoot at junctions of two interpolation lines

optimize the machine's contouring performance, an operator must measure such motion errors in advance and tune the parameters in a proper manner.

Motion errors due to servo control systems are often easier to observe in non-circular paths. Section 4 will present experimental examples to illustrate it.

3.2 An Overview of Diagnosis and Compensation Method of Motion Errors

For each of error sources shown in Table 1, there is a particular motion trajectory to efficiently diagnose it. That is, by choosing the motion trajectory where one error source causes a relatively large contouring error compared to the others, one can easily distinguish the error source. Unlike the DBB method, the KGM method allows us to design motion trajectories arbitrarily. Possible motion trajectories include: 1) circles and arcs, 2) straight lines (inclined by 0, 45, and 90 degree from one axis), 3) sharp, right angle, and dull corners connecting two straight lines, 4) connection of an arc and a straight line, and 5) connection of two arcs.

An overview of our diagnosis method is shown in Figure 2. Similarly as the DBB diagnosis method [1], an error vector can be determined from each of motion error sources. Then, the corresponding motion pattern is

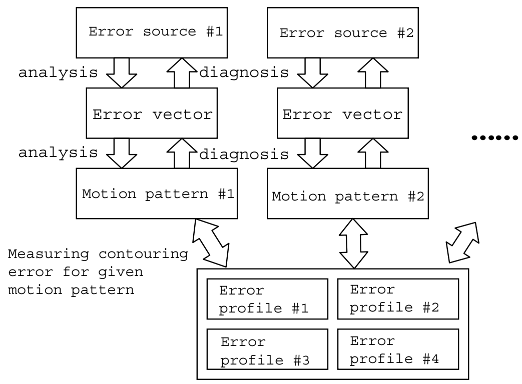

Figure 2: Basic concept of the diagnosis method based on the KGM measurement

designed such that each error vector causes the largest contouring error. Operating the machine by using each motion pattern as a reference trajectory, a contouring error profile is measured by using the KGM method or by sampling position feedback signal as shown in Section 2.1 and 2.2, respectively. From the measured contouring error profile for each of motion patterns, one can identify the error sources.

When the motion error corresponding to each error source is diagnosed, the parameters in CNC servo control systems are re-tuned such that contouring errors are reduced. By recursively repeating the measurement (diagnosis) of contouring errors and the tuning of servo control parameters, the optimal set of servo control parameters can be obtained.

4 Examples of Contouring Error Measurement and Diagnosis of Error Sources

4.1 Measuring Contouring Errors for Diagnosis of Error Sources

This section presents examples of contouring error measurement on noncircular paths by using the KGM method and position feedback signal. The measured machine (Machine A) is a high-speed vertical-type machining center with an open-architecture CNC controller. Its main specifications are shown in Table 2.

The reference motion trajectory used in the measurement is shown in Figure 3 [7]. It consists of straight lines (inclined by 0, 45, and 90 degree from the X-axis), arcs, a sharp corner, a right angle corner, and a dull corner. By using this path, the machine's contouring accuracy in single-dimensional and multi-dimensional liner interpolations, a circular interpolation and corner tracking can be measured at one time.

Table 2: Main specifications of Machine A

Strokes (mm)	X:630, Y:410, Z:460
Maximum feedrate (m/min)	50
Maximum feed acceleration (G)	0.7
Diameter and lead of ball screw (mm)	32, 16
Type of table guideways	Linear roller guides
Servo motor power (kW)	X:4.5, Y:7.0, Z:4.5
Type of positioning control	full-closed control
Spindle power (kW)	22
Spindle speed (min^{-1})	25,000

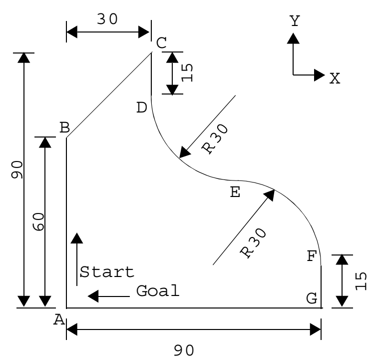

Figure 3: Reference trajectory

Note that Machine A has compensation algorithms for the backlash (lost motion), stick motion, and pitch error in servo control systems. In this experiment, the parameters in these compensation algorithms are set to their default values.

Figure 4 and 5 show contouring error profiles measured by the KGM method and position feedback signal, respectively. The measurement was performed on the X-Y plane of Machine A. The commanded feedrate was $2,000$ mm/min.

First, the error profile measured by the KGM method shows the deviation from the straight lines parallel to the X- and Y-axis (A-B and G-A in Figure 3), while that measured by using position feedback signal does not. It means that these contouring errors are due to errors in mechanical structures, not in servo control systems. It can be considered to be caused by the squareness error.

Secondly, two-axes interpolation introduces larger contouring errors, both on a straight line (B-C) and arcs (D-E and E-F). Since the deviation is approximately the same in Figure 4 and 5, these contouring errors are

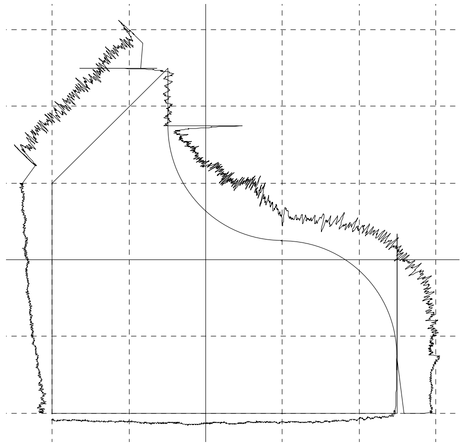

Figure 4: Contouring error profile measured by using the KGM method (one division: $5\mu m$)

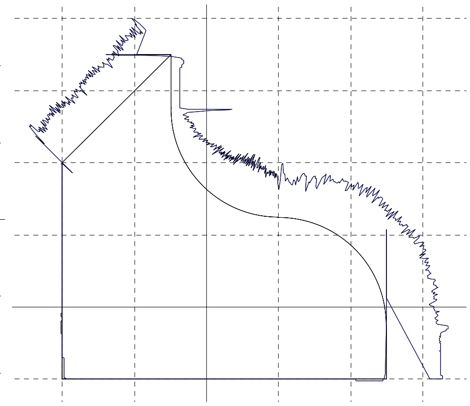

Figure 5: Contouring error profile measured by using position feedback signal (one division: $5\mu m$)

caused mostly by servo control systems. In this case, the deviation is considered to be caused by the mismatch of linear scales on X- and Y- axes, due to the improper setting of the pitch error compensation.

Furthermore, a notch-shaped error can be observed at the starting point of circular interpolation (D) both in Figure 4 and 5. This notch-shaped error was also observed in circular interpolation at quadrant changes. Since the deviation is in the negative direction, we conclude that it is due to the overcompensation of the stick motion. That is, by properly tuning the stick motion compensation, the size of the notch-shaped error can be reduced.

4.2 Effects of Servo Parameters on Contouring Accuracy

To illustrate the importance of properly tuning parameters in CNC servo control systems to optimize the contouring accuracy, consider a simple straight line interpolation [3]. Suppose that closed-loop transfer functions of the position feedback control systems for X- and Y- axes are given by $G_x(s)$ and $G_y(s)$, respectively. Consider the reference trajectory of a straight line inclined by θ radian from the X-axis. Assume that the commanded feedrate F is constant. Then, the actual position of the table, $(x(t), y(t))$, is given in the s-domain by:

$$X(s) = G_x(s) \cdot F \cdot \cos\theta \cdot \frac{1}{s^2}, \quad Y(s) = G_y(s) \cdot F \cdot \sin\theta \cdot \frac{1}{s^2} \qquad (1)$$

Therefore, the deviation of the table position from the reference trajectory is given as follows (see Figure 6).

$$e(s) = \{G_x(s) - G_y(s)\} \cdot \sin\theta \cdot \cos\theta \cdot F \cdot \frac{1}{s^2} \qquad (2)$$

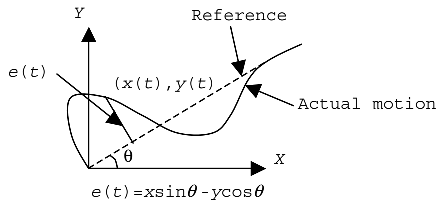

Figure 6: Contouring error in straight line interpolation

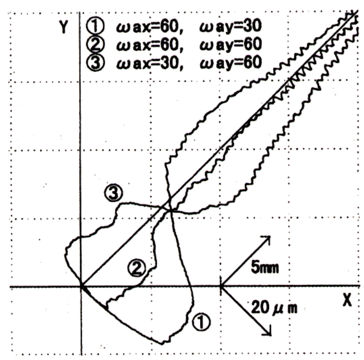

Figure 7: The effect of the cut-off frequency of velocity loop controllers, ω_{ax} for X- and ω_{ay} for Y-axis, on the contouring accuracy in a straight line interpolation (the commanded feedrate: $10,000$ mm/min).

To reduce the contouring error, the difference of transfer functions of X- and Y-axis closed-loop systems must be as small as possible. Since the dynamics of each axis' mechanical structure are generally different, the tuning of servo controllers is crucial to reduce the dynamic difference of the two closed-loop transfer functions.

Figure 7 shows contouring error profiles when the cut-off frequency of the velocity controller is changed. In Machine A, a PI (Proportional plus Integral) controller is used in the velocity loop. Although the effect of the velocity loop controller is generally not as much as that of the position loop controller, it still has a significant effect especially on the transient response, as can be observed in Figure 7. Therefore, it is an important issue to tune all parameters in servo control systems to achieve the optimal contouring performance.

5 Concluding remarks

Our objective is to develop a system to measure and diagnose motion errors in NC machine tools and then to re-tune parameters in servo control systems such that the optimal contouring performance can be obtained. For measuring the motion accuracy in arbitrary shape contouring, we use the KGM method. Contouring error profiles can be also obtained by simply using the position feedback signal. By combining these information, motion errors due to mechanical structures and those due to CNC servo control systems can be both identified.

This paper only presented a basic concept of the system to be developed. The system to be developed will focus on the tuning of servo control parameters to optimize the machine's contouring performance, by recursively measuring the contouring accuracies and tuning servo parameters. More researches on specific diagnosis/tuning algorithms will follow.

References

[1] Kakino, Y., Ihara, Y., & Shinohara, A., *Accuracy Inspection of NC Machine Tools by Double Ball Bar Method,* Hanser Publishers, Munich, 1993.

[2] ISO230-4, *Acceptance Code for Machine Tools – Part 4, Circular Tests for Numerically Controlled Machine Tools,* 1996.

[3] Fujita, J., Hayama, S., Hamamura, M., Shiba, K., Kakino, Y., Matsubara, A., A Study of Multi-Axis Contouring Error on the Transient State in NC Machine Tools, *Journal of the Japan Society for Precision Engineering,* **66**, pp. 434-438, 2000 (in Japanese).

[4] Heidenhain GmbH, *Measuring Systems for Machine Tool Inspection and Acceptance Testing*, Sept., 1997

[5] Teimel A., Technology and Application of Grating Interferometers in High Precision Measurement, *Precision Engineering,* **4**, pp. 147-154, 1992.

[6] Wang, C. & Griffin, B., A noncontact laser technique for circular contouring accuracy measurement, *Review of Scientific Instruments*, **72**, pp. 1594-1596, 2001.

[7] Kakino, Y., Ihara, Y., Lin, S., A Method for Quick Measurement and Diagnosis of the Arbitrary Shape Contouring Errors of NC Machine Tools, *Proc. of IMECO-XV World Congress,* Vol.IX, pp. 7-14, 1999.