A measuring instrument, Linked Ball Bar (LBB), is developed to measure machine tool motion errors quickly, flexibly, and robustly. The LBB employs the concept of double ball bar (DBB) and measures the distance between two balls attached to the spindle and table. The problem of short measurement range, the drawback of the DBB, is solved using a link. The measurement accuracy of the LBB is investigated. The analytical resolution of displacement measurement using the LBB is under 30 nm when the displacement direction coincides with the sensitivity direction. The difference between the LBB and the laser interferometer is less than 1 μm in the center measurement range of 75 mm. The repeatability of the LBB is ±0.4 μm and is at the same level as the interferometer. The kinematic error of a five-axis machine tool is measured using the LBB to demonstrate its validity. The parallelism between the C-axis and Z-axis identified using the LBB agrees with the result measured using the cylindrical square. The difference between the LBB and the cylindrical square is about 10 μm/m at the maximum. The LBB can provide quick and flexible measurements of the motion errors of five-axis machine tools.

Keywords: ball bar, motion error, measurement, rotary encoder, kinematic error

1. Introduction

Machining processes using five-axis machine tools are becoming more important because the demand for complex workpiece profiles is increasing. However, the motion accuracy of five-axis machine tools is generally lower than that of three-axis machines due to kinematic errors. Therefore, there is an urgent need for calibration of the kinematic error.

The kinematic error calibration of five-axis machine tools has traditionally been conducted using indicators and artifacts, such as squares. The traditional method requires many setup changes to measure various kinematic errors. The measurements should be completed in a short time because the number of kinematic errors of five-axis machines is increased compared to three-axis machines. Furthermore, a flexible measurement trajectory is required for the evaluation of complex motions consisting of linear and rotational motions. Robustness against measurement conditions such as temperature and contamination is also an important requirement of in-process or between-process measurements.

Many methods and instruments have been developed to measure the motion error of machine tools [1]. The double ball bar (DBB) method is one of the most popular methods and is widely used [2–5]. The R-test, proposed by Weikert [6], has also become popular in recent years. The concept of the R-test is to measure the three-dimensional displacement between the spindle and table using three displacement sensors. This concept has been used in several other studies [7–10]. These methods are focused on because they are included in measurement tests that are defined in the ISO standard for five-axis machine tools. However, these methods require synchronous motion between a linear axis and a rotational axis during the measurement because of their short measurement range. Therefore, errors resulting from these axes cannot be separated. In addition, the measurement trajectory is restricted in circular trajectories.

Laser interferometers are also often used to measure the motion error of machine tools [11–15]. The laser interferometer provides a measurement with a flexible motion trajectory if a target of a retro reflector and a tracking system of the target are used [11, 15]. Thus, the laser interferometer is suitable for measuring the volumetric error. However, the laser interferometer is sensitive to the conditions under which the measurements are made.

For more practical evaluation, machining tests have been proposed to identify the kinematic error of machine tools [16–18]. Methods using a touch-trigger probe are also practical because they can be easily adopted in automated measurements [19, 20].

According to the preceding literature review, no method is quick, flexible, and robust at the same time. Therefore, in this study, a measuring instrument, Linked Ball Bar (LBB), is developed to fulfill these requirements. The LBB employs the concept of the DBB and measures the distance between two balls attached to the spindle and table. The short measurement range, which is the drawback of the DBB, is solved using a link. The configuration and the specification of the LBB are described in the following section. Then, the measurement accuracy of the
LBB is investigated. Finally, to demonstrate its validity, the LBB is used to measure the kinematic error of a five-axis machine tool.

2. Developed Measuring Instrument

2.1. Configuration and Specifications

For quick and flexible measurements, the measurement range of the measuring instrument should be large because the motion trajectory for the measurement is restricted by the range. Furthermore, the setup for the measurement should be simple, and the number of the setup changes should be less. To fulfill these requirements, the concept of the double ball bar (DBB) is modified and its measurement range increased in this study. The aim of the development is to measure the motion error of machine tools with 5–10 μm accuracy and sub-micrometer resolution.

Figure 1 is a schematic drawing of the developed instrument. It measures the distance between two balls fixed at the top of two bars. The two bars are connected by a link. The developed instrument is called Linked Ball Bar (LBB). In Fig. 1, l and L are the length of the bars, θ is the angle between two straight lines passing through the center of the balls and the rotation center of the encoder, and r is the distance between the two balls. The lengths l and L are identified before the measurement. The angle θ is obtained using the rotary encoder. Then, derived from the law of cosines, the distance r is obtained through the following equation:

\[ r = \sqrt{l^2 + L^2 - 2lL \cos \theta}. \quad \ldots \ldots \ldots \ldots \quad (1) \]

The specifications of the LBB are listed in Table 1. An absolute rotary encoder (HEIDENHAIN) is used to obtain θ. The resolution of the measured distance depends on the distance, as described in section 3.1. Fig. 2 is a photograph of the LBB attached to a machine tool. A magnetic spherical socket is fixed at the table and the tool holder, respectively. The two balls of the LBB are attached to the spherical sockets to measure the distance between them during various movements of the machine.

Compared to the laser interferometer, the effects of measurement conditions, such as oil mist or atmospheric pressure, are smaller for the LBB because a shield-type rotary encoder is used. The setup of the LBB is simple, as is that of the DBB, because the basic concepts are similar. Furthermore, the measurement trajectory is flexible for the LBB because the measurement range is larger than that of the DBB. A square motion and a straight motion can be used for the LBB, for example. The flexibility of the measurement trajectory is valuable for measurements of 5-axis machine tools.

2.2. Parameter Identification

2.2.1. Required Parameters

The parameters l and L are required to obtain r using Eq. (1). In addition, the angle θ is not equal to the angle

![Fig. 1. Schematic drawing of Linked Ball Bar.](image1)

![Fig. 2. Linked Ball Bar attached to machine tool.](image2)
\[ \theta = \theta_m + \theta_{off} \]  

\[ r = \sqrt{l^2 + L^2 - 2ll\cos(\theta_m + \theta_{off})} \]

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Measurement number & \( L \) [mm] & \( l \) [mm] & \( \theta_{off} \) [deg.] \\
\hline
1 & 200.2633 & 179.9235 & 127.2083 \\
2 & 200.2636 & 179.9229 & 127.2082 \\
3 & 200.2649 & 179.9213 & 127.2082 \\
4 & 200.2617 & 179.9247 & 127.2080 \\
5 & 200.2622 & 179.9244 & 127.2079 \\
\hline
\end{tabular}
\caption{Identified parameters.}
\end{table}

3. Accuracy Verification of Linked Ball Bar

3.1. Resolution of Displacement Measurement

Displacement measurement is widely used in the motion error measurement of machine tools. This section describes the resolution for displacement measurement using the LBB. The sensitivity direction of the LBB is the direction of the straight line passing through the two balls. If the displacement in an arbitrary direction is measured in a flexible measurement trajectory, the two cases shown in Fig. 5 can be assumed. One is that the measurement direction for the displacement coincides with the sensitivity
Linked Ball Bar for Flexible Motion Error Measurement for Machine Tools

(a) Measurement direction coincides with sensitivity direction

(b) Measurement direction does not coincide with sensitivity direction

Fig. 5. Two cases in displacement measurement.

The relationship between the displacement resolution and the distance \( r \) is calculated for various \( \alpha \) using Eq. (4). The calculated relationships are compared in Fig. 7. The resolution is negatively correlated to the distance and is positively correlated to \( \alpha \). The resolution is smaller than 30 nm when \( \alpha = 0^\circ \). The resolution is smaller than 100 nm when \( \alpha < 70^\circ \). Therefore, \( \alpha \) should be smaller than 70° if motion errors are measured with sub-micrometer resolution.

3.2. Measurement Accuracy of Displacement

3.2.1. Comparison of Linked Ball Bar and Laser Interferometer

The LBB was compared to a laser interferometer to experimentally verify its measurement accuracy. Fig. 8 shows the experimental setup. A stepwise motion in the Z direction of the machine tool shown in Fig. 3 was measured using the LBB and the laser interferometer (Renishaw). The setup of the LBB was conducted similarly to the setup in the experiment described in section 2.2.2. For laser interferometer measurement, a target mirror and a beam splitter were attached to the spindle head and the table, respectively. The step distance was set to 1 mm, and the measurement length was 150 mm. The Z-axis motion was stopped for 2 s between each step. The feed rate of the Z-axis was set to 500 mm/min.

Figure 9 shows the comparison of displacements measured using the LBB and the laser interferometer. In Fig. 9, the difference between the LBB and the laser interferometer is magnified by 10000 times along the vertical axis. In the range from \(-25\) mm to \(+50\) mm, the difference between the LBB and the laser interferometer is less than about 1 \( \mu \)m. However, the difference increases to 6 \( \mu \)m at both ends of the measurement range.

3.2.2. Repeatability of Measurement

The repeatability of the LBB is evaluated in this section. The measurement setup and method are similar to those described in section 3.2.1. In this case, the measurement range was \( \pm 5\) mm at the center. Measurements were taken 10 times.
3.3. Effects of Attitude of Linked Ball Bar on Measurement Accuracy

When the LBB is used for measurements with a three-dimensional trajectory, the attitude of the LBB changes, as shown in Fig. 11. In Fig. 11, $\theta_e$ is an elevation angle. It can be estimated that the angle $\theta_e$ affects the measurement accuracy because the direction of the gravity force is changed relative to the sensitivity direction of the LBB. Therefore, the effect of the angle $\theta_e$ on the measurement accuracy is investigated in this section.

The machine tool shown in Fig. 3 is used in the experiment. The distance between the two balls is measured at various $\theta_e$. The measured distance is compared to the nominal distance calculated from the commanded position of the machine. The distance is measured at the cross grids shown in Fig. 12. The pitch of the grid is 10 mm in the Y and Z directions.

The difference between the measured and nominal distances is shown in color scale in Fig. 13. The difference is less than 5 $\mu$m and at minimum when $\theta_e = 90^\circ$. This difference can mainly be caused by the measurement error shown in Fig. 9 and the setup of the reference position. Also, the difference increases when $\theta_e$ decreases. The difference is about 16 $\mu$m and at maximum when $\theta_e = 50^\circ$. The 11 $\mu$m increase of the difference is caused by the effects of $\theta_e$ and the positioning accuracy of the machine. According to the calibration sheet, the positioning accuracy of the machine is less than 4 $\mu$m on each axis. Thus,
the influence of the positioning accuracy is estimated to be 6 μm at the maximum. Therefore, the influence of $\theta_e$ is at least about 5 μm.


To demonstrate the performance of the LBB, the kinematic error of the five-axis machine tool shown in Fig. 3 was measured using the LBB. In this section, the parallelism between the C-axis and the Z-axis is measured. The parallelism is also measured using a cylindrical square for verification.

4.1. Measurement Method for Kinematic Error

A method of measuring the parallelism between the C-axis and Z-axis is described. Fig. 14 is a schematic drawing of the measurement. One ball of the LBB is attached to the spindle using a tool holder and is located approximately at the center of C-axis rotation. The other ball is attached to the table. The distance between the two balls is then measured as the C-axis rotates, as shown in Fig. 14(a). In the next step, as shown in Fig. 14(b), the center shift of the circular trajectory of the table ball is identified in the X and Y directions from the measured distance using the least squares method. If the rotation axis of the C-axis coincides with that of the Z-axis, the center shift should be zero because the distance between the two balls does not change. Then, the center shift is identified at different heights of the spindle ball. The parallelism is obtained from the variation of the center shift.

The measurement described here is not affected by the measurement error due to the elevation angle $\theta_e$. This is because $\theta_e$ does not change as the C-axis rotates. This method can be used for any other configuration of five-axis machine tools, such as a spindle tilt type and a combination type.

The parallelism between the rotational axis and the linear axis can also be measured using the DBB. However, linear axes must be synchronously driven during the rotational axis movement because of the short measurement
range of the DBB. Therefore, the obtained parallelism contains the error of linear axes and the synchronous error between each axis. The method described in this study provides a simpler measurement without the synchronous motion.

4.2. Methodology

The parallelism between the C-axis and the Z-axis was measured in the X and Y directions using the LBB. The measurement was conducted at $+0.001^\circ$, $0^\circ$ and $-0.001^\circ$ of the B-axis to artificially change the parallelism in the X direction. The table is nominally horizontal at $0^\circ$ of the B-axis. The location of the table ball was shifted 141 mm from the table center. The center shift of the C-axis rotation was identified at every 10 mm height from 200 mm to 300 mm. The feed rate was set to 720 deg./min. The sampling frequency was 1 kHz.

The parallelism was also measured using a cylindrical square and an electric micrometer (Tokyo Seimitsu) for verification. The measurement was conducted at the same height as the measurement using the LBB. The reversal method was used to eliminate the geometrical error of the cylindrical square. The feed rate was 100 mm/min.

4.3. Experimental Results

Figure 15 shows a comparison of the motion trajectories of the table ball. The comparison shows that the center of rotation shifted at the micrometer level. The center shift varied due to the height variation.

The relationship between the height and the center shift is plotted in Figs. 16 and 17. The error bar represents the standard deviation multiplied by three. The measurements taken using the cylindrical square are also shown in Figs. 16 and 17. In the center shift in the Y direction shown in Fig. 16, the parallelism identified using the LBB was similar to that measured using the cylindrical square. In the center shift in the X direction shown in Fig. 17, the parallelism changed according to the rotation angle of the B-axis. This artificial change of the parallelism was also correctly identified using the LBB. The repeatability of the identified center shift was about $\pm 3\,\mu m$.

The parallelism was obtained using the least squares method and is summarized in Table 4. The difference between the LBB and the cylindrical square was about $10\,\mu m/m$ at the maximum. This accuracy meets the aim of this study. Therefore, the LBB can provide a flexible measurement for the motion errors of five-axis machine tools.

5. Conclusion

Linked Ball Bar (LBB) was developed for quick, flexible, and robust measurements of the motion errors of machine tools. The LBB employs the concept of Double Ball Bar (DBB) and measures the distance between two balls.
attacked to the spindle and the table. The problem of the short measurement range, which is the drawback of the DBB, is solved by a link. Then, the measurement accuracy of the LBB was investigated. The parallelism of a five-axis machine tool was measured between the C-axis and the Z-axis. Parallelism was also measured using a cylindrical square for verification. The following conclusions were drawn in this study.

- The analytical resolution of displacement measurement using the LBB is smaller than 30 nm when the measurement direction coincides with the sensitivity direction. If the resolution should be of sub-micrometer level, the angle between the measurement direction and the sensitivity direction should be smaller than 70°.

- When the measurement direction coincides with the sensitivity direction, the difference between the LBB and the laser interferometer is less than 1 μm at the maximum. This accuracy meets the aim of this study. Therefore, the LBB can produce flexible measurements of the motion errors of five-axis machine tools.

- The measurements taken using the LBB are affected by the attitude of the LBB. The measurement error due to the attitude is estimated to be about 5 μm at least when the elevation angle is 50°.

- The parallelism identified using the LBB agrees with the results measured using the cylindrical square. The difference between the LBB and the cylindrical square is about 10 μm/m at the maximum. This accuracy meets the aim of this study. Therefore, the LBB can produce flexible measurements of the motion errors of five-axis machine tools.

- A future issue to be solved is the measurement error due to the attitude of the LBB. A lighter LBB will be developed to decrease the influence of the gravity force. An error table for compensation will be also developed.

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