



## A New Device for Accuracy Measurements of Multi-axis NC Machines

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### **Abstract**

In this paper, a new device is proposed for accuracy measurement of multi-axis machines. The proposed new device is designed such that to overcome all the drawbacks that are with ball bar and R-test measuring instruments, low cost and easy usage. In this paper the design of the new device, applications and comparison of measurement results of three devices are discussed.

**Keywords:** Five-axis, NC machines, Accuracy, Measurement.

### **1. Introduction**

With the developments of the multi-axis machine tools, the necessity of accuracy measurement methods and devices is also increasing. In accuracy measurements, the double ball bar [1] is a widely used instrument. There are many application methods and research works by using this instrument [2]. However, to measure in three orthogonal directions each and every time the measuring setup have to be relocated and time consuming work. Recently, a device named R-test [3] was introduced to this field. This instrument consists of three displacement sensors located at 45° to vertical plane (considering the axis of the

instrument is in upright position) and equidistance about its axis. This instrument can be used to measure all the three directions in one setup but it uses sophisticated software to convert the data to three orthogonal directions. And also this is very sensitive and additional care must be needed to handle.

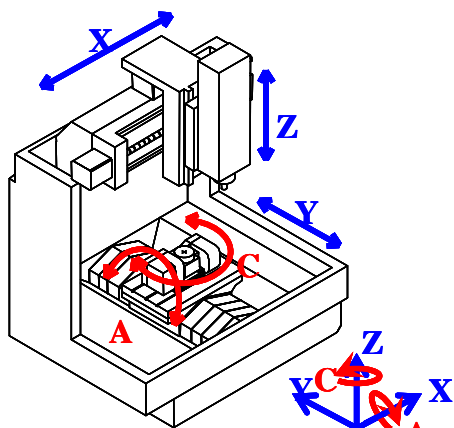
The proposed new device is designed such that to overcome all these drawbacks, low cost and easy usage. In this paper the design of the new device, applications and comparison of measurement results of three devices are discussed.



**2. Existing measuring methods**

**2.1 Measuring object**

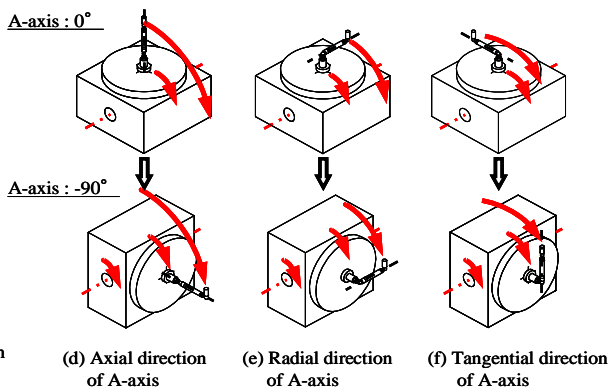
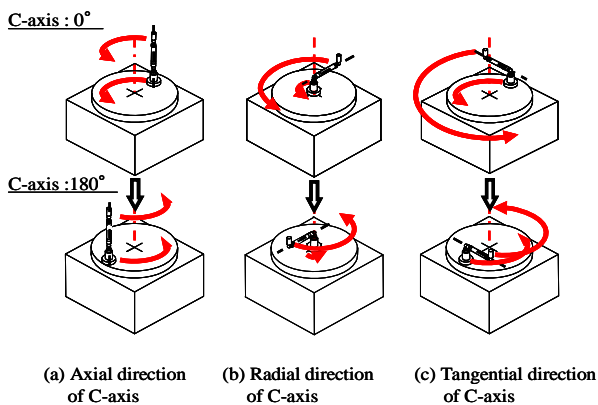
Schematic view of five-axis machining center which is used in this study is shown in Fig.1.



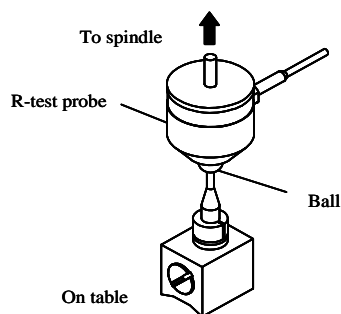
**Fig.1** Five-axis machining centers with a tilting rotary table

**2.2. Ball bar method**

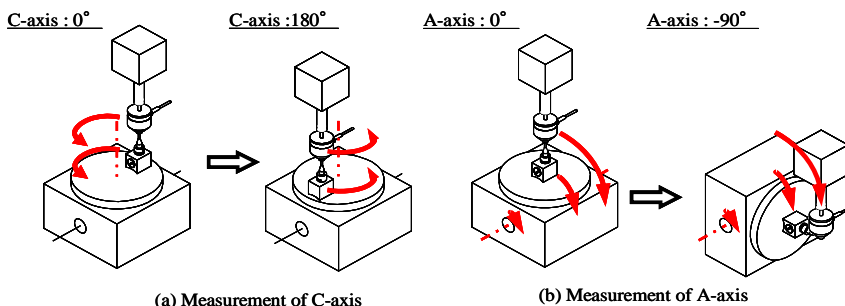
Schematic view of ball-bar is shown in Fig. 2. Ball-bar consists of telescopic bar and two steel balls that attested enough sphericity. As depicted in Fig.2 ball-bar is applied in between two sockets which are fixed to spindle and table.



**Fig.3** Measurement by means of ball bar



**Fig.4** Schematic view of R-test



**Fig.5** Measurement by means of R-test

This machine consists of three linear X, Y and Z and two rotary A and C axes as depicted in Fig.1.

In the unit a LVDT is used for measuring the displacement.

There are number of motions which proposed by researchers that used the ball bar to assess the accuracy of multi-axis machines [4]. By considering the rotary axis of machine and the sensitive direction of the ball bar, the ball bar can be applied in three ways: axial, radial, and tangential directions to the motion as illustrated in Fig.3(a,b,c) respectively.

**2.3. R-test**

Schematic view of R-test instrument is shown in Figs.4 and 6. This instrument consists of a probe with three displacement sensors located at 45° to vertical plane (considering the axis of the instrument is in upright position) and equidistance about it's axis and master ball.



Out put of three sensors are transformed into the orthogonal coordinate system by means of sophisticate software. These data are recorded as measured data. Furthermore, these data can be transformed in to axial, radial and tangential directions by means of the software. The setup of the R-test instrument is illustrated in Fig.5.

**3. Measuring principle of new device**

When these instruments used in measuring the simultaneous three-axis motion, the ball-bar has to be rearranged to its sensitive direction. Meanwhile, R-test instrument can be used in one setup as depicted in Figs.4 and 5. But it has some drawbacks: data transformation is needed, high tendency to breakage, professional person is needed to handle the unit, and high cost. There fore, a new

device was designed to avoid all these drawbacks.

This instrument consists of three probes which set in such a way that the axis of each probe represents the orthogonal coordinate axis as shown in Fig. 7. The instrument is named as 3D-probe. The probe head was selected as flat surface to reduce the setting errors as illustrated in Fig.8. 3D-probe can be used in two ways. It can be applied to spindle if the X, Y and Z direction deviations are needed or can be applied to table if axial, radial and tangential direction deviations are needed. Therefore complex coordinate transformation is not necessary.

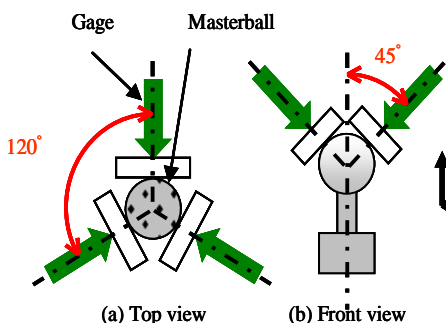


Fig. 6 Schematic view of R-test probe

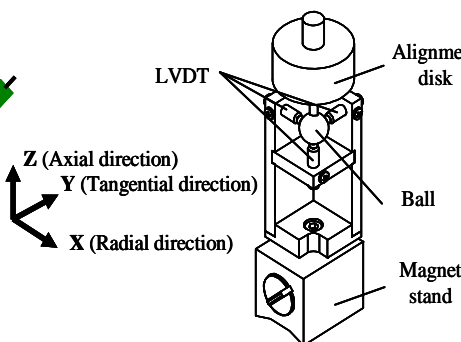


Fig. 7 Outline of developed 3-D probe

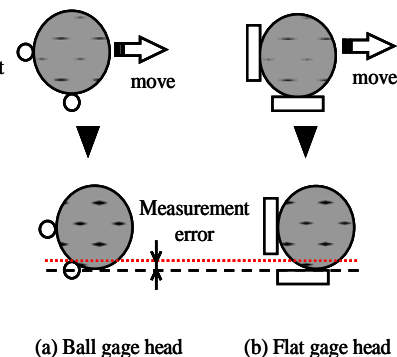


Fig. 8 Effect of flat stylus

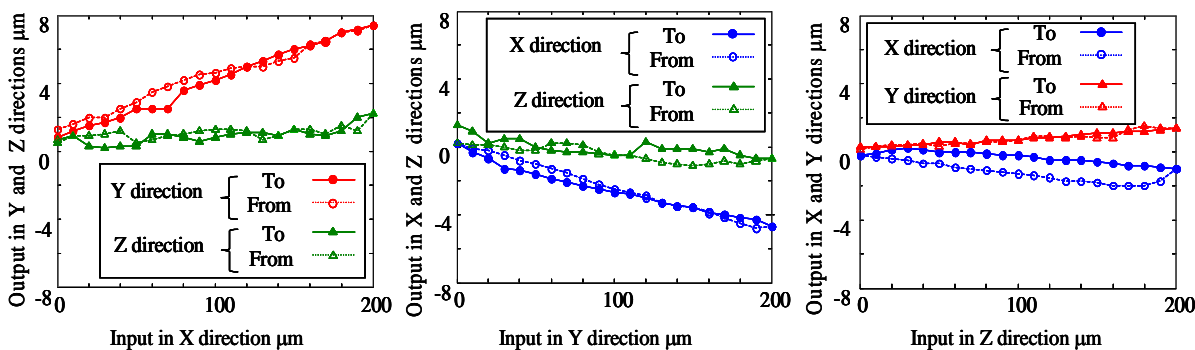


Fig. 9 Effect of parallelism error



## 4. Experiments

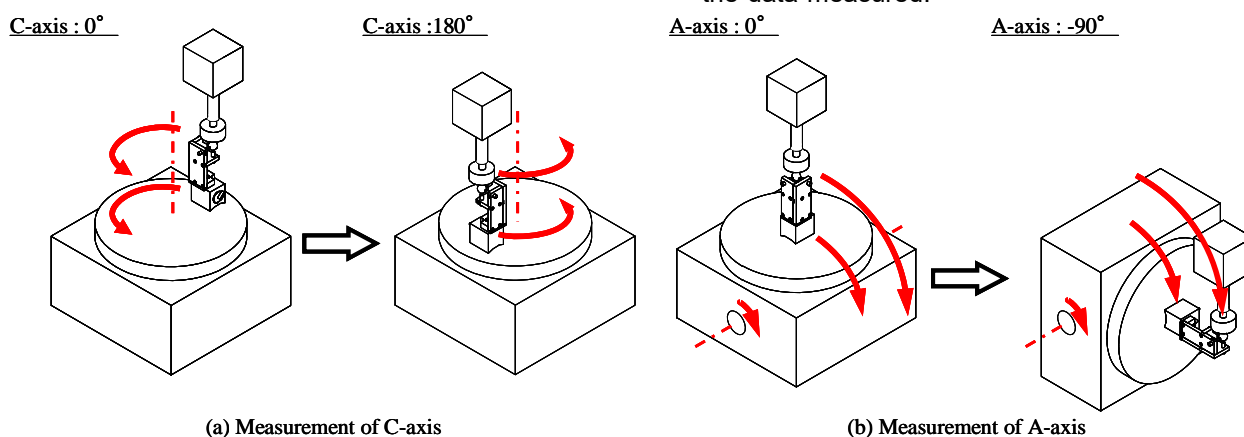
### 4.1 Influence of probe parallelism on Measurements

The flatness error of probe head, assembly error of 3D-probe and installation error of instrument may cause parallelism error between direction of probes of 3D-probe and machine coordinate system and thus affect to the measurements. To identify the effect of parallelism on measurements the one axis was moved  $200\mu\text{m}$  back and forth at  $10\mu\text{m}$  steps and measurements were taken in two directions. The results are given in Fig. 9.

As shown in Fig.9, measured deviations in X, Y and Z directions are almost

proportional to the input displacement. In the developed 3D probe instrument, as shown in Fig.9, the maximum displacement is  $6\mu\text{m}$  at  $200\mu\text{m}$  input. This means that the mutual interference is approximately 3% or less.

To correct the interference, it is necessary to perform the same experiment as above prior to the real measurement. Based on the measurement, the parallelism error between the sensitive direction of the probe and the linear motion direction are evaluated. Then the measurement errors are cancelled by the appropriate coordinate transformation based on the data measured.



**Fig.10** Measurement by means of 3D-Probe designed for centering the master ball and the ball used in ball bar instrument. The procedure is as follows.

### 4.2 Measurement about the C-axis

Measurements about C-axis were carried out by using ball bar, R-test and 3D probe instruments to compare the results and evaluate the 3D probe instrument. In this measurement the master ball was fixed on the spindle and the 3D probe was fixed on the table. Before starting the measurements the center of the master ball was coincided with the axis of rotation of spindle by means of the alignment disk which was specially

First, move the master ball until the 3D probe readings changed. Second, adjust the master ball on the 3D probe until the probe readings of the X and Y axes equal to zero by the jog feed. Next, record the amount of change of 3D probe readings



after rotating the spindle  $180^\circ$ , manually. Adjust the amount of change of the 3D probe readings until the readings are halved by adjusting the set screws. Repeat this procedure until the 3D probe readings do not change significantly when the spindle is rotated. The disk is adjusted such that the fluctuation of readings is within  $2\mu\text{m}$ .

After the eccentricity error is cancelled, move the master ball to the start position of the simultaneous three-axis motion by jog feed. Then, align the center point of the master ball and 3D-probe. Finally, conduct the measurements with the 3D-probe. For comparison, the measurements with the ball bar and the R-test are also conducted under the same measurement conditions.

The movement shown in Fig.10 (a) is required in the case of motion about the C -axis. Similarly, the movement shown in Fig.10 (b) is required in the case of motion around the A - axis. In this paper, the radius of circular motion is 50 mm and the rotational velocity is 720 deg/min for easy comparison with the ball bar.

#### 4.2.1 Comparison of trajectories of C-axis

The measured trajectories of the simultaneous three-axis motion which include the C -axis are shown in Figs. 11 to 13. These results are displayed by  $1\mu\text{m}$  per division for the axial and radial directions and by  $2\mu\text{m}$  per division for the tangential direction. Figs.11,12 and 13 shows the results of the 3D-probe, ball-bar, and R-test instruments respectively.

As shown in Figs. 11 to 13, the shape of trajectories coincides with the results measured by different instruments. For example, in the axial direction, the shape is ellipsoidal and two steps can be seen around  $0^\circ$  and  $180^\circ$ . It is supposed that these steps are caused by the reversal motion of the X-axis. In the radial direction, large quadrant glitches, which are prominent errors, are observed at the reversal points of the linear axes at  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$  and  $270^\circ$ . In addition, the motion trajectory in the tangential direction takes a large glitch near  $225^\circ$ . This is due to that the worm gear used for the rotary table is worn. It can be

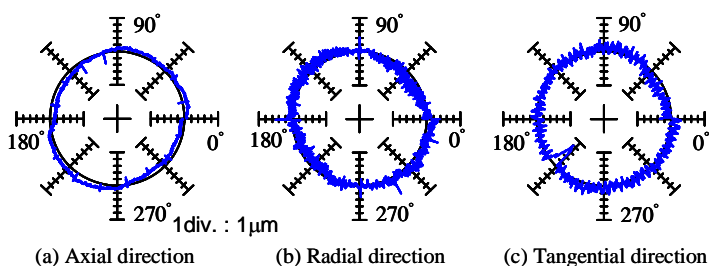


Fig. 11 Circular trajectories of 3D-Probe

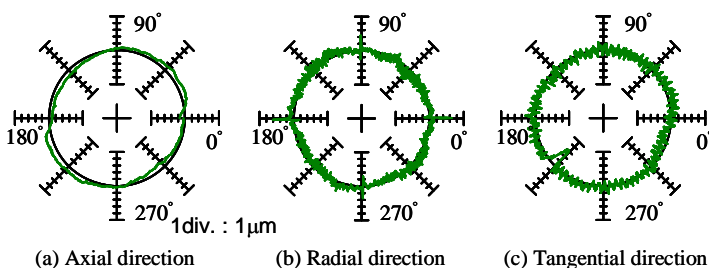
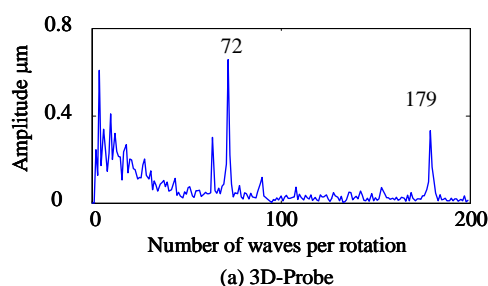
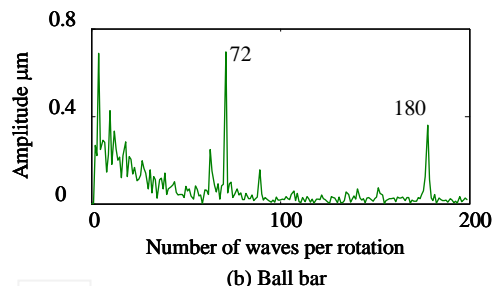


Fig. 12 Circular trajectories of Ball bar



(a) 3D-Probe



(b) Ball bar

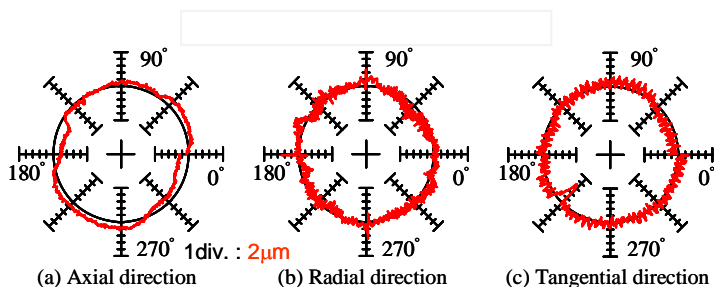


Fig. 13 Circular trajectories of R-test

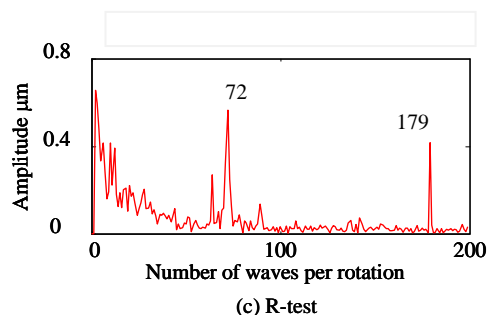


Fig. 14 Frequency analysis of tangential direction

said from these results that the machine characteristics are correctly grasped. If all shapes of the measured trajectories are considered, the motion trajectory of the 3D-probe coincides well with the motion trajectory of the R-test. However, the motion trajectory of the 3D-probe does not coincide as well with the motion trajectory of the ball-bar. The reason for this difference between the 3D-probe and ball-bar is the difference of the circular trajectory radius between the table side ball and the spindle side ball for the reference length of the ball-bar itself.

**4.2.2 Comparison of frequency components of C-axis**

Motion trajectories of the tangential direction are analyzed for frequency components because the characteristics of the rotary table are often grasped in these trajectories. The components are shown in Fig. 14. The horizontal axis is the number of peaks during a single rotation of the rotary table. The vertical axis is the amplitude of vibration. The component of 72 peaks is observed in Fig. 14. The pitch error of the rotary table is correctly observed because the number of 72 peaks coincides with the number of teeth in the worm gear integrated in the mechanism of the rotary table.

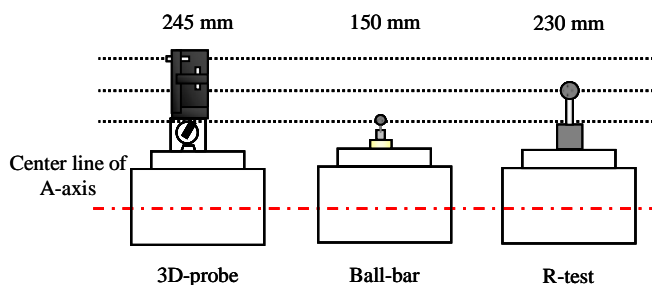


Fig. 15 Differences of radius in A-axis motion

In comparing the results corresponding to each instrument, same frequency components are observed.

**4.3 Measurement about A-axis**

As same in C-axis, the measurements were carried out about A-axis by using three types of instruments. As shown in Fig. 15, the radius of circular motion about A-axis is different in each instrument because the distance between the axis rotation of the A-axis and the center of the master ball is different in each instrument. The feed speed is 1000 mm/min on each circular path of the spindle side.

**4.3.1 Comparison of trajectories of A-axis**

Measured trajectories of the A-axis are shown in Figs.16, 17 and 18. These figures show the results measured by the 3D-probe, ball-bar and R-test, respectively, and the scale of the circular plots is expressed by 2 μm per division for the axial and radial directions, and by 5 μm per



division for the tangential direction. It can be seen from Figs. 16 and 18 that

vibration amplitude is affected by the motion radius.

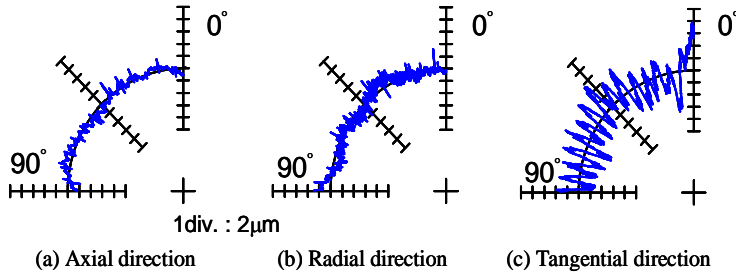


Fig. 16 Circular trajectories of 3D-Probe

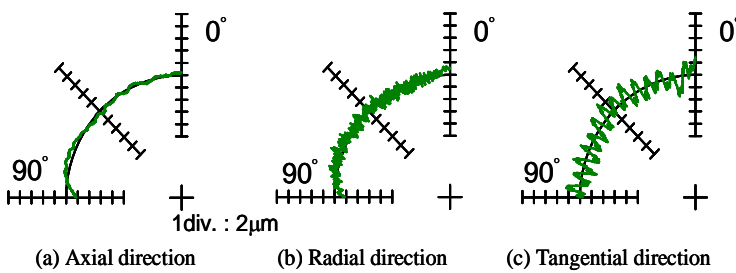
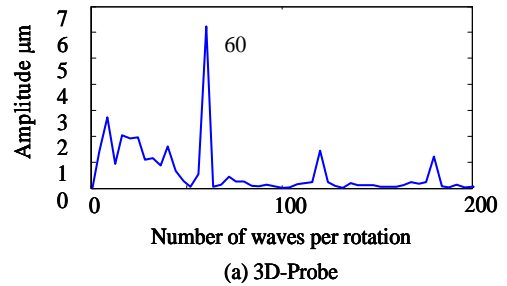


Fig. 17 Circular trajectories of Ball bar

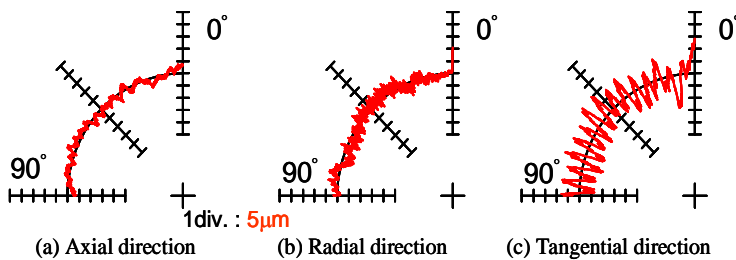
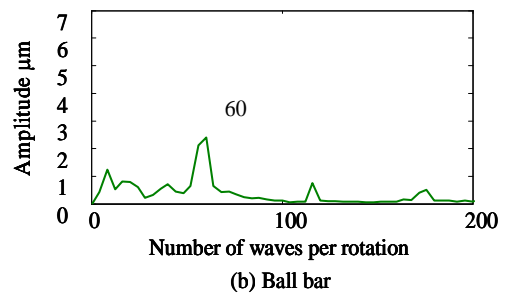


Fig. 18 Circular trajectories of R-test

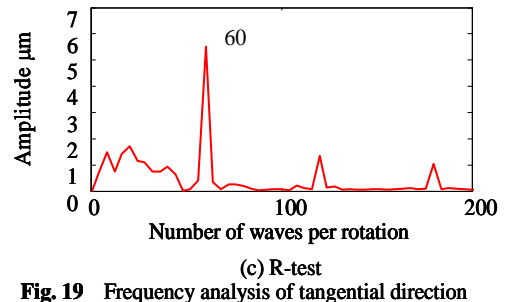


Fig. 19 Frequency analysis of tangential direction

these motion trajectories measured by the 3-D probe and R-test are corresponding well. In the point of view of the vibration amplitude, the two instruments give the same results in every direction. However, the results of the ball bar are different from the results of the other two instruments. Particularly, the vibration amplitude in the tangential direction as shown in Fig.17 (c) is smaller than that of the other two instruments. Thus, the vibration amplitude and the circular motion radius for each instrument are compared. As shown in Table 1, it is found that the

#### 4.3.2 Comparison of frequency components of A-axis

As in the C-axis direction, the motion trajectories of the tangential direction are analyzed for the frequency components. The results are shown in Fig. 19. Vibration components of 60 peaks are observed in the figure. This is due to the pitch error of the tilting axis.



Table 1 Comparing oscillation amplitude

	3D-probe	Ball-bar	R-test
radius [mm]	245	150	230
Ratio of radius compared to ball-bar	1.69	1	1.54
amplitude [mm]	8.6	5.1	7.9
Ratio of amplitude compared to ball-bar	1.63	1	1.53

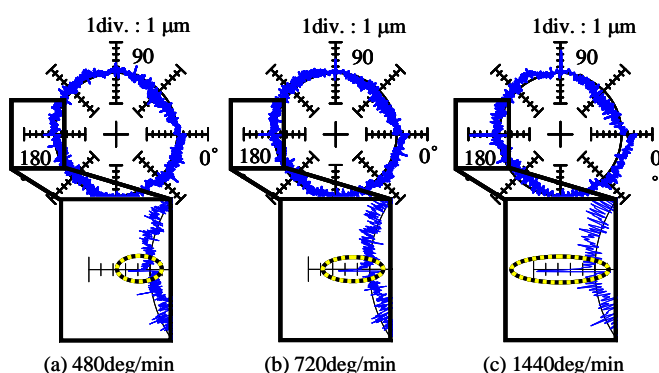


Fig.20 Influence by changing feed rate

#### 4.4 Influence of changing the feed speed

To investigate how feed speed fluctuation affects the motion trajectory, measurements are conducted at three rotational speeds: 480, 720 and 1440 deg/min. Fig. 20 shows the enlarged view of the trajectories around  $180^\circ$ . It can be seen that the height of the quadrant glitches increases with the increasing rotational speed. This change of the quadrant glitch height is due to the X and Y axes.

#### 7. Conclusion

This paper proposed a new instrument for accuracy measurements of multi-axis machining centers. In addition, reasonability of 3D-probe is evaluated throughout comparing ball-bar and R-test. As the results, following conclusions were obtained

- 1) Same information about machine characteristics are shown in motion trajectories measured by means of 3D-probe, ball-bar and R-test.
- 2) Characteristics of frequency components in motion trajectories measured by each measurement instruments coincide.
- 3) The new instrument 3D probe can be used for accuracy measurements of multi-axis machining centers.

#### 7. References

##### 7.1 Article in Journals

- [1] J.B. Bryan, A simple method for testing measuring machines and machine tools: Part 1: Principles and applications, Precision Engineering, Vol.4, No.2(1982),pp:61-69.
- [2] Kenji Higashiyama, K.M. Muditha Dassanayake, Masaomi Tsutsumi, Ken Yamamoto, Identification of geometric deviations based on simultaneous five-axis machining center with a tilting rotary table, Transactions of Japan Society of Mechanical Engineering, Vol73, No.736(2007), pp:3309-3315.
- [3] S. Weikert, W. Knapp, R-Test: a new device for accuracy measurements on five-axis machine tools, Annals of the CIRP, Vol.53(2004), pp:429-432.
- [4] M. Tsutsumi, A. Saito, Identification and compensation of systematic deviations particular to 5-axis machining centers, International Journal of Machine Tools & Manufacturing, Vol.43(2003), pp:771-780.