DEVELOPMENT AND MANUFACTURING OF A MEASUREMENT APPARATUS FOR NC MACHINE TOOLS DIAGNOSIS BY DOUBLE SHAFT-HOLE BAR (DSB) METHOD

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Abstract

Manufacturing industries rely mostly on machine tools. Product quality produced by these industries depends on machine tools quality used to machine the product. In order to determine the machine tools quality, measurement must be conducted by using measurement apparatus. One of the apparatus is DBB (double ball bar) system. Unfortunately, the price of commercial DBB is quite expensive. To solve the problem, a new measurement apparatus based on Double Shaft-Hole Bar (DSB) method has been developed. The new design uses two precision shaft-hole pairs, instead of two high precision balls, connected by an extension bar. The design resembles ISO 230-1 basic design with some modifications, according to developing countries manufacturing capability. Data acquisition for the measurement system consists of 1μm accuracy LVDT as a position sensor, amplifier, 14 Bit ADC and personal computer. The measurement apparatus capability is measured by comparing apple-to-apple with Renishaw® ball bar system. The results show that an accuracy of 5 μm can be reached in CCW direction. While, in CW direction the accuracy is about 22 μm, due to mechanical clamping system stability, which needs further study. The system, apart from the computer, can be manufactured with a budget less than USD 1,500.

Keywords: Accuracy, Circular interpolation, Renishaw® ball bar system, Shaft-hole bar

Introduction

Machine tools are machines used to manufacture products from raw materials. High quality products can only be manufactured by high accuracy and high precision machine tools. In this case, high accuracy refers to process repeatability while precision refers to conformity degree to its exact value. Therefore, high quality machine tools must not only be precise, where it can produce product's dimensions closed to its design dimensions, but it must be accurate as well, where it can produce following products with similar dimensions. In year 2000, Taniguchi categorized manufacturing process as "precision" when the process could reach precision less than 10μm and "high precision" when less than 1μm [1].

Machine tools quality can be determined by conducting certain testing, such as: geometric accuracy testing, chatter testing, power testing, cutting test, etc. In the geometric accuracy testing, laser interferometer is powerful apparatus for measuring single axis, especially in measuring positioning accuracy. However, when more than one axis moving simultaneously (interpolation) must be measured, then circular interpolation measurement apparatus must be used. A popular apparatus for measuring circular interpolation is DBB (Double Ball Bar).

The DBB measurement is simpler than measurement using laser interferometer. Furthermore, its price is about one-third, compared to laser interferometer. Nevertheless, the price is still unaffordable, especially by many machine tools builder in developing countries. Based on that condition, this research is aimed to develop an affordable price measurement apparatus whose function is similar to DBB, without too much sacrificing the accuracy.

Review on Previously Existing Measurement Apparatus Design

Several apparatus have been developed to measure the circle interpolation, and the most common one is developed by Bryan [2-4], as shown in Figure 1.

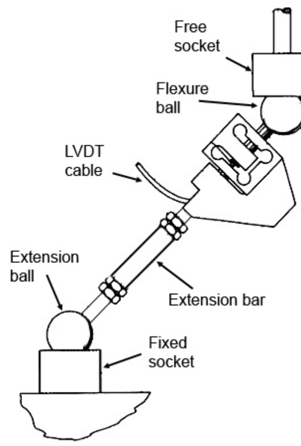

Figure 1. The measurement apparatus developed by J. B. Bryan, USA [2-4]

This design uses two precision balls with two magnetic sockets connected by an extension bar, and it is called Magnetic Ball Bar (MBB). Kakino, et. al. [5], further developed the Bryan design by using moiré scale instead of LVDT as well as diagnosis methodology for interpreting the results. The design, which is popularly called DBB (Double Ball Bar), is now widely used commercially, such as by Renishaw® and Heidenhain®. Another design is developed by Pahk, H. J. [6], which uses two precision balls, one bar and one sleeve-post (hole-shaft) pair, as shown in Figure 2.

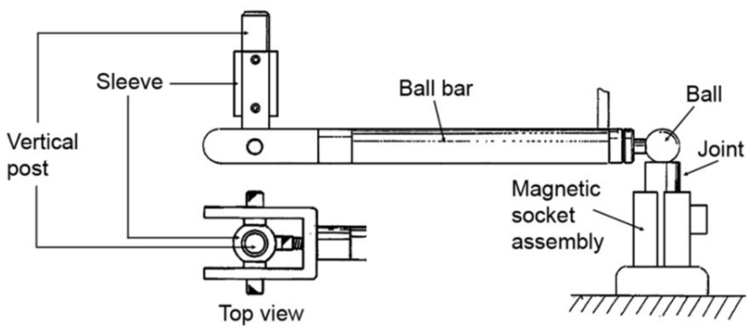

Figure 2. The measurement apparatus patented by H. J. Pahk, South Korea [6]

The previous designs are particularly utilized for measuring a circular path. Iwai, H. and Mitsui, K. [7], developed a measurement apparatus which can be used for arbitrary path, such as square as well as circular path. The design consisted of links and rotary encoders, as shown in Figure 3.

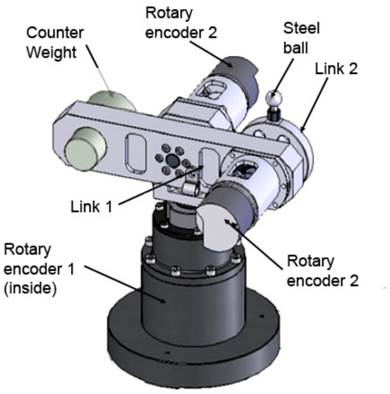

Figure 3. Measurement apparatus developed by H. Iwai and K. Mitsui, Japan [7]

All previous designs use high precision ball which is relatively difficult to manufacture, especially in developing countries. There is another design, which is proposed by ISO 230-1 Standard [8], as shown in Figure 4.

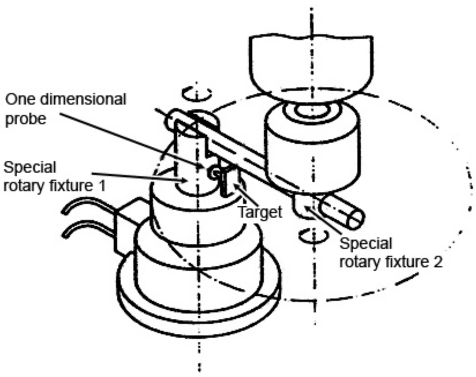

Figure 4. Design proposed by ISO 230-1 standard [8]

New Measurement Apparatus Design

Basic Design of the Measurement Apparatus

After reviewing several measurement apparatus design, the ISO 230-1 design is selected because it uses two pairs of shaft-hole instead of ball. Precision shaft and hole are easier to manufacture than precision ball, especially in developing countries. The new design used in this research is shown Figure 5.

The design uses two pairs of precision shaft-hole and an extension bar. Upper shaft-hole is connected to machine tools spindle while the lower one is put on machine tools table.

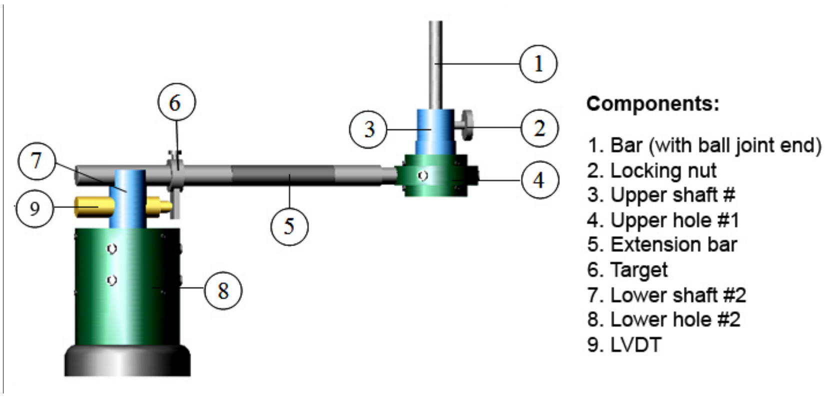

Figure 5. Basic design of the measurement apparatus

One end of the extension bar is fixed-connected to the upper hole, while another one is laid on the guiding-way which is precisely cut on lower shaft so the bar can slide freely during measurement. With this configuration, the design can be used to measure not only in horizontal plane but also in vertical one. Component number 1 is a bar with a ball joint end which is inserted into hollow upper shaft #1, therefore the extension bar is allowed to have some degree of angular freedom. When installing the extension bar to the upper ring, another end of the bar should be pushed against the guiding way on the lower shaft in order to ensure the perpendicularity between extension bar axis and shaft axis.

The new measurement apparatus is designed for the following specification:

a) Measurement Range = 0 - 2 mm.
b) Resolution = 1 µm.
c) Accuracy = 5 µm.
d) Bar Length = 200 mm.

Detailed Design of the Measurement Apparatus

The Shaft and hole are main components manufactured with high precision (< 3µm) and equipped with system to compensate machining imperfections. The machining imperfections compensating system consists of three point supports, two fixed point supports and another one is floating point support as shown in Figure 6.

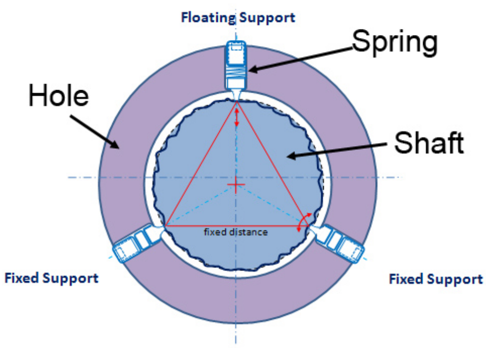

Figure 6. Three point contact supports, two fixed and one floating

The floating point support will keep the shaft contacting the other two fixed supports. By this configuration, it is possible to compensate shaft center position at every angular position of the shaft.

Data Acquisition System

Data acquisition system of the measurement apparatus consists of:

a) LVDT as a position sensor with 1 µm resolution and 2 mm measurement range.
b) Amplifier for signal amplification from the position sensor (mV order) into signal which can be read by ADC (5 Volt, 20mA).
c) Analog to Digital Converter (ADC) for converting analog signal from the sensor into digital signal which can be read by computer.
d) Personal Computer or Notebook for collecting and analyzing data.

Design Analysis of the Measurement Apparatus

Error Budget

Error budgets for the measurement apparatus are as follow:

a) Total measurement system accuracy specification = 5 µm
b) Mechanical components accuracy specification = 3µm
c) Data acquisition system accuracy specification = 3µm.

If point b) and c) interaction results in accuracy higher than 5µm then a software compensation technique is required to keep the total system accuracy to less than 5 µm.

Extension Bar Deformation due to its Own Weight

Analysis of extension bar deformations due to its own weight is conducted by using Finite Element Analysis Software, and the result is shown in Figure 7.

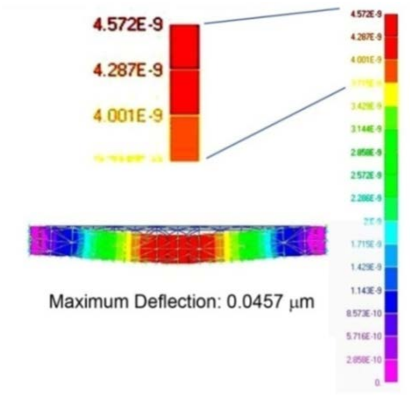

Figure 7. FEM analysis of the extension bar deflection due to its own weight

Extension Bar Expansion due to Temperature Change

Analysis of the extension bar expansion due to temperature change during measurement is conducted by using Finite Element Analysis Software, and the result is shown in Figure 8.

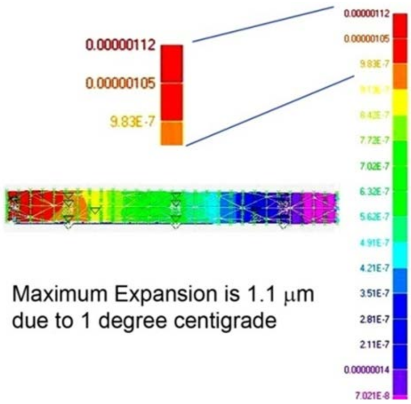

Figure 8. FEM analysis of the extension bar expansion due to 1°C temperature change

It is shown that every 1°C temperature change will result in 1.1 µm expansion of the guiding bar. Maximum temperature change permitted during measurement is 3°C therefore the expansion is still within measurement system tolerance.

Manufacturing Error Simulation (Compensation Technique)

Manufacturing error of main components (shaft-hole) is simulated by using Matlab® Software. Data for the simulation are as follow:

a) Roundness tolerance : 3 µm
b) Number of wave (waviness) : 5 peaks
c) Surface Roughness : Rz 1µm.

Those errors are shown in Figure 9.

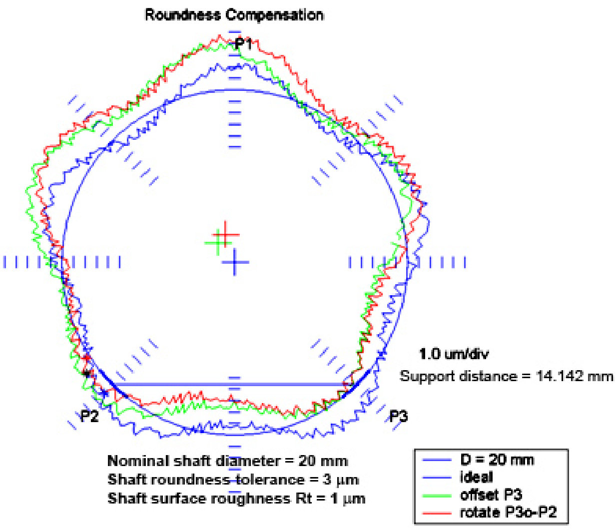

Figure 9. Manufacturing error of main component (shaft-hole) simulation

With those errors, dispersion of shaft center position when it turns 360°, can be calculated and the result is shown in Figure 10.

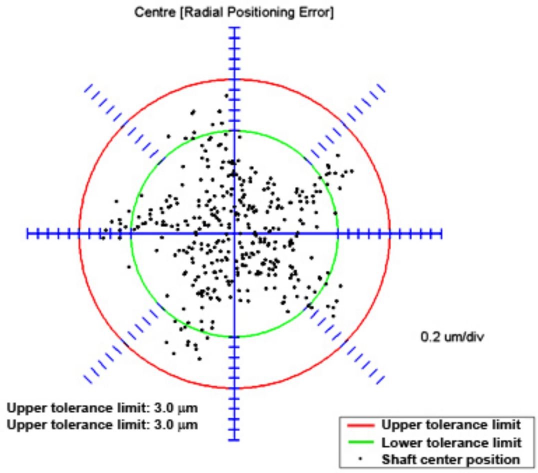

Figure 10. Manufacturing error of main component (shaft-hole) simulation

Measurement Apparatus Manufacturing

Manufacturing process of the measurement apparatus is conducted following process:

a) Turning
b) Heat Treatment
c) Grinding
d) Polishing
e) Accuracy Measurement

Firstly, all components are manufactured by turning process until reaching the desired dimensions. After that, both upper and lower shaft are heat treated before grinding process. Their hardness values are between 50 HRc - 52 HRc. Grinding process is conducted on the previously heat treated shaft in order to reach its designed accuracy (20h2) with tight tolerance of 0 - 2 µm. Grinding wheel with grain size of 100 mesh is used in this process. Spindle speed is 2400 rpm and chuck speed is 100 rpm.

After grinding, then both shafts are polished to reach surface quality of N3 (Rz 1µm). This process is conducted by using turning machine with 2800 rpm spindle rotation. The polishing process is conducted by rubbing shaft with abrasive contained cloth. In this case, Autosol metal polish number 1000 is used for the abrasive.

After manufacturing processes, then roundness accuracy and cylindricality are measured by using CMM (Coordinate Measuring Machine). The measurement results are:

a) Roundness = 1 µm - 4 µm
b) Cylindricality = 1 µm - 3 µm.

Surface roughness after polishing then is measured by Roughness Tester (Hommel Tester T1000). The measurement result is: Ra: 0.08 µm - 0.10 µm (Rz : 0.68 µm - 0.86 µm).

Shaft-Hole Pair Calibration

This calibration is needed to measure shaft roundness, and conducted as follow:

- Shaft is put inside its mating hole/ring.
- LVDT is inserted into available hole.
- While rotating the shaft relative to the fixed hole/ring, position data sensed by the LVDT are recorded.

— The measurement is conducted on both upper shaft-hole pair (#2) and lower shaft-hole pair (#4).
— Another measurement is also conducted to measure drift due to machine tools vibration. In this case, the measurement is conducted while the shaft does not rotate.

Lower Shaft-Hole (#2) Calibration

The calibration setup is shown in Figure 11.

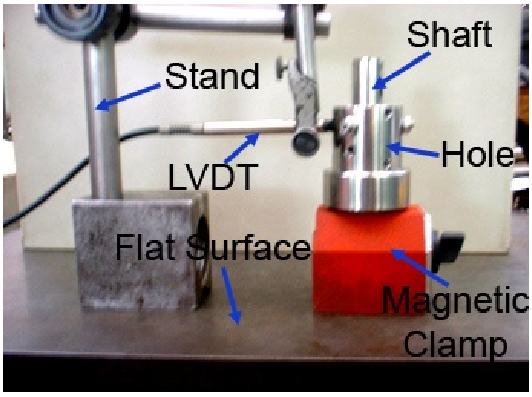

Figure 11. Lower shaft-hole (#2) calibration setup

Figure 12 shows corresponding calibration result.

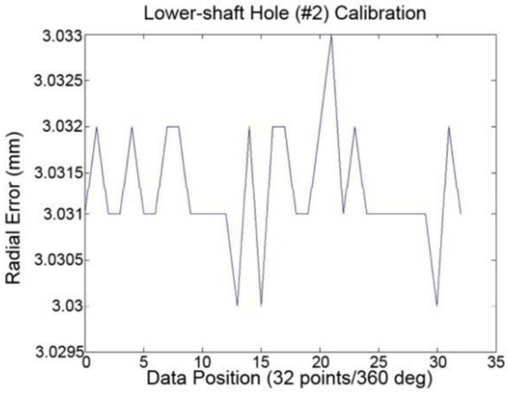

Figure 12. Lower shaft-hole (#2) calibration result

Figure 12 shows that lower shaft-hole (#2) roundness is 3 µm.

With similar setup, the upper shaft-hole (#1) roundness as well as its drift are measured, and the results are as follow:

a) Upper shaft-hole (#1) roundness = 4µm
b) Drift error = 5µm

LVDT System Calibration

This calibration is conducted to determine data acquisition system accuracy compared to reference within its measurement range. The calibration setup is shown in Figure 13.

Calibration is conducted by using precision micrometer with 1µm resolution. The calibration results are as follow:

a) ADC/DAC accuracy is better (l < 5µm) when its input voltage is positive.

b) LVDT will give minimum readout error when stylus position is at around 3 mm. Therefore before conducting measurement, zero position of the stylus is set at 3 mm.

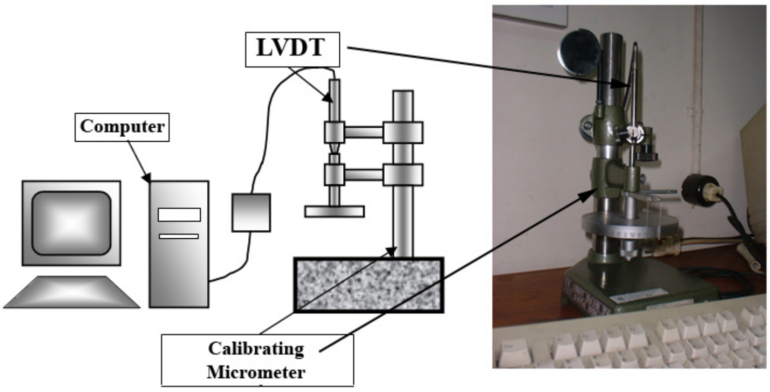

Figure 13. LVDT system calibration setup

Total System Calibration

Finally, total measurement system accuracy is calibrated by comparing, apple-to-apple, to a commercial ball bar system. In this case, Renishaw® ball bar system is used as a reference. The reference specifications are as follow:

- Bar Length =100 mm (between ball center)
- Resolution = 0.1 µm
- Meas. Range = ± 1 mm
- System Accuracy = ± 1.0 µm (at 20°C)
- Sampling rate = 250 data/sec. (maximum)

Testing object is machine tools CNC MAHO MH 500W, located in Production Engineering Laboratory, Programme Study of Mechanical Engineering, ITB, Bandung.

The calibration process is conducted by measuring the testing object (Machine Tools CNC Milling type Maho MH500W) with Renishaw® ball bar system. After that the same measurement is conducted with the new measurement apparatus developed in this research.

The diagnosis software for the measurement apparatus is still being developed. In order to conduct apple-to-apple comparison, data from the new measurement apparatus system will be diagnosed by using Renishaw® software too. Therefore, the data must be formerly formatted according to Renishaw® software data structure format.

The measurement result measured by the Renishaw® ball bar system is shown in Figure 14. Figure 15 shows the measurement result measured by the developed measurement apparatus.

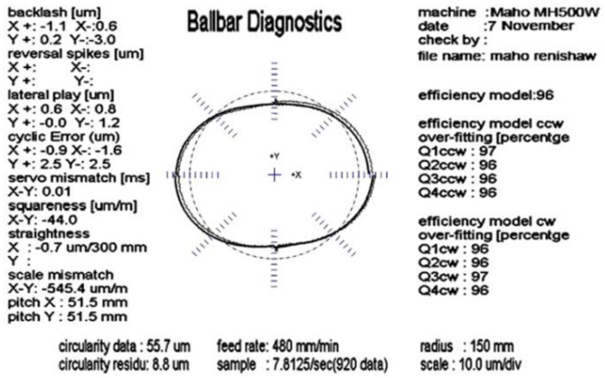

Figure 14. Measurement data measured by the Renishaw® ball bar system

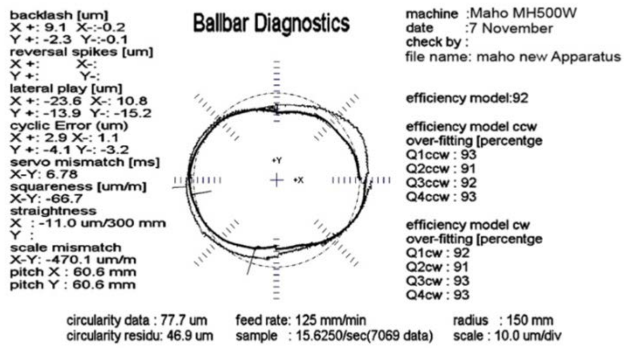

Figure 15. Measurement data measured by the developed measurement apparatus

The apple-to-apple comparison results are as follow:

a) Both patterns in CCW direction are similar
b) In CW direction, the pattern is deviated about 20 μm compared to the Renishaw® ball bar system data.
c) Backlash and cyclic error data differences are < 5 μm
d) Lateral play data difference is 23 μm
e) Perpendicularity and circularity data differences are around 22 μm

When analysis is conducted only in CCW direction then all data differences will fall within 5μm. From the results, it is found that there is still a problem concerning mechanical clamping stability during shaft rotation, especially in the CW direction.

This apparatus resolution is still far away from 0.1 μm, needed by recent machine tools. Further research will be focused on increasing shaft roundness and cylindricality to less than 1 μm, utilization of 0.1 μm LVDT resolution and 16 bit ADC.

Conclusions

In this research, a measurement apparatus prototype for NC machine tools condition diagnosis by Double Shaft-Hole Bar (DSB) method has been developed. In this research, a new development has been made, that is two precision center made of two high precise shafts each with three supports, instead of two high precision balls used in commercial ballbar.

The measurement apparatus uses a LVDT whose resolution of 0.1 μm and measurement range of 4 mm, as a position sensor. As a data acquisition system, a 14 bit ADC card has been used.

With this measurement apparatus, an accuracy of 4 - 5 μm has been reached in CCW direction and 22 μm in CW direction. This CW direction problem is probably due to mechanical clamping system stability, which needs further study.

The new measurement apparatus can be manufactured with a budget less than USD1,500 (without computer). It is about 5% compared to the commercial ball system price.

Next research will be focused on achieving 1 μm resolution by improving shaft roundness and cylindricality to less than 0.1 μm, utilizing 0.1 μm LVDT resolution and 16 bit ADC.

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