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DEVELOPMENT OF THE AXIAL PRECISION INSPECTION SYSTEM FOR SPINDLES IN TOOL GRINDERS

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Abstract: Because of the rapid development of precision machinery, the demands on the dimensional precision of cutting tools have much increased. In the investigation, a rotary axis measurement system with laser diodes and Position Sensitive Device (PSD) has been proposed. The parallel deviation between the spindle axis and correlated linear axis of the machine can be measured by the developed system. With the aid of this system, error of the rotation axis during installation or operation can be reduced Measurement results of the spindle axis with Y-axis have demonstrated that horizontal angle error is 5.557 arc-seconds and the vertical angle error comes to -19.961 arc-seconds.
Keywords: tool grinder, linear axis, rotation axis, parallel error

INTRODUCTION

In comparison with other machine tools, the tool grinder is more complex and requires higher precision and reliability. The grinding of a tool grinder is performed by the wheel spindle and tool-holder axis. Details regarding the tool design and grinding method can be found in [1-3]. Hence the installation of rotation axis will determine the grinding precision and the inspection of the rotation axis is the key factor. Currently dial gauges inspection with master gauges is employed for the measurement such that error of the master gauge will affect the measurement results and the correction for machines is not ideal. That will lead to the incorrect geometrical dimensions during the grinding of tools.

Castro [4] estimated the error analysis method for the rotation axis of machine tool with aid of laser interferometer, i.e. with HP laser interferometer and a laser diode module for inspecting the rotation error of a lathe where the standard reflector sphere was hold on the rotating body and actuation error of the standard reflector sphere was measured by Laser beam combined with a convergent lens. The speed data of the spindle were acquired by Laser diode system. The results indicated that during the increment of the spindle speed the radial error the rotation axis decreased from 1.49μm to1.08μm and the axial error increased from 0.30μm to 0.87μm.

Prashanth [5] proposed that the radial error of machining with the high-speed spindle was able to be detected by Doppler axial measurements method. By the mutually perpendicular laser beam to irradiate on the sphere and infrared sensor to capture the rotation angle of the spindle, the measured data after analysis revealed that the spindle will generate axial and radial error as the speed increased.

Wen-Yuh Jywe [6] developed an optical measuring device for detecting rotary axis error by a master gauges set up in the rotation axis of machine tool and a mirror fixed on the top of master gauge. With the reflection principles of optics, the displacement and angular error of rotation axis can be measured by the laser beams and the corresponding detectors.

In this study, the laser beam has been arranged on the rotation axis and laser optical axis can be regarded as the rotary axis by the optimal adjustments of the fixture. With the integration of PSD and LabVIEW software, the parallelism inspection system for the rotary axis of the spindle can be developed and the parallelism error of the spindle axis will be improved.

FUNDAMENTAL THEORY

Errors of rotation axis

With the development of multi-axis machine tool, the error of rotation axis must be considered, because this error will affect the whole accuracy of the machine. The error inspection items of conventional rotation axis include radial error, axial error, tilt error and positioning error, according to the specification ISO230-7 case C-axis, as shown in Figure 1.

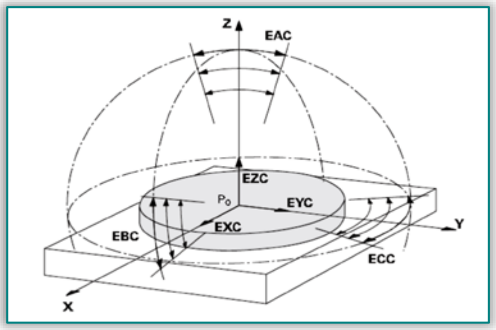

Figure 1 – Scheme of errors in C rotation axis [4]

In the experimental tool grinder, spindle has been installed on the linear axis (Y-axis). The tool grinding wheel is fixed on the spindle shown in Figure 2.

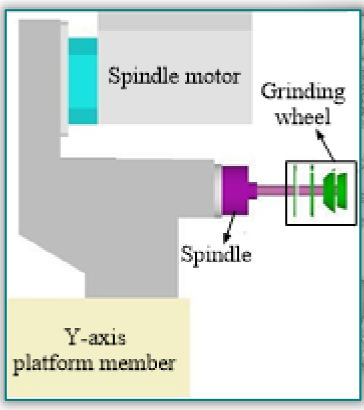

Figure 2 – Wheel installed on spindle

If there is the tilt error in the spindle, the error EAB and the ECB in the spindle and the wheel will appear. That will directly result in the grinding position deviation of the wheel such that the machining precision will be reduced, as shown in Figure 3 and Figure 4.

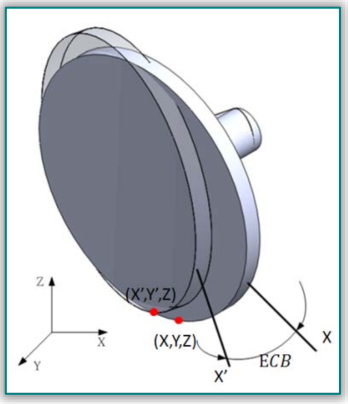

Figure 3 – ECB error

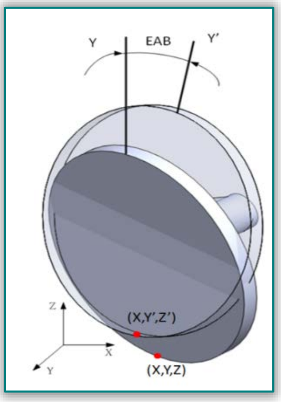

Figure 4 – EAB error

Position sensitive device

Position Sensitive Device (PSD) is based on the photoelectric effect to detect the position drift on a linear axis or a plane. It is a new type of semiconductor position sensitive detector, in addition to the photodiode array and positioning performance of the CCD, but also with the features of high sensitivity, high resolution, fast response and the uncomplicated circuit configuration. In this investigation, two-dimensional PSD has been employed to measure the displacements by detecting the position change of the laser beam installed on the rotation axis when the dynamic rotation took place.

Operational amplifier

Operational Amplifier (OPA) serves as a high-gain voltage amplifier with DC-coupled differential input and single-ended output. Generally it is used for addition and subtraction and other analog arithmetic circuit by an operational amplifier and its output will be connected to its inverted input terminal and a negative feedback configuration can be formed. In this study, the combination of an operational amplifier has been employed by an operational amplifier circuit and serves as the offset signal of the amplifying medium PSD, as shown in Figure 5.

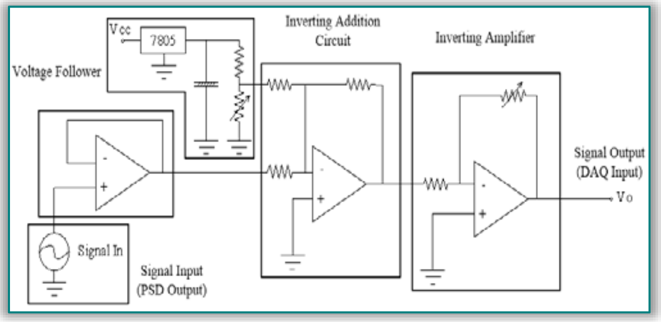

Figure 5 – Circuit of signal amplification

CONSTRUCTION OF SYSTEM

The spindle has been installed the parallel movement of the linear axis (Y-axis), as shown in Figure 2.This research is used parallelism measurement system for the spindle axis, the parallelism measurement system for the spindle axis will directly impact the geometry error of the tool. This research used the laser characteristics of the higher scheduling and collimated, and used the PSD to measurement the distance of the linear axis (Y-axis) to measure the angle error. The angle error can be summarized as shown in Figure 6.

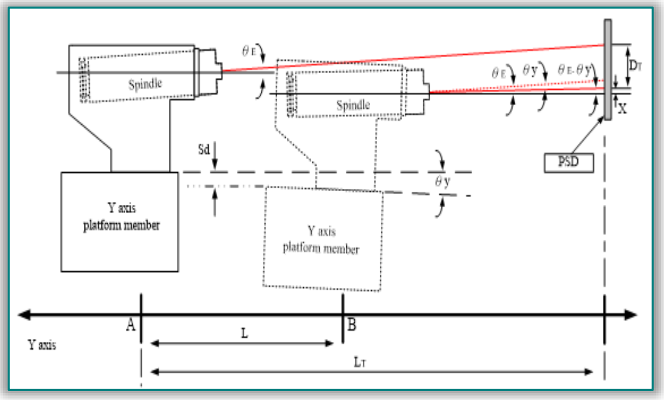

Figure 6 – Angle error analysis (The mechanical side view - vertical error)

The core of all the questions was spindle assembling precision, hence the measurement rotation axis system was used laser diode module, and PSD was installed the laser beam front end, the PSD measurement system can be explained by the parallel angle of the spindle axis and the Y-axis. Trigonometric functions of error angle can be expressed as follows:

$$\tan\theta_E = \frac{D_T+X}{L_T} \Rightarrow X = L_T \times \tan\theta_E - D_T \qquad (1)$$

where θ_E is the parallel angle of the spindle axis and the Y-axis, L_T is the distance between the leaser source and the PSD, D_T is the PSD traveling distance, X is the PSD measured displacement to calculate θ_E formula.

The Y-axis platform member from point A to point B, hence the Y-axis assembling precision will directly impact the PSD measurement results. Trigonometric functions of error angle can be expressed as follows:

$$\tan(\theta_E-\theta_y) = \frac{Sd+X}{L_T-L} \Rightarrow \left(\frac{\tan\theta_E-\tan\theta_y}{1+\tan\theta_E\times\tan\theta_y}\right) = \frac{Sd+X}{L_T-L} \qquad (2)$$

Where θ_y is the Y-axis pitch angle or yaw angle, Sd is the Y-axis horizontal straightness and the vertical straightness, L is the Y-axis traveling distance.

The PSD measure displacement (X) of the continuity equation can be expressed as follows:

$$\left(\frac{\tan\theta_E-\tan\theta_y}{1+\tan\theta_E\times\tan\theta_y}\right) = \frac{Sd+L_T\times\tan\theta_E-D_T}{L_T-L} \qquad (3)$$

Expansion formula (3) can be expressed as follows:

$$\left(L_T\times\tan\theta_y\times(\tan\theta_E)^2\right)+\left(L\text{-}(D_T\text{-}Sd)\times\tan\theta_y\right)$$
$$\times\tan\theta_E+(L_T\text{-}L)\times\tan\theta_y\text{-}D_T+Sd=0 \qquad (4)$$

The parallel angle of the spindle axis and the Y-axis are solved used quadratic equation. The error angle can be expressed as follows:

$$\tan\theta_E = \frac{-B\pm\sqrt{B^2-4AC}}{2A} \qquad (5)$$

The parallel angle of the spindle axis and the Y-axis (θ_E) are solved used A、B and C.

$$A = L_T\times\tan\theta_y$$
$$B = L-(D_T\text{-}Sd)\times\tan\theta_y \qquad (6)$$
$$C = (L_T-L)\times\tan\theta_y\text{-}D_T+Sd$$

Fixture design

Details of the fixture for Laser beam include a laser diode module and the adjustment of the angle and position, the structure shown in Figure 7.

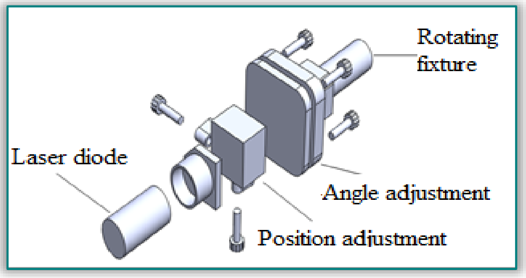

Figure 7 – Fixture construction of laser beam

Because the laser diode module arranged on the rotation axis will create angle α and displacement S shown in Figure 8, the arrangement error α (shown in Figure 9) can be determined with the position change induced by the arrangement. And the error can be eliminated by adjusting the angle and the position of the fixture.

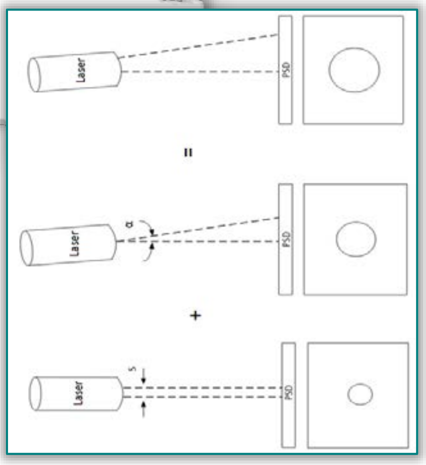

Figure 8 – Install error of the fixture

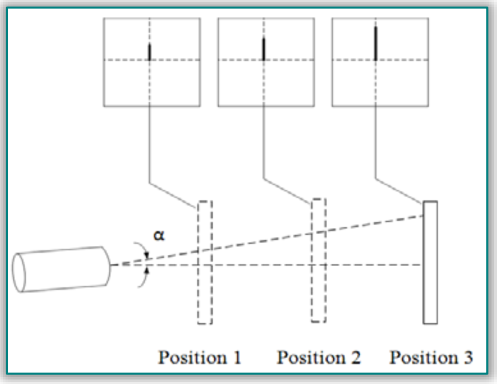

Figure 9 – PSD single change cause by arrangement error of laser beam

The position sensor fixtures will hold a PSD and is installed on the precision platform, the structure shown in Figure 10.

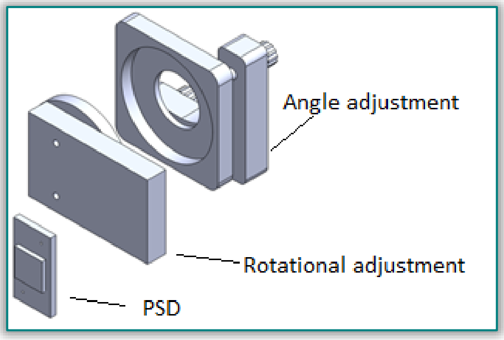

Figure 10 – The fixture structure of the position sensor

PSD fixture must be orthogonal with laser beam, because installation will develop the angle αi and angle βi, shown in Figure 11.The quadrature error can be eliminated by adjusting the angle and rotation of the fixture.

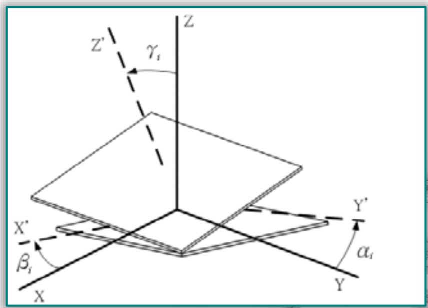

Figure 11 – Arrangement errors of the fixture for the position sensor

Development of measurement program

The LabVIEW software was used to develop the parallelism inspection system for the rotary axis of the spindle, the PSD to receiving laser beam and the light spot centroid position converted into a voltage value, use DAQ signal acquisition card, a voltage signal acquisition to computer to calculates and stores data, its signal the processing flow shown in Figure 12.

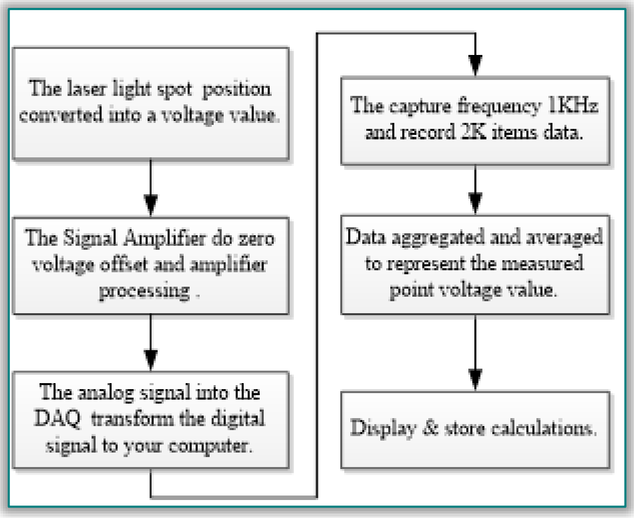

Figure 12 – Signal processing of PSD

Systematic measurement

After system correction, inspection parallelism error between laser source and Y-axis, spindle rotation to each 30 point measurement, and moving the Y-axis machine position from 0mm to -200mm position to observe the PSD measured value, calculate the parallelism error between laser source and Y-axis.The measurement process shown in Figure 13.

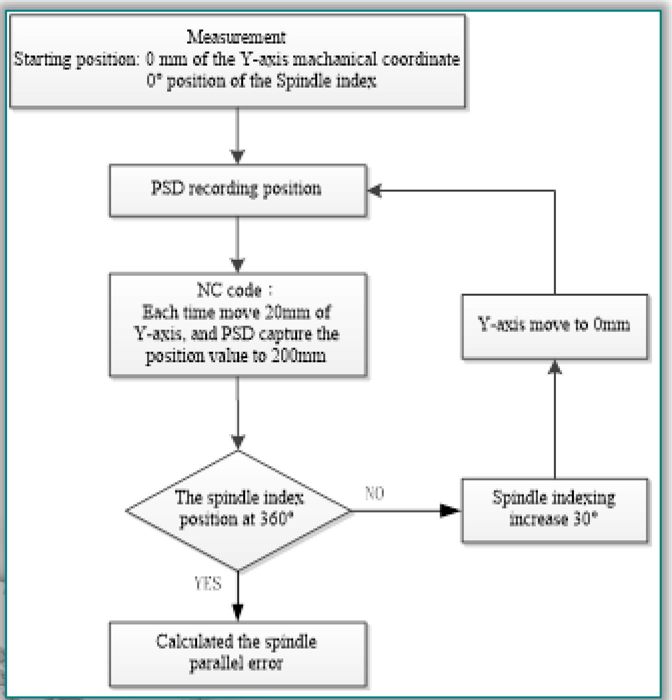

Figure 13 – Measurement processes for parallelism of Spindle

RESULTS AND DISCUSSION

By adjustment fixture of laser beam and PSD, angle and displacement offset can be regulated. If laser beam is coincident with the spindle axis, the measurement data result from the conical geometry of laser beam and the corresponding position coordinates of Y-axis which will form a circular cross, as shown in Figure 14.

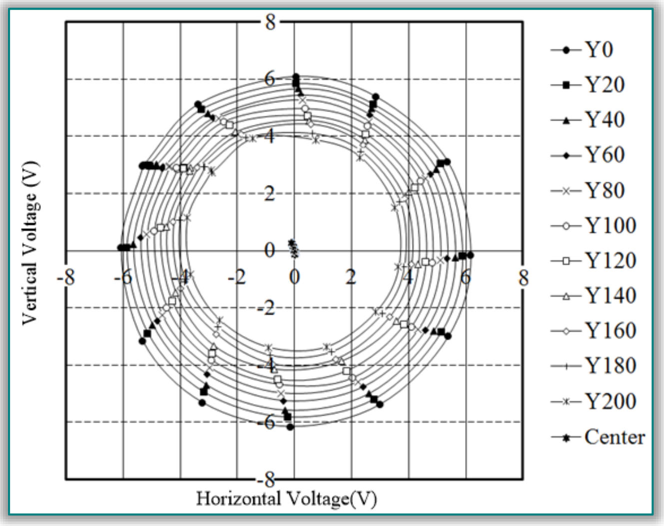

Figure 14 – Measurement results of the PSD

The application of Renishaw laser interferometer will perform measurements of angle error and straightness errors in the Y-axis. After error compensation, the displacement of the spindle axis is expressed as Figure 15.

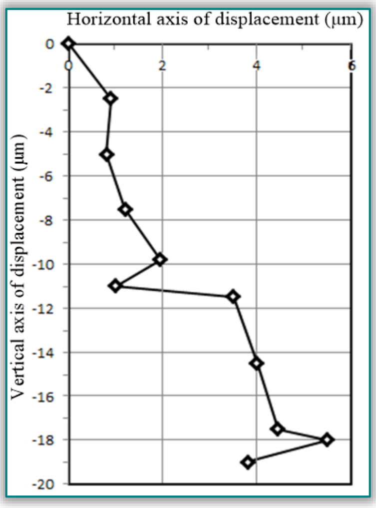

Figure 15 – Displacement of the spindle axis

Measurement results

By the measured data of the axis displacement in horizontal and vertical direction and position coordinates of each point in Y-axis, the horizontal and vertical error curve can be described. With the fitting equations, angle errors can be calculated as shown in Figure 16 and Figure 17, Table 1. It reveals that the average value of horizontal angle is 5.557 arc-seconds and that of vertical angle -19.961 arc-seconds, while measurements have been repeated 10 times.

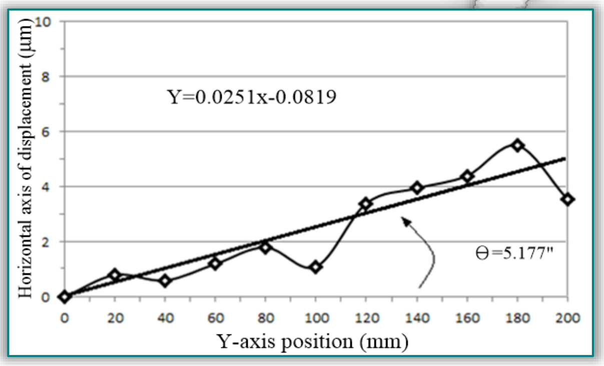

Figure 16 – Error curve of Horizontal position

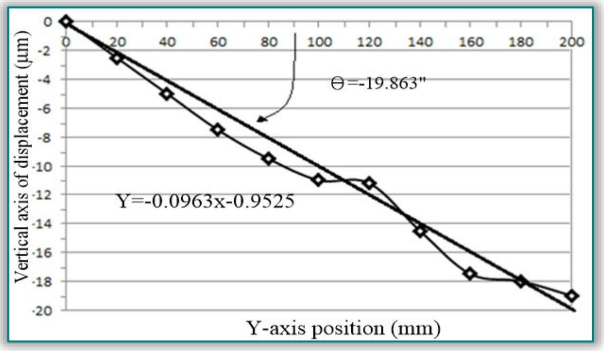

Figure 17 – Error curve of Vertical position

Table 1 – Measurement results

NO.	Horizontal angle (arc-seconds)	Vertical angle (arc-seconds)
1	5.177	-19.863
2	5.878	-20.379
3	5.094	-20.317
4	5.981	-20.007
5	5.734	-20.193
6	5.647	-19.716
7	5.358	-19.161
8	5.552	-20.644
9	5.896	-20.281
10	5.252	-19.039
Average value	5.557	-19.961
Standard deviation	0.322	0.526

Validation results

Measurement results resulting from the parallelism measurement system of spindle axis and the master gauges have been shown in Table 2.

Table 2 – Parallelism verification of the spindle axis

Angle error / System	Horizontal angle (arc-seconds)	Vertical angle (arc-seconds)
Master gauges	5.761	-4.839
Laser system	5.557	-19.961

The error of the horizontal angle of master gauge is 5.761 arc-second that of the vertical angle 4.839 arc-second. Experimental analysis demonstrated that the straightness error of master gauges is 5μm and roundness error 6μm. The total resultant error will contribute to 11μm. In measuring range of 160mm, the angle error of master gauges is 14.184 '' and the measurement results is close to result measured by this system 15.122"as shown in Figure 18.

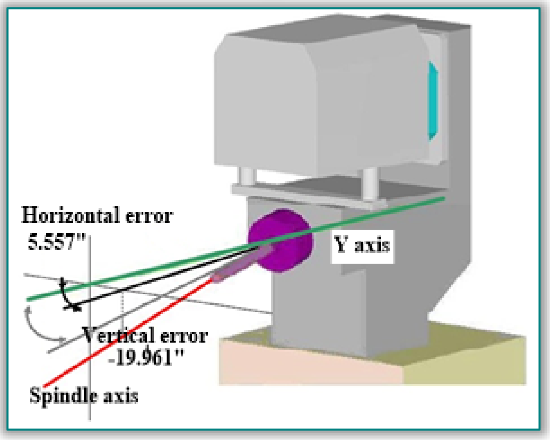

Figure 18 – Parallel state of spindle axis

Horizontal angle is adjustable by fixing screw during assembling procedure and hence the error can be corrected as shown in Figure 19. The error of vertical angle can be compensated by scraping technology. Therefore an error measurement result of the vertical angle is larger and parallelism between the spindle axis and Y-axis of the machine can be realized by the measurement results.

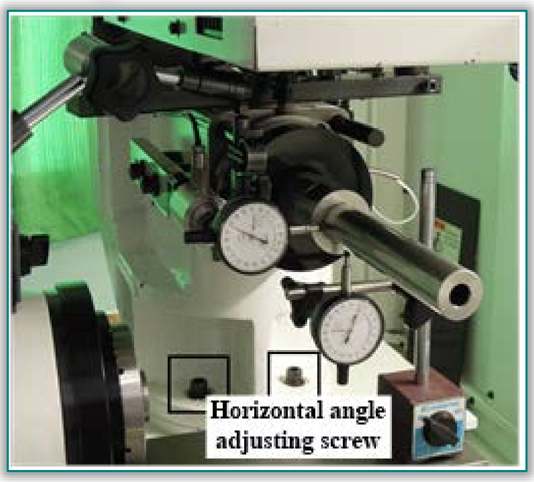

Figure 19 – Adjustment screw
for horizontal angles of Spindle

CONCLUSION

This research of parallelism measurement system for the spindle axis can be summarized by two points:

- The horizontal angle deviation between the spindle axis and Y-axis is 5.557 arc-seconds, the vertical angle deviation -19.961 arc-seconds.
- This difference between the system and master gauge value is 15.122”. Because the master gauges exists the error of 14.184"at length 160mm, this difference subtracts the error of master gauge is only 0.938".
- It reveals that the use of the laser beam visualizing the linear axis integrated with PSD is available for error measurements of parallel axis.

Note

This paper is based on the paper presented at The International Conference Management of Technology – Step to Sustainable Production (MOTSP 2016), organized by the Faculty of Mechanical Engineering and Naval Architecture, Croatian Association for PLM and the University of North, in Porec/Parenzo, Istria, CROATIA, June 01–03, 2016.

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