Application Notes **AP-1116**

Calibration of a 5-axis machine by volumetric positioning and tool tip positioning measurement

I. What is the problem

For a 5-axis machine tool it is very important to calibrate both the volumetric positioning (X, Y, Z) and the two rotational axes, A and B or A and C. Using a laser interferometer to calibrate the 3 linear axes and the 2 rotational axes separately and independent of each other is not enough. There are straightness errors for each of the 3 linear axes, and squareness errors between the 3 linear axes, skew, Non-orthogonal and non-intersection of the 2 rotational axes, and the non-intersection of the center lines of the spindle and the z-axis. Hence it is important to measure the volumetric positioning (X, Y, Z) by the laser vector method and the tool tip positioning (A, B, and R) by the tool tip positioning measurement.

II. How to solve this problem

First, using the laser vector method [1] to calibrate and compensate the volumetric positioning errors including the 3 displacement errors, 6 straightness errors and 3 squareness errors. Second, using the non-contact laser spindle tester [2] to measure the tool tip displacement errors at various rotational angles. This measurement can be used to calibrate or to compensate the angular errors of the 2 rotational axes. Finally, to measure the tool tip positioning errors dynamically at various tool paths and geometries.

III. How it works

The laser vector method is described in Ap-1109 and the spindle tester is described in Ap-1114. After calibrating and compensating the volumetric positioning accuracy by the laser vector method, mount the spindle tester with a precision sphere to the spindle and mount the laser head at position 2 as shown in Fig. 1. Align the laser beam with a focus lens to be focused at and perpendicular to the surface of the precision sphere as shown in Fig. 2. Move the 5 axes such that the center of the tool tip, represented by the center of the precision sphere, is at a fixed position. Measuring the changes of the tool tip positions due to various movements, the angular errors of A and B at various angles can be determined.

IV. Positioning of a 5-axis machine

The machine coordinate is defined as (Xm, Ym, Zm, A, B).
The center of rotation of A and B is defined as (Xp, Yp, Zp).
The tool tip position is defined as (Xt, Yt, Zt).
The relations

$$Xp = Xm + Cx,$$
$$Yp = Ym + Cy,$$
$$Zp = Zm + Cz,$$

where Cx, Cy, and Cz are constants.

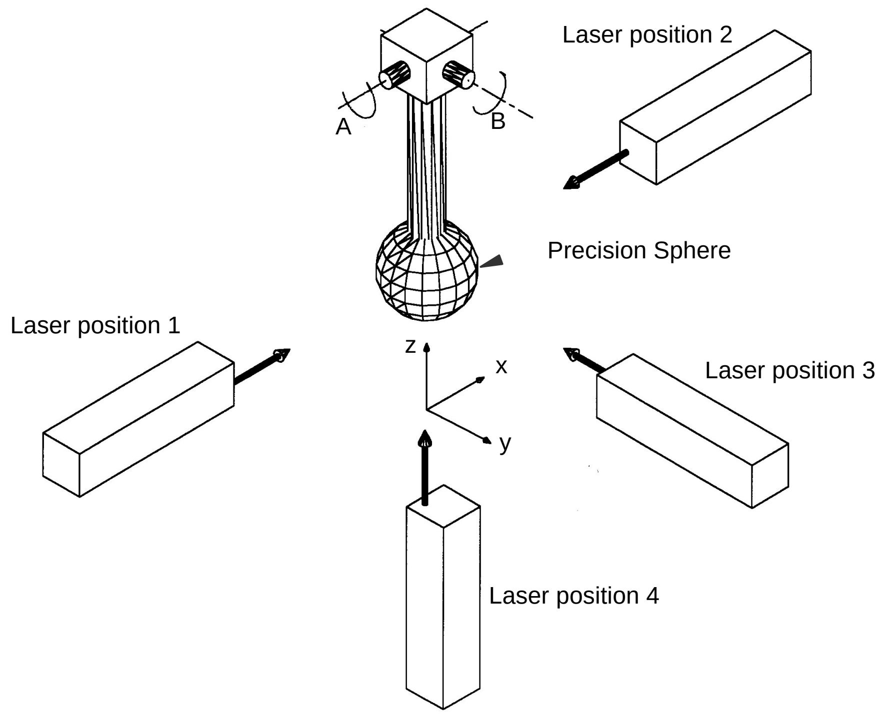

Fig. 1, Schematics of a 5-axis spindle with a precision sphere and laser positions

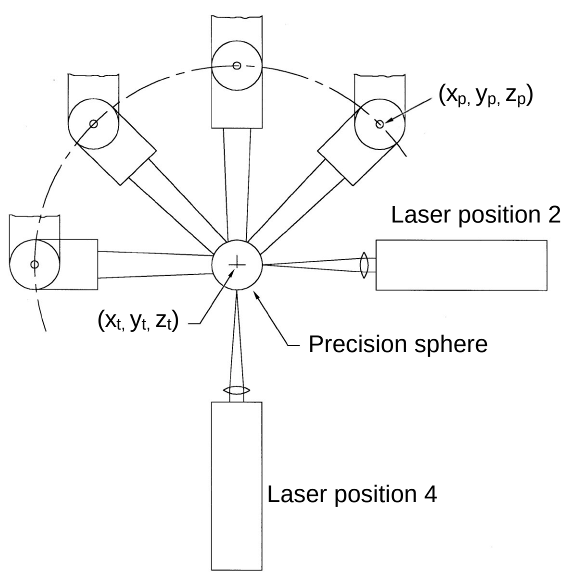

Fig. 2, Schematics of a 5-axis motion with the center of the precision sphere at a fixed position

$$Xt = Xp + R\sin B\cos A,$$
$$Yt = Yp + R\cos B\sin A,$$
$$Zt = Zp + R\cos A\cos B,$$

Where R is the distance between center of rotation and the tool tip.

V. Calibrate A-axis angular accuracy

Mount the laser head at position 2 as shown in Fig. 2.
Starting position is at $Yp = Zp = A = B = 0$,
Move A-axis with 5 degrees increment while keeping the tool tip position fixed. That is,

$$Yp = -R\sin A$$
$$Zp = -R(1- \cos A), \quad \text{where } A = 0°,5°,10°\ldots..90°.$$

Hence, $dA = -dYp/(R\cos A)$, where dA is the angular error at A degrees and dYp is the measured deviation at A degrees.

A sample parts program is shown in Table 1. The measured deviations in x-direction are shown in fig. 3 and the calculated angular errors are shown in Fig. 4.

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Table 1, A sample parts program moving along a circle and keep the tool tip at a fixed position by rotating A-axis.

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5AXIS SAMPLE PPM
(5-axis,R=15",5-degree linear interpolation)
(up to 90 degrees)
G0 Y0.Z0.
G91 G01 G93 F2.
M00
Y-1.3073Z-0.0571A5.
Y-1.2974Z-0.1708A5.
Y-1.2776Z-0.2832A5.
Y-1.2480Z-0.3935A5.
Y-1.2090Z-0.5008A5.
Y-1.1607Z-0.6042A5.
Y-1.1036Z-0.7031A5.
Y-1.0382Z-0.7966A5.
Y-0.9648Z-0.8841A5.
Y-0.8841Z-0.9648A5.
Y-0.7966Z-1.0382A5.
Y-0.7031Z-1.1036A5.
Y-0.6042Z-1.1607A5.
Y-0.5008Z-1.2090A5.
Y-0.3935Z-1.2480A5.
Y-0.2832Z-1.2776A5.
Y-0.1708Z-1.2974A5.
Y-0.0571Z-1.3073A5.
M30
%
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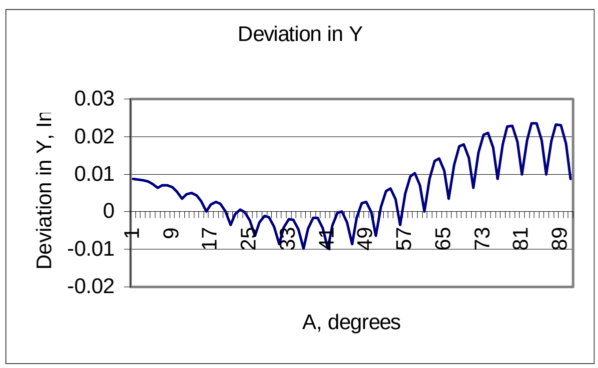

Fig. 3, Measured deviations in Y-direction due to the angular errors

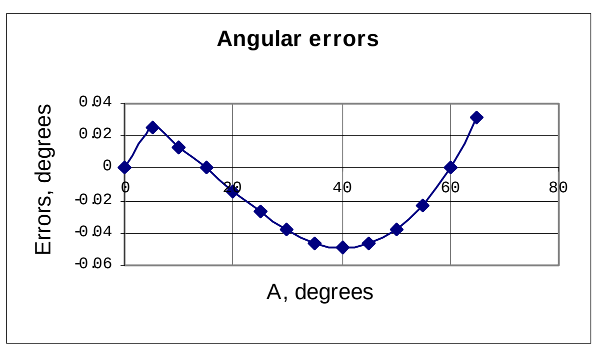

Fig. 4, Angular errors of the rotational-axis.

VI. Dynamic positioning accuracy

To measure the dynamic tool tip positioning errors, continuously move A-axis from 0 to +/-90 degrees back and forth 5 times at B = 0. Repeat the same at B = 30 degrees and 60 degrees. Continuously move B-axis from 0 to +/-90 degrees back and forth 5 times at A = 0. Repeat the same at A = 30 degrees and 60 degrees. For a complete measurement, repeat the above with laser head at positions 1, 2, 3, and 4, and use the 2D time base to collect data continuously.

VII. Measurement errors of tool tip positioning measurement

Laser system errors: 0.000010”
Precision sphere: 0.000025”
Machine positioning: 0.000500”
Lateral coupling: 0.000070” (assume the maximum lateral movement is less than 0.010” and 1.5” diameter sphere).

The largest error is the machine positioning error 0.0005”. Hence any improvement in the machine positioning accuracy will improve the tool tip positioning measurement accuracy.

VIII. References

[1] C. Wang and G. Liotto, “A laser non-contact measurement of static positioning and dynamic contouring accuracy of a CNC machine tool”, Proceedings of the Measurement Science Conference, Los Angeles, CA January 24-25, 2002.

[2] C. Wang, “A new laser non-contact method for the measurement of spindle error motion”, Proceedings of ASPE 2001 Summer Topic Meeting, State College, PA June 18-19, 2001.

IX. Need more information

Call Optodyne at 310-635-7481 or
your local representative.