Measurement of Volumetric Positioning Accuracy of a 5-axis Machine By Laser Vector Technique

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Abstract

For a 5-axis machine tool, the 3D volumetric tool-tip positioning accuracy is very important for parts accuracy and quality assurance. Just calibrate the 3 linear axes and the 2 rotational axes is not enough. There are straightness errors for each of the 3 linear axes, and squareness errors between the 3 linear axes, misalignment errors between the linear axes and the rotary axes. Hence, it is very important to measure the over all positioning accuracy by measuring the tool-tip positioning errors.

Reported here are the measurement of 3D volumetric positioning accuracy by the laser vector method; the measurement of the rotary axes angular accuracy by a dual-beam laser system; and a theoretical analysis on the tool tip positioning accuracy measurement by a single aperture laser system.

The performance of these measurements is relatively simple, fast and straight forward. Its applications in the calibration and compensation of 5-axis machines will improve the parts accuracy and quality without incurring high costs and long machine down time.

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1. Introduction

The world wide competition demands higher machining efficiency and better quality. As 5-axis machine tool is a high added value work machine, it is not only provided with 3 axis of CNC machine but also has 2 rotary axes to produce blade or complex parts. 5-axis is applied in aerospace industries, die manufacturing, and other precision applications. Furthermore, due to the needs for complex components to be machined, the usage of 5-axis machining center has been increasing in recent years. The contouring accuracy or tool-tip positioning accuracy is considered to be one of the most important features especially for machining mold components. For a 5-axis machine tool, just calibrate the 3 linear axes, X, Y, Z and the 2 rotational axes, A and B, or A and C, is not enough. There are vertical and horizontal straightness errors for each of the 3 linear axes, and squareness errors between the 3 linear axes, misalignment errors, such as 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 very important to calibrate and compensate the 3D volumetric positioning errors and the rotational axes angular errors, and to check the over all tool-tip positioning errors.

Reported here are the measurement of 3D volumetric positioning errors by the laser vector method and the rotary axes angular errors by a dual-beam laser system. The theoretical analysis on the over all tool-tip positioning errors measured by a single-aperture laser system and a spherical target are presented.

2. Measurement of 3D volumetric positioning errors

2.1 Basic theory

Based on the rigid body motion assumption, for a 3-axis machine, there are 21 errors, namely 3 displacement errors, 6 straightness errors, 9 angular errors and 3 squareness errors. These 21 rigid body errors can be expressed as the following [1].

Linear displacement errors: $D_x(x)$, $D_y(y)$, and $D_z(z)$
Vertical straightness errors: $D_y(x)$, $D_x(y)$, and $D_x(z)$
Horizontal straightness errors: $D_z(x)$, $D_z(y)$, and $D_y(z)$
Roll angular errors: $A_x(x)$, $A_y(y)$, and $A_z(z)$
Pitch angular errors: $A_y(x)$,$A_x(y)$, and $A_x(z)$
Yaw angular errors: $A_z(x)$, $A_z(y)$, and $A_y(z)$
Squareness errors: $Ø_{xy}$, $Ø_{yz}$, $Ø_{zx}$,
where, D is the linear error, subscript is the error direction and the position coordinate is inside the parenthesis, A is the angular error, subscript is the

axis of rotation and the position coordinate is inside the parenthesis.

2.2 The laser vector measurement technique

In the conventional body diagonal displacement measurement, the target trajectory is a straight line and it is possible to use the corner cube as target [2,3]. The new vector measurement method or *Sequential Diagonal Measurement Method* [4,5] differs from the traditional method because each axis is moved separately and the positioning error is collected after each single movement of the X axis, of the Y axis and than of the Z axis, as shown in Fig. 1. For this reason, 3 times more data is collected and also the positioning error due to each single axis movement can be separated. The collected data can be processed as the projection of the displacement of each single axis along the diagonal. The 12 sets of data can be used to determine the 3D volumetric positioning errors.

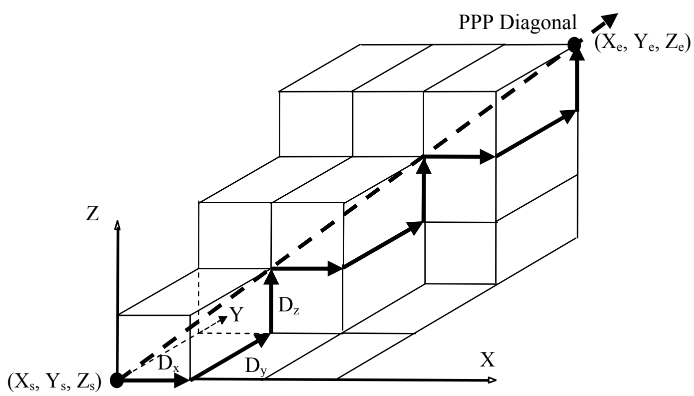

Fig 1, The vector measurement, laser is pointing in the ppp diagonal direction and sequence is moving x-axis, stop, collect data, moving y-axis, stop, collect data, moving z-axis, stop, collect data and continue.

As shown in Fig. 1 the laser is pointing in the positive diagonal direction and the sequence is moving x-axis, stop, collecting data, moving y-axis, stop, collecting data, moving z-axis, stop, collecting data and continue until reached the other corner. Here the laser beam direction and the moving direction are not the same, hence it is not possible to use a conventional laser interferometer. A single aperture laser with a flat-mirror as target is needed.

2.3 Measurement results

Measurement has been performed on a 5-axis horizontal machining center with a working volume of X from 0 to 650 mm, Y from 0 to 500 mm, and Z from 0 to 500 mm. The measured squareness is XY -3.9 arcsec, YZ -7.88 arcsec and ZX -10.03 arcsec. The measured volumetric positioning errors are shown in Fig. 2. Fig. 2a is the displacement errors (top traces), vertical straightness (middle traces) and horizontal straightness (lower traces) errors of X-axis. Fig. 2b is the displacement errors (top traces), vertical straightness (middle traces) and horizontal straightness (lower traces) errors of Y-axis. Fig. 2c is the displacement errors (top traces), vertical straightness (middle traces) and horizontal straightness (lower traces) errors of Z-axis. It is noted that the maximum straightness error is 24 µm which is much larger than the maximum displacement error 6.5 µm. For many other measurement results see Ref. [6].

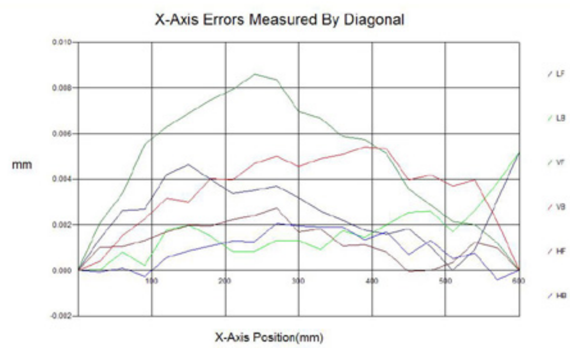

Fig 2a, Measured volumetric positioning errors of X-axis, top traces are displacement errors, middle traces are vertical straightness errors and lower traces are horizontal straightness errors.

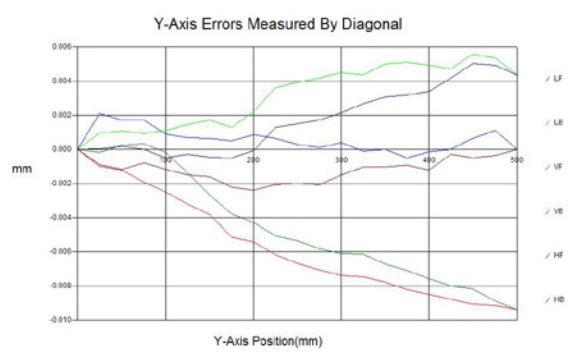

Fig 2b, Measured volumetric positioning errors of Y-axis, top traces are displacement errors, middle traces are vertical straightness errors and lower traces are horizontal straightness errors.

Fig 2c, Measured volumetric positioning errors of Z-axis, top traces are displacement errors, middle traces are vertical straightness errors and lower traces are horizontal straightness errors.

3. Measurement of rotary axis angular errors

3.1 Dual-beam laser head

The LDDM dual-beam laser system can measure both linear displacement and rotational angle of a dual-retroreflector up to +/-10 degrees. With a small motorized turn table shown in Fig. 3, the angular measurement range can be extended to 360 degrees. Hence it can be used to calibrate the rotary axes of a 5-axis machine. Briefly, a dual-reflector is placed on top of a small motorized turn table, which in turn mounted on the center of rotation of one of the rotary axis. The rotary axis is programmed to move in incremental steps of up to 10 degrees. At the end of each step with 5 seconds dwell time, the angular readings will be automatically recorded by the notebook PC. Then the motorized turn table is programmed to rotate in the opposite direction to the starting position and it position recorded. The rotary axis is again rotating the same incremental step with 5 seconds dwell time, the angular readings will be automatically recorded. Continue the same procedure until reached 360 degrees or the maximum angular range of the rotary axis. After the data is collected, the angular errors can be calculated.

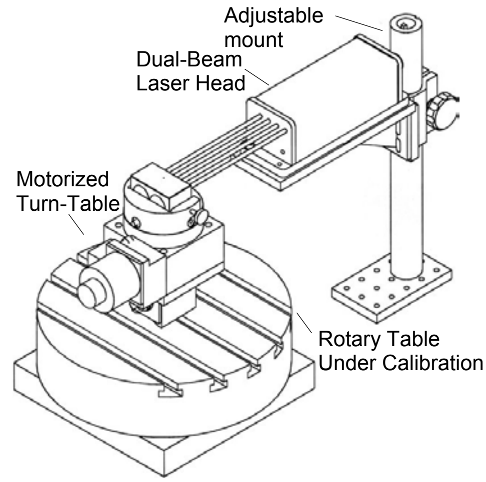

Fig. 3, Schematic of the basic setup with a motorized turntable

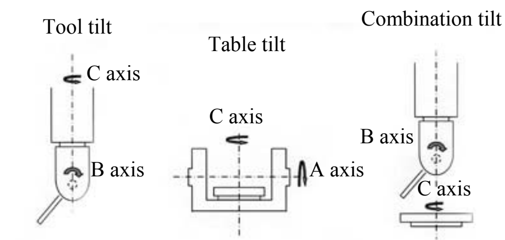

Fig 4, Types of rotary axes of 5-axis machine

3.2. Laser measurement setup

There are many types of 5-axis machines. As shown in Fig. 4, the basic rotary axes are tool tilt, table tilt and combination of both. It is important to mount the dual-retroreflector or the small turn table at the center of rotation of the rotary axis to be measured. In many cases, an accessory such as a L-shaped mounting bracket shown in Fig. 5 is used to mount the small turn-table. The alignment and setup are relatively simple and straightforward.

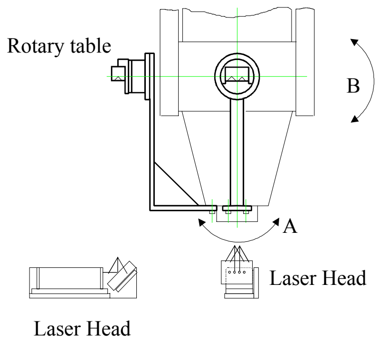

Fig. 5, Setup for the rotary A- and B-axis measurement

3.3 Measurement results

The errors of a C-axis were measured in the cw directions 3 times. The result is shown in Fig. 6. The maximum angular errors are +50 arcsec and -300 arcsec.

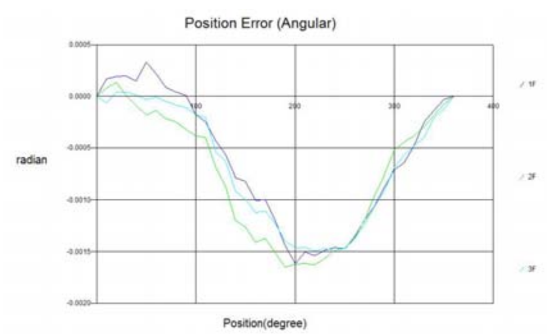

Fig 6, Rotary calibration error plot

4. Theoretical analysis of tool-tip positioning error measurement

4.1 Basic theory

The machine coordinate is defined as (X_m, Y_m, Z_m, A, B).

The center of rotation of A and B is defined as (X_p, Y_p, Z_p).

The tool tip position is defined as (X_t, Y_t, Z_t).

The relations

$$X_p = X_m + C_x,\quad Y_p = Y_m + C_y,\quad Z_p = Z_m + C_z, \tag{1}$$

Where C_x, C_y and C_z are constants.

$$X_t = X_p + R\sin B,\quad Y_t = Y_p + R\sin A,\quad Z_t = Z_p + R\cos A\cos B, \tag{2}$$

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

4.2 Laser measurement setup and operation

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 as shown in Fig. 7. Align the laser beam with a focus lens to be focused at and perpendicular to the surface of the precision sphere. Hence the displacement in XZ of the sphere can be measured by the 2 lasers. Move the 5 axes machine 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.

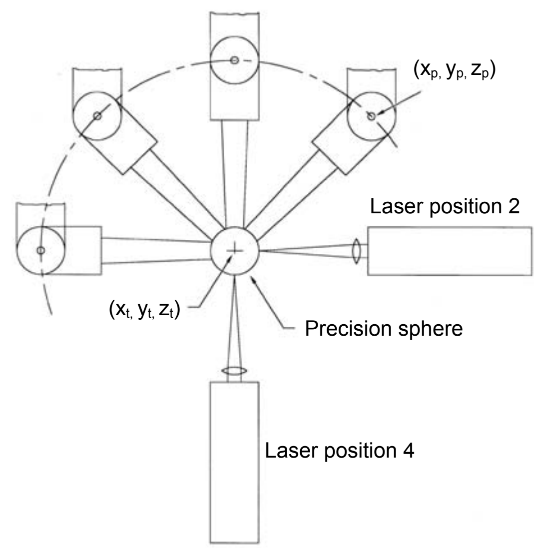

Fig 7, Schematic of a 5-axis motion with the center of the precision sphere at a fixed position

4.3 Error analysis

Starting position is at $X_p = Z_p = A = B = 0$,
Move A-axis with 5 degrees increment while keeping the tool tip position fixed. That is,

$$Y_p = -R\sin A,\quad Z_p = -R(1-\cos A), \text{ where } A = 0^\circ, 5^\circ, 10^\circ \ldots 90^\circ. \tag{3}$$

Hence,

$$dR = -(dX_p*\sin A + dZ_p*\cos A)$$
$$dA = -(dX_p*\cos A - dZ_p*\sin A)/R, \quad (4)$$

where dR is the center of rotation error, dA is the angular error at A degrees, dX_p and dZ_p are the changes of the tool tip position in the X and Z directions respectively. The measured errors DX_p and DZ_p in the direction X and Z respectively can be expressed as,

$$DX_p = dX_p + dZ_p*dZ_p/2r,$$
$$DZ_p = dZ_p + dX_p*dX_p/2r, \quad (5)$$

Where r is the radius of the precision sphere. Substitute the measured DX_p and DZ_p into equations 4 and 5, the dR and dA can be calculated.

Similarly, for the B-axis, pointing the laser in the Y direction and Z direction. dR and dB for the B-axis can be determined.

5. Summary and conclusion

In summary, we have used the laser vector method to calibrate and compensate the 3D volumetric positioning errors. Then, we have used a dual-beam laser system to calibrate and compensate the angular errors of the rotary A and B axes. Finally, the tool-tip positioning errors could be measured by 2 single aperture laser system and a precision sphere target. The measured tool-tip positioning errors could be used to determine the center of rotation and angular errors of the rotary A- and B-axis.

In conclusion. the straightness and squareness errors usually are larger than the displacement errors. Hence just calibrate and compensate the 3 axes displacement errors is not enough. The calibration and compensation of 3D volumetric positioning errors is important to achieve higher parts accuracy. Furthermore, to determine the alignment errors, it is important to check the tool-tip positioning errors.

Figure captions

1. The spindle movement in the vector measurement, here the laser is pointing in the positive diagonal direction and the sequence is moving x-axis, stop, collect data, moving y-axis, stop, collect data, moving z-axis, stop, collect data and continue.
2. Measured volumetric positioning errors, 2a is the displacement errors, vertical straightness and horizontal straightness errors of X-axis, 2b is the displacement errors, vertical straightness and horizontal straightness errors of Y-axis, 2c is the displacement errors, vertical straightness and horizontal straightness errors of Z-axis.
3. Dual-beam laser setup for the measurement of rotary angular errors.
4. Types of rotary axes of a 5-axis machine.
5. Setup for the rotary A- and B-axis measurement.
6. Measured rotary axis angular errors.
7. Schematics of a 5-axis motion with the center of the precision sphere at a fixed position.

References

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