Measurement and Control of 3D volumetric positioning errors with thermal deflections

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Abstract

To manufacture good quality or accurate parts, the measurement and compensation of three dimensional (3D) volumetric positioning errors of machining centers are very important. Also, in a real shop environment and under various spindle loads, the machine thermal expansion may cause additional positioning errors.

Recently, Optodyne has developed a laser vector technique for the measurement of 3D volumetric positioning errors, including linear displacement errors, straightness errors and squareness errors of a milling machine in a very short time. Using this technique combine with the data obtained from a set of thermocouples placed at key locations of the machine tool structure, the correlations between the machine temperature distribution and the 3D positioning errors can be determined. Using the measured position errors, several error maps could be generated. Compensation tables at an actual thermal state can be interpolated to achieve higher accuracy at various thermal loadings.

Reported here are the 3D volumetric positioning errors; the laser vector technique; the measurement of 3D volumetric positioning errors with different thermal loadings and environment temperatures, and some preliminary results.

1. Introduction

For manufacture of high quality parts, machine tool builders are striving to increase machine tool accuracy and productivity by applying various methods covering machine frame design optimization, assembly work improvement, introduction of several cooling systems, etc. Furthermore, in a real machine shop environment and under various spindle loads, the machine thermal expansion may cause large 3D volumetric positioning errors. Hence, to improve the machine positioning accuracy under various thermal loadings, measurement and control of 3D volumetric positioning errors become important. These errors can be properly compensated, provided that the positioning errors and the machine temperature distributions can be measured and their correlation determined.

Twenty years ago, the largest machine tool positioning errors are simply lead screw pitch errors and its thermal expansion. Now, most of the lead screw pitch errors have been reduced by better ball-screw, including internal cooling, or linear encoder and pitch error compensation. Hence, the largest machine tool positioning errors become squareness errors and straightness errors.

Furthermore, the machine temperature changes with the environment, heating of the lead screw, high speed machining, cutting force and coolant, etc., it may cause additional straightness and squareness errors. Using a conventional laser interferometer to measure the straightness and squareness errors are very difficult with complex optics and difficult setups. The equipment is expensive and the measurement time consuming. Furthermore, if the duration of the measurement is too long, the measured positioning errors may vary due to the temperature changes.

Recently, Optodyne has developed a laser vector technique for the measurement of 3D volumetric positioning errors, including 3 linear displacement errors, 6 straightness errors and 3 squareness errors in a very short time [1]. This technique was used for a quick measurement of 3D volumetric positioning errors of a CNC machining center under various spindle loads, machine movement and ambient conditions. Correlation calculations were performed to determine the key temperatures and the various positioning errors. Based on the measured 3D positioning errors and the key temperatures at various thermal loadings, several error maps can be generated. For a particular thermal loading, a linear interpolation can be used to generate a new error map. Hence download these error maps into the CNC controller, the 3D positioning errors can be compensated under various thermal loadings.

2. 3D volumetric positioning errors

For a 3-axis machine, there are 6 errors per axis or a total of 18 errors plus 3 squareness errors [2,3]. These 21 rigid body errors can be expressed as the following.

Linear displacement errors: Dx(x), Dy(y), and Dz(z)

Vertical straightness errors: Dy(x), Dx(y), and Dx(z)

Horizontal straightness errors: Dz(x), Dz(y), and Dy(z)

Roll angular errors: Ax(x), Ay(y), and Az(z)

Pitch angular errors: Ay(x),Ax(y), and Ax(z)

Yaw angular errors: Az(x), Az(y), and Ay(z)

Squareness errors: Øxy, Øyz, Øzx,

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.

The sum of all errors in each axis direction can be expressed as:

$$Dx(x,y,z) = Dx(x) + Dx(y) + Dx(z)$$

$$Dy(x,y,z) = Dy(x) + Dy(y) + Dy(z) + Øxy*x/X$$

$$Dz(x,y,z) = Dz(x) + Dz(y) + Dz(z) + Øyz*y/Y + Øzx*x/X$$

All these errors may change under various machine temperature distribution or thermal loadings.

3. Measurement of 3D volumetric positioning errors by vector technique

The majority of measurement techniques and devices are based on the philosophy "from a measurement one obtains the information about a single geometric error". This yields to extensive time and equipment requirements if the 3D volumetric positioning errors are sought. The laser vector measurement technique represents a different concept of measurement. It is a composite measurement, namely, with 4 setups and measurements, 12 sets of errors can be determined. It is a very efficient and effective technique.

In the laser vector measurement [1], similar to the ASME B5.54 and ISO230-6 standards body diagonal displacement measurement [4, 5, 6], the laser beam is pointing in the body diagonal direction as shown in Fig. 1. However, instead of move x, y, and z-axis together along the body diagonal direction, stop and collect data, now move x only, stop and collect data, then move y only, stop and collect data, then move z only, stop and collect data, and so on until the opposite corner is reached. Hence, 3 times more data can be collected. For 4 body diagonal measurements, a total of 12 sets of data can be collected and the volumetric positioning errors determined. The measurement time is short, the equipment is compact, and the setup and alignment is simple.

4. Measurement of temperature distributions with various thermal loadings

The causes of thermal deviations may be divided into two basic categories. The first part is from the thermal loadings resulting from the machine tool operation. The most significant sources of heat in a CNC machine tool are the spindle, ballscrews alternatively linear motors and heat coming from the cutting process. The second part is represented by deviations raised from the thermal deformations of the machine frame caused by external influences - mainly the environmental temperature in the shop floor, temperature variations, Coolant temperature and flow, air flow, direct sunshine, etc. To measure temperature distribution, thermal sensors were placed at key locations. The temperatures were continuously measured during the measurement cycles, spindle heating and rapid xyz-axes motion.

5. Test setup and results of measurement

The measurements were performed on a vertical machining center, MCFV5050LN, in Prague, Czech Republic. The machine is equipped with linear motor drives, a cross bed with two driven axes X, Y and a vertically oriented spindle (Z-axis) form the structure of the machine. The strokes of each axis are as follows X-axis 500mm, Y-axis 400mm, Z-axis 400mm.

The laser measurement system used is a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500 with SD-500 sequential step diagonal measurement accessory. Two lasers were mounted on the machine bed and used a steering mirror to align the laser beam parallel to the body diagonal. Two 75×100mm flat mirrors were mounted on the spindle with the surface perpendicular to the laser beam. The machine was programmed to move the spindle relative to the worktable starting from one corner to the opposite corner. The air temperature and pressure were measured to compensate the changes in speed of light and the machine temperature was measured to compensate the machine thermal expansion. Detailed measurement and test results are in the Ph.D thesis by O. Svoboda [7].

Reported here are data taken after high spindle speed and rapid axes motion. The duty cycle consists of a continuous spindle run at maximal speed of 15000 rpm and xyz-axes motion at maximum stroke in the body diagonal direction at 50% maximum rapid feed rate. The temperature data is displayed in Fig. 2 for the sensor located on the spindle, z-column, x-middle and y-front at 6 measurement runs. It is clear that the main heating occurs in parts close to the spindle. The temperatures were continuing increased due to the spindle heating and rapid xyz-axes motion. These temperature changes caused different thermal deformations of the z-column and the xy-bed yielding into the measured variations of the 3D volumetric positioning accuracy.

The measured maximum deviations of linear displacement error data of all 3 axes are shown in Fig. 3. Both the y-axis and z-axis showed the lead screw thermal expansion. The increasing of the displacement errors or pitch errors was proportional to the increase of machine bed temperature or thermal growth as expected. However, for the x-axis, the increasing of displacement error was much larger than the thermal growth of pitch error. The excessive increase of the linear displacement errors at high temperature is due to the increase of XZ squareness error.

Straightness errors were measured for all x, y, and z-axis. The maximum straightness error deviations are shown in Fig. 4. The thermal deviation for the z-axis straightness (ZDX and ZDY) and y-axis vertical straightness (YDZ), are relative large and for the x-axis straightness (XDY and XDZ) and y-axis horizontal straightness (YDX) the thermal changes were relatively small.

The squareness errors represent one of the main parts of the machine error budget. As shown in Fig. 5, the maximum squareness error deviations in XY- and ZX-plane were positive and in the YZ-plane were negative. The maximum deviations were 40 microns/m and -75 microns/m.

6. Summary and conclusion

In summary, the laser vector measurement technique has been effectively used to study the 3D volumetric positioning errors with various thermal states. The correlation between thermal loadings and the 3D volumetric positioning errors have been determined. The preliminary data showed that some straightness errors were very sensitive to the machine temperature changes and the largest errors caused by thermal loadings are the z-axis sag errors. Based on the measurement results, it is concluded the 3D volumetric error compensation strategy, using the vector method to measure the volumetric positioning errors at various machine temperatures and working conditions to generate several compensation tables at different temperatures should work very well.

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Keywords: Positioning errors, Thermal deflections, Error compensation, and Machine temperature.

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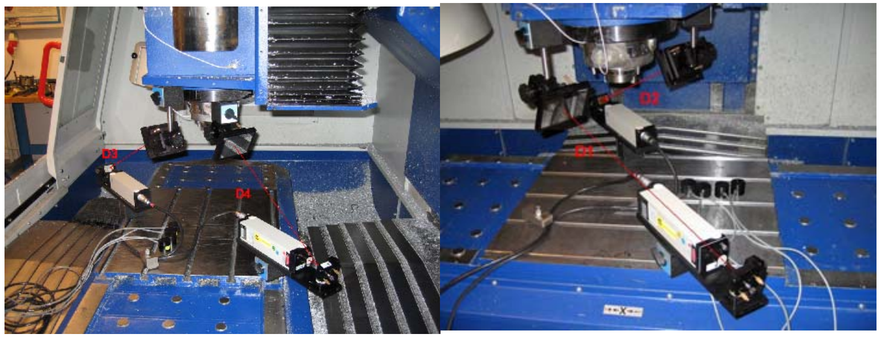

Fig. 1, A photo of the machining center and the vector measurement setup. D1, D2, D3 and D4 are the 4 body diagonal directions.

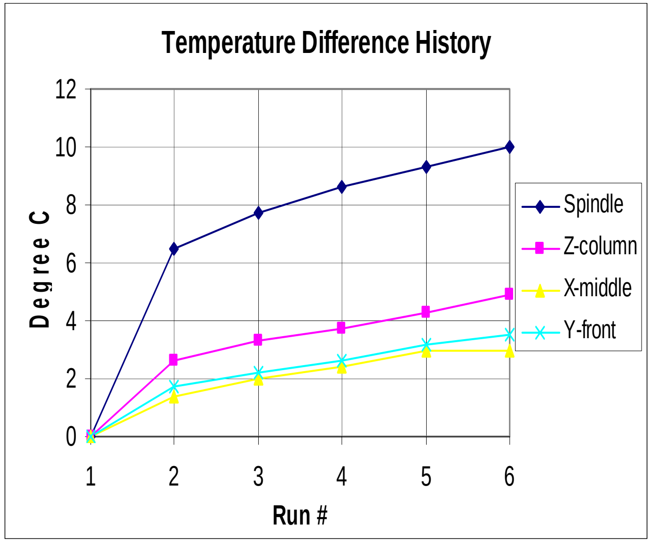

Fig. 2, A plot of temperature history of the spindle, Z-column, X-middle and Y-front vs. run # 1 to 6.

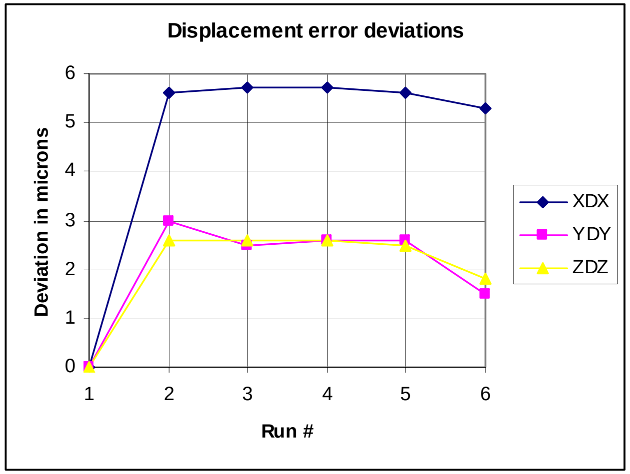

Fig. 3, Maximum deviations of linear displacement errors of 3 axes, XDX, YDY and ZDZ at 6 different thermal conditions run # 1 to 6.

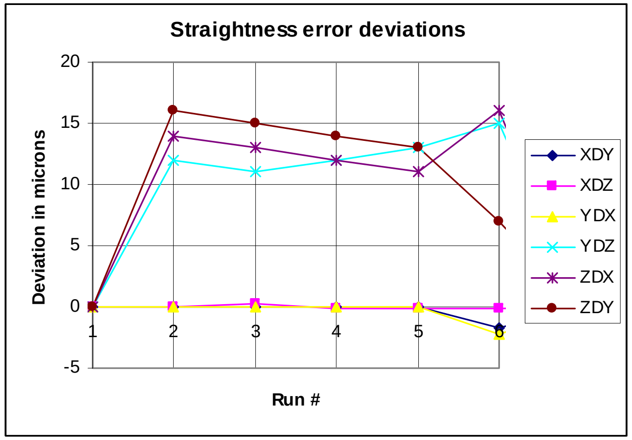

Fig. 4, Maximum deviations of straightness errors of 3 axes, XDY, XDZ, YDX, TDZ, ZDX and ZDY at 6 different thermal conditions runs # 1 to 6.

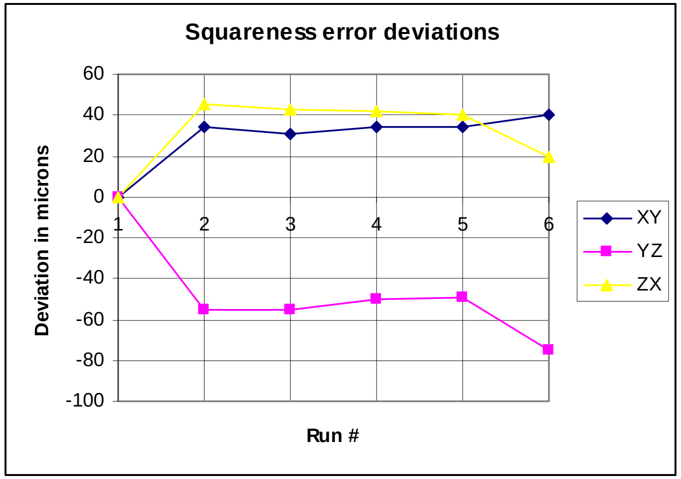

Fig. 5, Maximum deviations of squareness errors in XY, YZ and XZ plans at 6 different thermal conditions runs #1 to 6.