3D Volumetric Positioning Error Measurement and Compensation over Part

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Abstract.
Competition in global manufacturing today requires improving machine tool performance to achieve higher productivity, better quality and less downtime. Using the laser vector technique, the 3D volumetric positioning errors can be measured in a few hours. The results can be used to compensate the part program (or G-code) and achieve higher part accuracy. Reported here are the basic theory, measurement of 3D positioning errors, the test part program without compensation and with compensation, and the measured accuracy of these 2 parts. The improvement of the part accuracy is significant.

Introduction

To improve the volumetric positioning accuracy of the existing machine tools and to cut more accurate parts, the key is 3 D volumetric calibration and compensation.

To improve the volumetric-positioning accuracy of machine tools and to machine parts with consistent and tighter tolerances, 3-D volumetric measurement and compensation is essential. Twenty years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. Now, most of these errors have been reduced by better ball-screw or linear encoder and pitch error compensation. Hence, the largest machine tool positioning errors become squareness errors and straightness errors. Until recently, measuring volumetric errors has been time-consuming and costly. Furthermore, high-end controllers capable of 3D error compensation are expensive and rare. For these reasons, 3D volumetric measurement and compensation have not been widely used.

Recently, Optodyne has developed a new revolutionary laser vector measurement technique [1] capable of measuring the 3 D volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors, in a short time. Furthermore, compensate the part program or G-code makes it unnecessary the need of a high-end controller. Hence a low cost CNC machine can perform as a high cost machine.

What are 3D volumetric positioning errors?

The positioning error in an arbitrary point within the working volume over the part is composed by the positioning errors of the individual axes in all 3 axis directions, the linear displacement error, and the straightness errors - horizontal and vertical. The total error at each point is the sum of errors in all 3 axis directions, and the error in each axis direction is the sum of errors caused by all 3 axes movement, plus the errors caused by the non-perpendicular of the 3 axes.

The 3D positioning error at each position is a vector of errors in x-direction, y-direction and z-direction. It is the sum of all errors in each axis direction as shown below.

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

Where D is the linear error; subscript is the error direction; position coordinate is in parenthesis (x), (y), or (z); Øxy, Øyz, and Øzx are squareness errors in the xy-, yz- and zx-plane respectively.

How to measure 3D volumetric positioning errors
Using conventional laser interferometers to measure the straightness and squareness errors are very difficult with complex optics, expensive equipment and time consuming. To solve this difficulty, Optodyne has developed a new laser vector measurement technique for the measurement of straightness and squareness errors. The setup and operation is simple. It can measure the volumetric errors in 2 hours for a machine working volume of 1 cubic meter.

Similar to the ASME B5.54 and ISO230-6 standards body diagonal displacement measurement [2], the laser beam is pointing in the body diagonal direction as shown in Figure 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 measurement, 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.

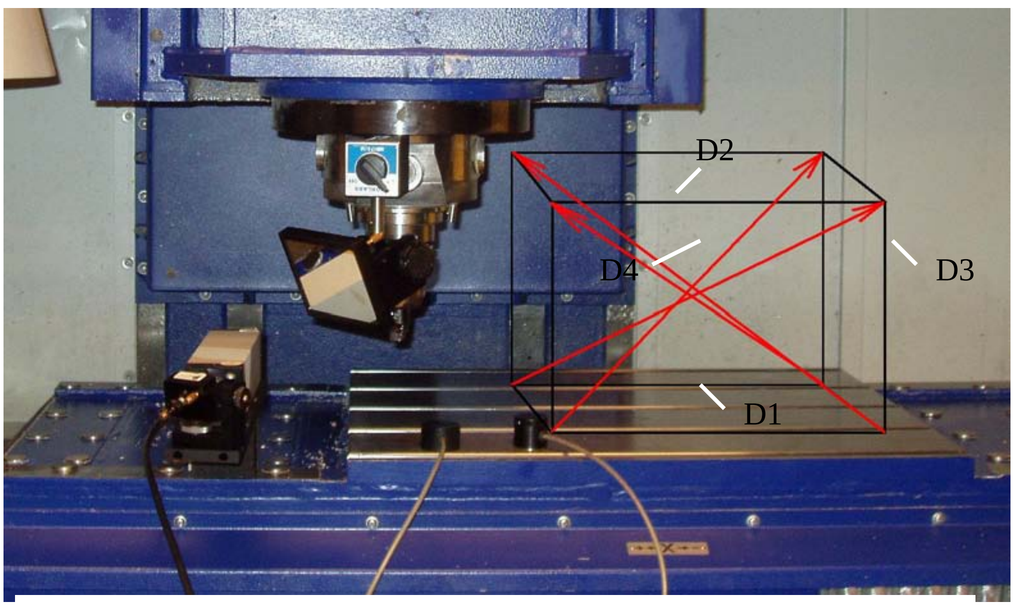

Fig. 1, a photo of the machining center and the vector measurement setup. D1, D2, D3 and D4 are the 4 body diagonal directions.

Experimental verifications
Once the 3D volumetric errors are measured, a compensated part program can be generated. Both the uncompensated part program and compensated part program for a test part are show below.

(Uncompensated G-code)	(Compensated G-code)
G90 G0	G90 G0
X0.Y0.Z2.	X0. Y0. Z2.
M00	M00
X3.25 Y3.85	X3.2494 Y3.8509
M00	M00
M03	M03
S600	S600
G01 F3	G01 F3
Z0.9	Z0.9
X6.25	X6.2498
X7.55 Y5.15	X7.5496 Y5.1503
Y6.85	Y6.8504
X6.25 Y8.15	X6.2487 Y8.1506
X4.55	X4.5484
X3.25 Y6.85	X3.2486 Y6.8508
Y5.15	Y5.1507
X4.55 Y3.85	X4.5495 Y3.8506
G0 Z2.	G0 Z1.9999
M05	M05
M30	M30

Based on these G-codes, 2 parts were machined with 0.5” diameter end-mill as shown below.

Fig. 2, the part on the left is not compensated and on the right is compensated.

The dimensions were measured by a micrometer. The values were averaged over 3 measurements. The repeatability of the micrometer is 0.0001”. The results are shown below.

Parts	Un-compensated	Compensated	Calculated values
X-axis direction, Inches	3.7999	3.8001	3.8000
Y-axis direction, Inches	3.7995	3.7997	3.8000
+ 45 degrees direction, Inches	3.7409	3.7414	3.7416
- 45 degrees direction, Inches	3.7424	3.7417	3.7416

The linear errors in X and Y directions are relatively small. This is because the machine was compensated for lead screw pitch errors. But the **squareness error** is rather large. The uncompensated errors in + 45 degrees and -45 degrees are differed by 0.0015” (0.038 mm), which corresponds to a squareness errors of 70.5 arcsec. After compensation, the errors in +45 degrees and – 45 degrees are differed by 0.0003” which corresponds to a squareness error of 14.1 arcsec. a significant improvement.

Summary and conclusion

The conventional laser measurement and compensation is over the whole machine working volume. It takes more time for the measurement and less compensation points in the whole volume. However, for most applications, the part volume is much smaller than the machine working volume and the time required to measure over the part volume is much shorter. Also, in a real shop environment, such as in summer or winter the measured positioning errors include the effect of material thermal expansions and distortions, and also the angular errors. Furthermore, more compensation points in a smaller volume, higher accuracy can be achieved. Hence, this is a more viable or economic approach.

References

[1] C. Wang, "Laser Vector measurement Technique for the determination and compensation of volumetric positioning errors. Part I: Basic theory", *Review of Scientific Instruments*, Vol. 71, No 10, pp 3933-3937, 2000.

[2] ISO 230-6: 2002 Test code for machine tools – Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)", *an International Standard*, by International Standards Organization, 2002.