Current Issues in CNC Machine Tools—
3D Volumetric Positioning Accuracy

Charles Wang

Optodyne, Inc.,
1180 Mahalo Place
Rancho Dominguez, CA 90220, USA
Tel. :+ 1 (310) 635-7481 Fax : +1 (310) 635-6301 Email: optodyne@aol.com

Keywords: 3D positioning accuracy, laser measurement, volumetric error definition.

Abstract

World competition requires good quality or accurate parts. Hence the CNC machine tool 3D volumetric positioning accuracy becomes very important. Using the laser Vector measurement technique, the accuracy can be determined in a few hours instead of a few days. Reported here are the basic theories, relations between the 4 body diagonal displacement errors and the 21 rigid body errors, and the measurement results.

1. Introduction

Using a conventional laser interferometer to measure the 3D volumetric positioning errors is very difficult and time consuming. Twenty years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. Now, most of the above errors have been reduced by better lead screw, linear encoder and pitch error compensation. The largest machine tool positioning errors become squareness errors and straightness errors or 3D volumetric error.

Using a conventional laser interferometer to measure the 3D volumetric positioning errors is very difficult and time consuming. 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.

It has been proposed to use the body diagonal displacement errors to define the volumetric positioning error [1]. However, the relations between the measured body diagonal displacement errors and the 21 rigid body errors are not clear, and a more practical definition of a volumetric position error has been discussed but not defined.

2. Rigid body positioning errors

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

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.

3. Positioning error compensation modelling

The sum of all errors in the x, y, and z direction are Ex, Ey, and Ez respectively.

$$
\begin{aligned}
Ex(x, y, z) = {} & Dx(x) + Dx(y) + Dx(z) + Dx^{x}(y)x - (z + Zt) * Ay(x) \\
& + Yt * Az(x) - (z + Zt) * [Ay(y) + Ay^{x}(y)x] \\
& + Yt * Az(y) - Zt * Ay(z) + Yt * Az(z), \qquad (1) \\
Ey(x, y, z) = {} & Dy(y) + Dy^{x}(y)x + Dy(z) + Dy(x) - (x + Xt) * Az(y) \\
& + (z + Zt) * [Ax(y) + Ax^{x}(y)x] - Xt * Az(z) \\
& + Zt * Ax(z) - Xt * Az(x) + (z + Zt) * Ax(x), \qquad (2) \\
Ez(x, y, z) = {} & Dz(z) + Dz(x) + Dz(y) + Dz^{x}(y)x - Yt * Ax(z) \\
& + Xt * Ay(z) - Yt * Ax(x) + Xt * Ay(x) \\
& - Yt * [Ax(y) + Ax^{x}(y)x] + (x + Xt) * [Ay(y) + Ay^{x}(y)x], \qquad (3)
\end{aligned}
$$

For the case the reference point is the tool tip, then $Xt = Yt = Zt = 0$. Hence the sums of errors, Eqs. 1, 2 and 3, reduce to the followings.

$$
\begin{aligned}
Ex(x, y, z) = {} & Dx(x) + Dx(y) + Dx(z) + Dx^{x}(y)x - z * Ay(x) \\
& - z * [Ay(y) + Ay^{x}(y)x], \qquad (4) \\
Ey(x, y, z) = {} & Dy(y) + Dy^{x}(y)x + Dy(z) + Dy(x) - x * Az(y) \\
& + z * [Ax(y) + Ax^{x}(y)x] + z * Ax(x), \qquad (5) \\
Ez(x, y, z) = {} & Dz(z) + Dz(x) + Dz(y) + Dz^{x}(y)x + Ax^{x}(y)x \\
& + x * [Ay(y) + Ay^{x}(y)x], \qquad (6)
\end{aligned}
$$

4. Body diagonal displacement measurement

Using a conventional laser interferometer to measure the straightness and squareness errors is rather difficult and costly. It usually takes days of machine down time and experienced operator to perform these measurements. For those reasons the body diagonal displacement error defined in the ASME B5.54 or ISO 230-6 standard is a good quick check of the volumetric error [3]. Furthermore, it has been used by Boeing Aircraft Company and many others for many years with very good results and success.

Briefly, similar to a laser linear displacement measurement, instead of pointing the laser beam in the axis direction, pointing the laser beam in the body diagonal direction. Mount a retroreflector on the spindle and move the spindle in the body diagonal direction. Starting from the zero position and at each increment of the three axes, which are moved together to reach the new position along the diagonal, the displacement error is measured. There are 4 body diagonal directions and the accuracy of each position along the diagonal depends on the positioning accuracy of the three axes, including the straightness errors, angular errors and squareness errors. Hence the 4 body diagonal displacement measurement is a good measure of 3D volumetric accuracy.

The relations between the measured 4 body diagonal displacement errors and the 21 rigid body errors have been derived. For the FXYZ, the measured error DR at each increment can be expressed as [4],

$$
\begin{aligned}
DRppp = {} & a/r * Dx(x) + b/r * Dy(x) + c/r * Dz(x) \\
& + a/r*[Dx(y) + y\,Øxy] + b/r*Dy(y) + c/r*Dz(y) \\
& + a/r*[Dx(z) + z\,Øzx] + b/r*[Dy(z) + z\,Øyz] + c/r * Dz(z) \qquad (7) \\
& + Ay(x)*ac/r - Az(x)*ab/r + Ay(y)*ac/r - Ax(y)*bc/r.
\end{aligned}
$$

$$
\begin{aligned}
DRnpp = {} & -a/r * Dx(x) + b/r * Dy(x) + c/r * Dz(x) + \\
& - a/r*[Dx(y) + y\ Øxy] + b/r*Dy(y) + c/r*Dz(y) \\
& - a/r*[Dx(z) + z\ Øzx] + b/r*[Dy(z) + z\ Øyz] + c/r * Dz(z) \qquad (8) \\
& - Ay(x)*ac/r + Az(x)*ab/r - Ay(y)*ac/r - Ax(y)*bc/r.
\end{aligned}
$$

$$
\begin{aligned}
DRpnp = {} & a/r * Dx(x) - b/r * Dy(x) + c/r * Dz(x) \\
& + a/r*[Dx(y) + y\ Øxy] - b/r*Dy(y) + c/r*Dz(y) \\
& + a/r*[Dx(z) + z\ Øzx] - b/r*[Dy(z) + z\ Øyz] + c/r * Dz(z) \\
& + Ay(x)*ac/r + Az(x)*ab/r + Ay(y)*ac/r + Ax(y)*bc/r. \qquad (9)
\end{aligned}
$$

$$
\begin{aligned}
DRppn = {} & a/r * Dx(x) + b/r * Dy(x) - c/r * Dz(x) \\
& + a/r*[Dx(y) + y\ Øxy] + b/r*Dy(y) - c/r*Dz(y) \\
& + a/r*[Dx(z) + z\ Øzx] + b/r*[Dy(z) + z\ Øyz] - c/r * Dz(z) \\
& - Ay(x)*ac/r - Az(x)*ab/r - Ay(y)*ac/r + Ax(y)*bc/r. \qquad (10)
\end{aligned}
$$

where the subscript ppp means body diagonal with all x, y and z positive; npp means body diagonal with x negative, y and z positive; pnp means body diagonal with y negative, x and z positive; and ppn means body diagonal with z negative, x and y positive. Also a, b, c and r are increments in x, y, z, and body diagonal directions respectively. The body diagonal distance can be expressed as $r^2 = a^2 + b^2 + c^2$. Similar relations have also been derived for XFYZ, XYFZ AND XYZF configurations.

For FXYZ configuration, shown in Eqs. 7, 8, 9, and 10, there are 4 angular error terms, Ay(x)*ac/r, – Az(x)*ab/r, Ay(y)*ac/r and – Ax(y)*bc/r. Similarly, for the XFYZ configuration there are only 2 angular error terms, Ay(y)*ac/r and - Ax(y)*bc/r. For the XYFZ configuration there are 2 angular error terms, Az(x)*ab/r and – Ax(x)*bc/r. For the XYZF configuration there are 4 angular error terms, Ay(x)*ac/r, – Az(x)*ab/r, Ay(y)*ac/r and – Ax(y)*bc/r same as in the FXYZ configuration. Hence, we concluded that the body diagonal displacement measurements are not sensitive to angular errors.

Furthermore, the 4 body diagonal displacement errors are sensitive to all of the 9 linear errors and 3 squareness errors. The errors in the above equations may be positive or negative and they may cancel each other. However, the errors are statistical in nature, the probability that all of the errors will be cancelled in all of the positions and in all of the 4 body diagonals are theoretically possible but very unlikely. Hence it is indeed a quick measurement of volumetric positioning accuracy.

5. Sequential step diagonal displacement measurement

It is noted that because there are only 4 sets of data and 9 sets of errors, there is not enough information to determine these errors. To overcome these limitations, a sequential step diagonal or vector technique [5, 6] has been developed by Optodyne to collect 12 sets of data with the same 4 diagonal setups. Based on these data, all 3 displacement errors, 6 straightness errors and 3 squareness errors can be determined. Furthermore, the measured positioning errors can also be used to generate a 3D volumetric compensation table to correct the positioning errors shown in Eqn. 4 - 6 and achieve higher positioning accuracy.

The basic concept of the vector method is that the laser beam direction (or the measurement direction) is not parallel to the motion of the linear axis. Hence, the measured displacement errors are sensitive to the errors both parallel and perpendicular to the direction of the linear axis. More precisely, the measured linear errors are the vector sum of errors, namely, the displacement errors (parallel to the linear axis), the vertical straightness errors (perpendicular to the linear axis), and horizontal straightness errors (perpendicular to the linear axis and the vertical straightness error direction), projected to the direction of the laser beam.

For each body diagonal measurement, because of the sequential steps, there are 3 sets of data. Hence for 4 body diagonal measurement, there are 12 sets of data. Using these 12 sets of data we can solve the 3 displacement errors, 6 straightness errors and 3 squareness errors. The setup is simple and easy and the measurement can be performed in a few hours instead of a few days using a conventional laser interferometer. More detailed theory is in Ref. [7].

In practice, first point the laser beam in one of the body diagonal directions, similar to the body diagonal displacement measurement in the ASME B5.54 standard. However, instead of programming the machine to move, x, y, and z continuously to the next increment, stop and take a measurement, the machine is now programmed to, move the x-axis, stop and take a measurement, then move the y-axis, stop and take a measurement, then move the z-axis, stop and take a measurement. A typical setup on a CNC machining center is shown in Fig. 1.

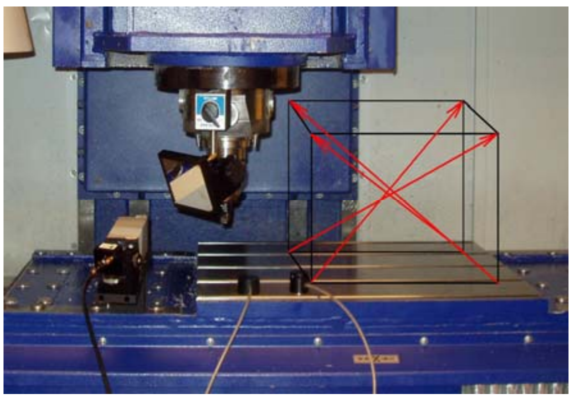

Fig. 1, The laser Vector measurement setup with a laser mounted on the bed and a flat-mirror mounted on the spindle. The laser beam is pointed in one of the 4 body diagonal directions as shown.

6. Current issues in machine errors

The volumetric error more accurately reflects the accuracy to be expected from a machine tool than any other measurement that can be made. Hence, the volumetric error should be determined and listed on the specification sheet of every machine tool offered to industry. On the other hand, the measuring of the 21 rigid body errors is challenging and time consuming. Hence a definition or a method of approximating true volumetric error that correlates well to true 3D positioning error, but is less difficult to measure, is very important [1].

Traditionally, manufacturers have ensured machine accuracy by linear calibration of each axis. The conventional definition of the 3-D volumetric positioning error is the root mean square of the three-axis displacement error. 20 years ago, the dominate error is the lead screw pitch error of 3 axes, this definition is adequate. However, now with better lead screw, linear encoder and compensation, the pitch error has been reduced considerably. The dominate errors are the squareness errors and straightness errors. Using a laser interferometer to measure straightness and squareness errors can be relatively difficult and time consuming.
Hence the current issues in machine errors modeling are to define and to determine the 3D volumetric positioning error of CNC machine tools. The definition should be directly linked to the 3D positioning errors and also practical to measure or determine such that it will be accepted by machine tool builders and used in the specification.

During the past few years, the industry has seen demand emerge for the 3D volumetric accuracy specification on machine tools. The issue has been discussed in many Standards Committees, machine tool builders and the metrology community. In general, they fallen into two camps: One for a definition that would define the volumetric accuracy as the root-mean-square of all the rigid body errors, the other for a method, being used by Boeing and others, called body diagonal displacement measurement, which gives accurate volumetric measurements for most equipment. The 3D volumetric error is defined as the Maximum error of the 4 body diagonals, Ed = Max[DRppp/nnn, DRnpp/pnn, DRpnp/npn, DRppn/nnp], where the squareness error may not be included. A better definition, ESd can be defined as the (Max error – min error) or ESd=Max[DRppp/nnn, DRnpp/pnn, DRpnp/npn, DRppn/nnp]-min[DRpp/nnn, DRnpp/pnn, DRpnp/npn, DRppn/nnp]. To verify this, volumetric positioning errors of 10 CNC machines were measured [1] and the results plotted in Fig. 2, where ELSv is the maximum vector error in the volume. ELSv = SQRT{[MaxEx(x,y,z) – minEx(x,y,z)] ^2 + {[MaxEy(x,y,z) – minEy(x,y,z)] ^2 + {[MaxEz(x,y,z) – minEz(x,y,z)] ^2}. The result shows that the Ed under estimated the maximum vector error by a factor of from 1.5 to 2.7. The ESd under estimated the maximum vector error by a factor from 1.4 to 1.9. Hence, ESd, with less variations, is a good measure of the 3D volumetric error.

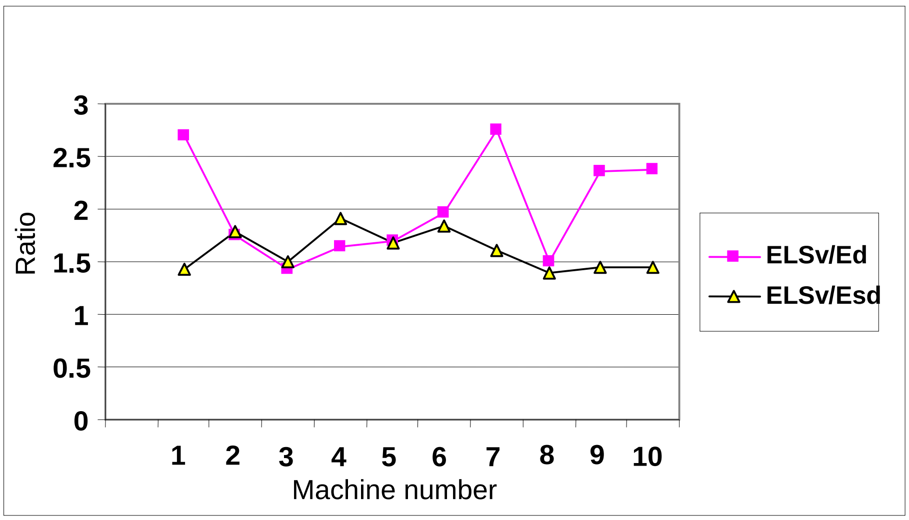

Fig. 2, Measurement results of 10 CNC machines on the volumetric errors, ELSv, Ed and ESd.

7. Summary and conclusion

The positioning errors of 10 CNC machine tools have been measured. Based on these measurement results, the 3D volumetric errors using various definitions can be calculated. It is concluded that the laser body diagonal displacement measurement in the ASME B5.54 or ISO 230-6 machine tool performance measurement standards is a quick check of the volumetric positioning error and the value ESd is a good measure of the volumetric error.

References

1. C. Wang, O. Svoboda, P. Bach, and G. Liotto. *Proceedings of the IMTS 2004 Manufacturing Conference*, Chicago, IL, 2004.
2. R. Schultschik, *Annals of the CIRP*, Vol.25, No.1, 1977.
3. ISO 230-6: 2002 Test code for machine tools – Part 6, *an International Standard*, by International Standards Organization, 2002.
4. G. Ren, J. Yang, G. Liotto, and C. Wang. *Proceedings of the LAMDAMAP Conference*, Cransfield, UK, 2005.
5. C. Wang. *Review of Scientific Instruments*, Vol. 71, No 10, 2000.
6. O. Svoboda, P. Bach, G. Liotto, and C. Wang. *Proceedings of the JUSFA 2004 Conference*, Denver, CO, 2004.
7. C. Wang. *Introduction to Precision Machine Design and Error Assessmen*", Chapter 8, CRC Press, New York, N.Y. 2008.