Volumetric positioning accuracy of CNC machining centers definitions and measurements

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Abstract

The worldwide competition and quality standards such as ISO 9000 and QS 9000, demanded tighter tolerance and regular maintenance of all machine tools. To generate good quality or accurate parts, the measurement of true 3 dimensional volumetric positioning accuracy of a machine tool is critical. However, the 3D volumetric accuracy has not been defined in the standards.

Currently, both the ASME B5(TC52) and ISO 230(TC39) are working on a new definition of volumetric accuracy. There are many possible definitions, such as the root mean square of the 3 axes displacement errors, the root mean square of the total errors in the 3-axis directions, the maximum 4 body diagonal displacement errors without squareness and the maximum 4 body diagonal displacement errors with squareness errors.

Reported here are some definitions of 3D volumetric positioning errors and their correlations. We have measured the positioning errors of 10 CNC machine tools, representing a selection of modern mid-size CNC machining centers. Based on these measurement results, the 3D volumetric errors using various definitions can be calculated. It is concluded that the 4 body diagonal displacement errors with squareness errors correlate with the true 3D volumetric errors very well. It may be used as a quick check of 3D volumetric accuracy of CNC machine tools.

Keywords
3D positioning error, Laser calibration, CNC machines, ISO standards, Manufacturing.

To be presented in the IMTS 2004 Manufacturing Conference, Chicago, Il, September 8-10, 2004. .

Introduction

The increasing demand for accuracy of machined parts is being fueled by economics because it reduces assembly, warranty, and ownership costs. Traditionally, manufacturers have ensured accuracy of parts with linear calibration of each axis of the machine tools. But linear calibration is inadequate for ensuring accuracy of three dimensional parts.

The conventional definition of the 3D volumetric positioning error is the root mean square of the 3 axes displacement error. 20 years ago, this definition is okay as long as the dominate errors are the displacement errors. Now the displacement errors are reduced considerably and the dominate errors are straightness and squareness errors.

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. However, it is not clear, what is the relation between the body diagonal displacement errors and the true 3D positioning errors.

Currently, both the ASME B5(TC52) and ISO 230(TC39) are working on a new definition of volumetric accuracy. There are many possible definitions, such as the root mean square of the 3 axes displacement errors, the root mean square of the total errors in the 3-axis directions, the maximum 4 body diagonal displacement errors without squareness and the maximum 4 body diagonal displacement errors with squareness errors.

Below are some definitions of 3D volumetric positioning errors and some measurements on the volumetric positioning errors. Based on these measurement results, various definitions of 3D volumetric errors can be calculated. It is concluded that the 4 body diagonal displacement errors with squareness errors correlate with the true 3D volumetric errors very well.

II. Basic 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. These 21 rigid body errors [1] 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.

III. Body diagonal displacement errors

The performance or the accuracy of a CNC machine tool is determined by the 3 D volumetric positioning errors, which includes the linear displacement error, the straightness error, the angular error and the thermal induced error. A complete measurement of those errors is very complex and time consuming, for those reasons the body diagonal displacement error defined in the ASME B5.54 [2] or ISO 230-6 [3] standard is a good quick check of the volumetric error. This is because all the errors, including 3 displacement errors, 6 straightness errors, 3 squareness errors and some angular errors, will contribute to the 4 body diagonal displacement errors [4]. Hence it is a good and efficient measurement of the volumetric error. The B5.54 body diagonal displacement tests have 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 from the lower corner (X=0 Y=0 Z=0) to the opposite upper corner (Xmax, Ymax, Zmax). 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.

The key question is, what is the correlation between the body diagonal displacement errors and the true 3D volumetric errors.

IV. Definitions of volumetric errors

There are various definitions on 3D volumetric errors. One conventional definition is the root mean square of the 3 axes displacement error. Here, the linear displacement error of each axis is Dx(x), Dy(y), and Dz(z).

The maximum error of each axis is

$$\begin{aligned} &\text{X-axis error, } ELx = Max[Dx(x)] - min[Dx(x)], \\ &\text{Y-axis error, } ELy = Max[Dy(y)] - min[Dy(y)], \\ &\text{Z-axis error, } ELz = Max[Dz(z)] - min[Dz(z)]. \end{aligned} \qquad (1)$$

Hence the volumetric error ELv can be defined as the root mean square sum of all the 3 linear displacement errors in Eq. 1. That is,

$$ELv = SQRT[\, ELx * ELx + Ely * Ely + ELz * ELz]. \qquad (2)$$

This definition is reasonable as long as the dominate errors are the 3 displacement errors (or lead screw pitch errors). Now, most of the lead screw errors have been reduced by linear encoder or error compensation. Hence, the largest machine tool positioning errors become squareness errors and straightness errors. Hence, the above definition is no longer adequate.

The true volumetric error, includes 3 linear displacement errors, 6 straightness errors and 3 squareness errors. The linear and straightness error of each axis are

$D_x(x), D_y(x), D_z(x),$
$D_x(y), D_y(y), D_z(y),$
$D_x(z), D_y(z), D_z(z),$
$Øxy, Øyz, Øzx.$

The error in each axis direction is

$$\begin{aligned} Dx(x, y, z) &= Dx(x) + Dx(y) + Dx(z), \\ Dy(x, y, z) &= Dy(x) + Dy(y) + Dy(z) + Øxy * y/Y, \\ Dz(x, y, z) &= Dz(x) + Dz(y) + Dz(z) + Øyz * z/Z + Øzx * z/Z. \end{aligned} \quad (3)$$

The maximum error in each axis direction is

$$\begin{aligned} ELSx &= Max[Dx(x, y, z)] – min[Dx(x, y, z)], \\ ELSy &= Max[Dy(x, y, z)] – min[Dy(x, y, z)], \\ ELSz &= Max[Dz(x, y, z)] – min[Dz(x, y, z)]. \end{aligned} \quad (4)$$

Hence the volumetric error ELSv can be defined as the root mean square sum of all the 3 errors in the axis direction. That is,

$$ELSv = SQRT[ELSx * ELSx + ELSy * ELSy + ELSz * ELSz]. \quad (5)$$

It is noted that, using a conventional laser interferometer, the measurement of these straightness and squareness errors are time consuming. Hence, the body diagonal displacement error measurement in the ASME B5.54 [2] or ISO 230-6 [3] standard may be a good quick check of the volumetric accuracy.

The body diagonal errors in each direction are

Dr(r) ppp/nnn,
Dr(r) npp/pnn,
Dr(r) pnp/npn,
Dr(r) ppn/nnp,

Where ppp/nnn indicates the body diagonal direction with the increments in x,y, and z all positive/negative, and npp/pnn indicates the increments in x, y, and z are negative/positive, positive/negative, and positive/negative, etc.

Based on the definition in ISO 230-6, the E is defined as

$$\begin{aligned} Eppp/nnn &= Max[Dr(r)ppp/nnn] – min[Dr(r)ppp/nnn], \\ Enpp/pnn &= Max[Dr(r)npp/pnn] – min[Dr(r)npp/pnn], \\ Epnp/npn &= Max[Dr(r)pnp/npn] – min[Dr(r)pnp/npn], \\ Eppn/nnp &= Max[Dr(r)ppn/nnp] – min[Dr(r)ppn/nnp]. \end{aligned} \quad (6)$$

The volumetric error is defined as

$$Ed = Max[Eppp/nnn, Enpp/pnn, Epnp/npn, Eppn/nnp]. \quad (7)$$

It is noted that this definition does not including the squareness errors. To include the squareness errors, the volumetric error can be defined as

$$ESd = Max[Dr(r)ppp/nnn, Dr(r)npp/pnn, Dr(r)pnp/npn, Dr(r)ppn/nnp] - min[Dr(r)ppp/nnn, Dr(r)npp/pnn, Dr(r)pnp/npn, Dr(r)ppn/nnp]. \quad (8)$$

In summary, the definition ELv is still commonly used as the definition of 3D volumetric error. The ELSv including the straightness and squareness errors is a true volumetric error. However it is more difficult to measure all the 3 linear displacement errors, 6 straightness errors and 3 squareness errors. The Ed is currently defined in the ISO230-6 and ASME B5.52 standards as a measure of volumetric error. The ESd, including the squareness errors, is proposed here as a measure of volumetric error.

V. Measurement on 10 selected CNC machines

Measurements were performed on 10 selected CNC machine tools, representing the modern mid-size CNC machining centers [5]. Eight were made by the German manufacturer Deckel Maho Gildemeister (DMG), one by the UK Bridgeport and one by the Czech company Kovosvit MAS. The DMG machines are for better illustration inscribed with a number behind each type description (e.g. DMU80T-2). A brief description of the 10 machines is in Table 1.

Table 1, Machine parameters of the 10 selected modern machining centers

Machine No.	**1**	**2**	**3**	**4**	**5**
Machine id.	DMC60H-1	DMC60H-2	DMC65V-1	DMC65V-2	DMU80T-1
Manufacturer	DMG	DMG	DMG	DMG	DMG
Type	horizontal	horizontal	vertical	Vertical	vertical
Axis stroke (X/Y/Z) mm	600 / 560 / 560	600 / 560 / 560	650 / 500 / 500	650 / 500 / 500	880 / 630 / 630
Control sys.	Sinumerik 840D	Sinumerik 840D	Sinumerik 840D	Sinumerik 840D	Heidenhein iTNC530
Service hours	2589	1655	3550	3338	2847

Machine No.	**6**	**7**	**8**	**9**	**10**
Machine id.	DMU80T-2	DMU80T-3	DMU80T-4	VMC500	MCV1000
Manufacturer	DMG	DMG	DMG	Bridgeport	MAS
Type	vertical	vertical	Vertical	Vertical	vertical
Axis stroke (X/Y/Z) mm	880 / 630 / 630	880 / 630 / 630	880 / 630 / 630	650 / 500 / 500	1016 / 610 / 720
Control sys.	Heidenhein TNC430	Heidenhein iTNC530	Heidenhein TNC430	Heidenhein TNC410	Heidenhein iTNC530
Service hours	4081	1672	3723	892	437

The laser calibration system used was a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500. 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. The automatic data acquisition, the error analysis and automatic generation of the compensation tables, were performed by the Optodyne LDDM Windows software version 2.50.

VI. Measurement results and correlations between various definitions

The measurement results are shown in Table 2. Measurements according to ISO 230-2 were performed along the three edges of the machine working volume. These are identified by the marks I, II and III. The angular errors are derived from the linear positioning by respecting the Abbe offsets and utilizing the equations (3-2) stated in [6] or equations (23), (24), (25) stated in [4]. The diagonal positioning accuracy is described by the parameter Ed (diagonal systematic deviation of positioning) according to ISO 230-6. The remaining geometric errors were evaluated from the laser vector method.

Table 2: Measurement results

Meas. techn.	**Error Type**	**Pos.**	**Machine No.**									
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
			Maximal deviation [µm], resp. [µm/m]									
ISO 230-2	Dx(x)	I	9.5	5.3	16.5	24.0	35.8	23.5	10.7	20.5	7.6	12.3
		II	7.2	7.3	31.1	22.5	47.7	24.1	12.0	54.3	X	X
		III	X	X	19.2	19.0	51.6	28.4	X	29.4	X	X
Calc	Ay(x)		X	X	53.0	4.0	-12.0	-7.0	X	14.0	X	X
	Az(x)		X	X	15.0	26.0	-36.0	5.0	X	84.0	X	X
ISO 230-2	Dy(y)	I	15.8	7.8	15.3	18.4	20.3	14.3	16.2	5.5	13.6	15.7
		II	12.0	8.7	4.9	20.4	18.3	19.2	17.1	6.3	X	X
		III	X	X	13.2	24.9	22.9	21.6	11.2	12.1	X	X
Calc	Ax(y)		X	X	60.0	-12.0	11.0	-3.0	7.0	-8.0	X	X
	Az(y)		X	X	38.0	6.0	2.0	-3.0	-9.0	28.0	X	X

ISO 230-2	Dz(z)	I	X	36.3	10.9	10.6	14.0	16.5	6.8	6.6	23.3	14.1
		II	14.3	17.8	14.9	7.1	15.5	19.2	8.4	8.7	X	X
		III	25.2	21.1	10.1	7.7	18.0	15.2	7.7	15.7	X	X
Calc	Ax(z)		X	-99.0	-2.0	5.0	-5.0	-8.0	-3.0	-15.0	X	X
	Ay(z)		X	-72.0	5.0	-14.0	7.0	15.0	-7.0	-6.0	X	X
ISO 230-6	Ed		15.9	33.4	34.4	38.3	45.4	31.8	15.8	41.5	33.2	26.9
Laser vector method	Dx(x)		2.7	8.4	20.2	7.8	18.6	11.8	1.7	16.8	12.8	6.9
	Dy(x)		2.9	2.9	7.5	2.9	3.9	5.6	6.2	2.8	7.1	15.6
	Dz(x)		2.4	3.4	9.2	4.1	2.5	3.1	2.4	1.9	8.5	6.6
	Dy(y)		2.2	8.2	15.2	8.3	14.0	8.9	1.5	12.6	8.2	9.4
	Dz(y)		2.3	2.8	2.3	1.2	2.0	4.0	7.3	3.3	2.3	3.5
	Dx(y)		2.4	8.8	6.7	11.9	5.2	4.5	10.3	4.0	18.4	7.9
	Dz(z)		2.6	9.7	10.8	4.2	10.8	6.8	2.7	9.7	15.3	7.8
	Dy(z)		6.1	13.1	5.3	23.3	25.1	23.9	5.2	9.3	27.5	21.3
	Dx(z)		15.9	28.2	7.2	5.2	5.2	2.1	8.5	15.8	25.6	6.4
	Bxy		-1	15	-18	-8	5	3	15	-8	56	11
	Bxz		41	-52	-31	-7	7	4	-18	-39	64	-37
	Byz		-18	-18	-8	-67	-53	-48	-16	-27	73	-7
3D Volumetric errors	ES d		30	33	33	33	46	34	27	45	54	44
	EL v		25.55	27.13	27.62	31.61	51.95	35.59	20.18	39.61	28.03	24.43
	ELS v		42.81	58.66	49.31	62.89	77.05	62.37	43.56	62.58	78.41	63.72
	Ed		15.9	33.4	34.4	38.3	45.4	31.8	15.8	41.5	33.2	26.9
	ELSv/ELv		1.67	2.16	1.79	1.99	1.48	1.75	2.16	1.58	2.80	2.61
	ELSv/Ed		2.69	1.76	1.43	1.64	1.70	1.96	2.76	1.51	2.36	2.37.
	ELSv/ESd		1.43	1.78	1.49	1.91	1.67	1.83	1.61	1.39	1.45	1.45

The 3D volumetric errors, such as ELv, ELSv, Ed, and ESd are calculated and tabulated in the Table 2. As compare with the true 3D volumetric error ELSv, the ELv is underestimating the 3D volumetric error. The Ed is also underestimating the 3D volumetric error and also varies with the squareness errors. The ESd is also underestimated the 3D volumetric position error but relatively stable and not effected by the squareness errors.

For more quantitative comparison, a multiple factor, M1 is defined as ELSv/ELv, M2 is defined as ELSv/Ed and M3 is defined as ELSv/ESd. Hence the true 3D volumetric error ELSv can be obtained by multiple the ELv by M1, multiple the Ed by M2 and multiple the ESd by M3. The multiple factors M1, M2 and M3 for various machine tools are plotted in Fig. 1. The M1 varies from 1.4 to 2.8, the M2 varies from 1.43 to 2.76, and the M3 varies from 1.4 to 1.9. The range of variations for M1 and M2 are relatively large, while the range of variation for M3 is relatively small. Hence the ESd is a good estimate of 3D volumetric position error.

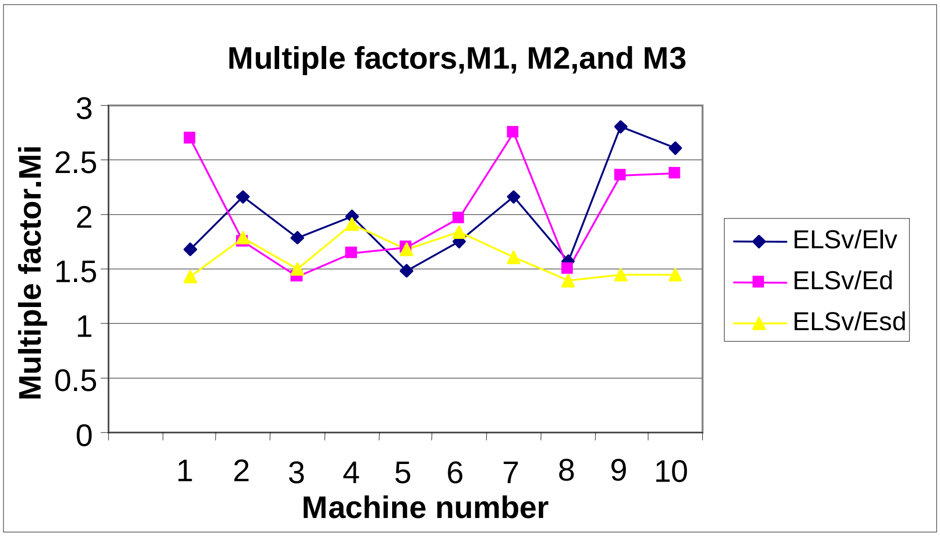

Fig. 1, Multiple factors for various definitions of volumetric errors.

VII. Summary and conclusion

Four definitions of the 3D volumetric positioning error have been provided. 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.

Acknowledgement

Research carried out by the RCMT is financially supported by the Ministry of Education of the Czech Republic under the project LN00B128.

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