What is 3D volumetric positioning accuracy and How to define and measure it

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I. Introduction

20 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 linear encoder and compensation. Hence, the largest machine tool positioning errors become squareness errors and straightness errors. Hence, to achieve higher 3D volumetric positioning accuracy, the measurement and compensation of the squareness and straightness errors are very important.

II. Machine tool 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 can be expressed as the followings [1].

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. Existing definition of volumetric accuracy

For a 3 axes machine, if the dominate positioning errors are the 3 displacement errors of each axis, Dx(x), Dy(y), Dz(z), then the volumetric error is the root-mean-square sum of all these displacement errors. That is.

$$\text{Volumetric error} = \text{sqrt}\ \{[\text{Max } Dx(x)-\text{Min } Dx(x)]^2 + [\text{Max } Dy(y)-\text{Min } Dy(y)]^2 + [\text{Max } Dz(z)- \text{Min } Dz(z)]^2\}.$$

This definition is okay as long as the dominate errors are the 3 displacement errors (or lead screw pitch errors). However, for current machine tools, the dominate errors are the straightness and squareness errors rather than the linear displacement errors. Hence, the above definition is no longer valid.

IV. New definition of volumetric accuracy

The positioning error in each axis direction, Dx(x,y,z), Dy(x,y,z), and Dx(x,y,z), is the sum of displacement error and straightness errors as the following.

$$Dx(x,y,z) = Dx(x) + Dx(y) + Dx(z),$$
$$Dy(x,y,z) = Dy(x) + Dy(y) + Dy(z),$$
$$Dz(x,y,z) = Dz(x) + Dz(y) + Dz(z).$$

Then the volumetric error is the root-mean-square sum of these total errors. That is,

$$\text{Volumetric error} = \text{sqrt}\,\{[\text{Max } Dx(x,y,z)-\text{Min } Dx(x,y,z)]^2 + [\text{Max } Dy(x,y,z)-\text{Min } Dy(x,y,z)]^2 + [\text{Max } Dz(x,y,z)-\text{Min } Dz(x,y,z)]^2\}.$$

However, 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 is a good quick check of the volumetric error.

V. The body diagonal displacement measurement

The volumetric positioning errors, including 3 displacement errors, 6 straightness errors, squareness errors and some angular errors, will show up as the 4 body diagonal displacement errors [4]. Hence it is a good and efficient measurement of the volumetric error. The volumetric error can be defined as [Max Dr(x,y,z) – Min Dr(x,y,z)], where Dr(x,y,z) is the diagonal displacement error.

The introduction of B5.54 and ISO230-6 machine tool performance measurement standards are increasing the popularity of laser body diagonal displacement measurement for a quick check 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.

VI. The sequential step diagonal or vector measurement

For a machine with small body diagonal displacement errors, the volumetric error is small. However for a machine with large body diagonal displacement errors, there is not enough data to determine which errors are causing the large volumetric error. Using Optodyne's Laser Doppler displacement meter (LDDM), the sequential step diagonal or vector measurement, 12 sets of data can be collected by the 4 sequential step diagonal measurement[4,5]. Hence the 3 displacement errors, 6 straightness errors and 3 squareness errors can all be determined. These measured errors can be used to compensate the volumetric positioning errors and improve the 3D positioning accuracy or the volumetric accuracy

VII. Maximum error in a 3D grid

For a machine working volume of X, Y, and Z, and each axis has I, J, K points respectively. That is, x-axis, i = 1,2,....I; y-axis, j = 1, 2, ...J; and z-axis, k = 1,2,...K. The 3 dimensional error map will have I*J*K points. At each point there are errors, dx = Dx(i,j,k), dy = Dy(i,j,k), and dz =Dz(i,j,k) in the x-, y- and z-axis respectively.

A sample format from Fanuc: Here I = 3, J = 4, and K = 3, and l =I*J*K=36 is the maximum line number. A1 = x-axis, A2 = y-axis, A3 = z-axis, and the number next to P is the error value [ ].

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N100001A1P[dx]A2P[dy]A3P[dz]        i=1, j=1, k=1, l=1,
N100002A1P[dx]A2P[dy]A3P[dz]        i=2, j=1, k=1, l=2,
N100003A1P[dx]A2P[dy]A3P[dz]        i=3, j=1, k=1, l=3,
N100004A1P[dx]A2P[dy]A3P[dz]        i=1, j=2, k=1, l=4,
N100005A1P[dx]A2P[dy]A3P[dz]        i=2, j=2, k=1, l=5,
N100006A1P[dx]A2P[dy]A3P[dz]        i=3, j=2, k=1, l=6,
N100007A1P[dx]A2P[dy]A3P[dz]        i=1, j=3, k=1, l=7,
N100008A1P[dx]A2P[dy]A3P[dz]        i=2, j=3, k=1, l=8,
N100009A1P[dx]A2P[dy]A3P[dz]        i=3, j=3, k=1, l=9,
N100010A1P[dx]A2P[dy]A3P[dz]        i=1, j=4, k=1, l=10,
N100011A1P[dx]A2P[dy]A3P[dz]        i=2, j=4, k=1, l=11,
N100012A1P[dx]A2P[dy]A3P[dz]        i=3, j=4, k=1, l=12,
N100013A1P[dx]A2P[dy]A3P[dz]        i=1, j=1, k=2, l=13,
N100014A1P[dx]A2P[dy]A3P[dz]        i=2, j=1, k=2, l=14,
N100015A1P[dx]A2P[dy]A3P[dz]        i=3, j=1, k=2, l=15,
…………………………………..           …………………..
…………………………………..           …………………..
N100034A1P[dx]A2P[dy]A3P[dz]        i=1, j=4, k=3, l=34,
N100035A1P[dx]A2P[dy]A3P[dz]        i=2, j=4, k=3, l=35,
N100036A1P[dx]A2P[dy]A3P[dz]        i=3, j=4, k=3, l=36,
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The volumetric error can be defined as the maximum error in the 3D grid. That is,
Volumetric error = Max sqrt[Dx(i,j,k)* Dx(i,j,k) + Dy(i,j,k)* Dy(i,j,k)
+ Dz(i,j,k)*Dz(i,j,k)].

The errors measured by the vector method can be used to generate this 3D error map and calculate the maximum error.

VIII. Summary and conclusion

20 years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. The volumetric error is defined as the root-mean-square sum of the displacement error of each axis is okay. Now, for most of the machines the dominate errors are the straightness and squareness errors, the volumetric error should be defined as the root-mean-square sum of the total error in the x, y, and z directions.

The ASME B5.54 or ISO 230-6 machine tool performance measurement standards the laser body diagonal displacement measurement is a quick check of the volumetric error. This body diagonal displacement measurement has been used by many aerospace company and many others for many years with very good results and success. The sequential step body diagonal or vector method is a very efficient and quick way to determine the displacement errors, straightness errors and squareness errors [4,5].

The maximum error in a 3D grid is very useful for machine tool users to determine how accurate a part can be machined and where is the sweet spot of the machine.

References

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