Understanding volumetric positioning errors

Body diagonal measurement is not sensitive to angular errors

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For years, the Body Diagonal Displacement Method defined in the ASME B5.54 or ISO 2306 standard has provided a quick check of volumetric error for such companies as Boeing Aircraft Company and many others with good results. Since these measurements are relatively simple and quick to make, cost and machine downtime are minimized. However, the relationships between the body diagonal displacement errors and the 21 rigid body errors have not been made clear. In addition, the importance of angular errors has been mistakenly inflated. To understand the relationships and the importance of angular errors, it is necessary to derive the relations between the 21 rigid body errors and the measured body diagonal displacement errors.

Matrix method to derive the relations

The rigid body 21 errors include three each of the following errors: linear displacement, vertical straightness, horizontal straightness, roll angular, pitch angular, yaw angular, and squareness. Using a conventional laser interferometer for measuring the straightness and squareness errors requires a prohibitive amount of time, leading to the development of the body diagonal displacement method for a quick check as defined in the ASME B5.54 or ISO 230-6 standards.

Body diagonal displacement errors

The body diagonal displacement method is a measurement of the volumetric positioning accuracy with a laser interferometer. A laser is mounted on the machine bed and a retroreflector mounted on the spindle reflects a laser beam aligned along the machine diagonal. The 4-body diagonal displacement measurement directions are ag, bh, ce, and df (see figure 1).

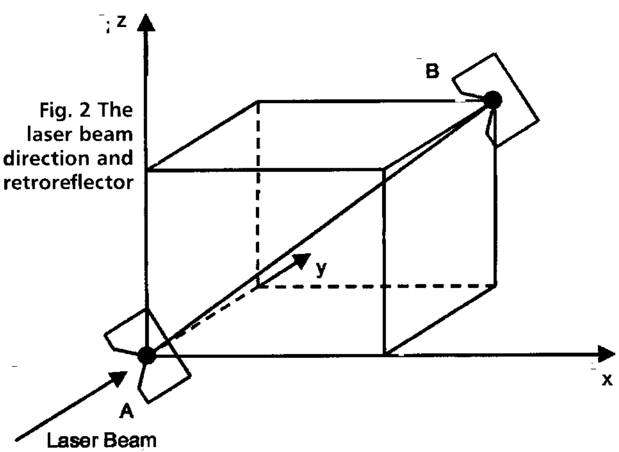

Fig. 2 The laser beam direction and retroreflector

The measurements are taken with the laser pointing along the body diagonal direction and the retroreflector moving along the body diagonal at a specified increment (see figure 2). Beginning at the zero position and at each increment of the three axes, which are moved together to reach a new position along the diagonal, the displacement error is measured. The body diagonals are defined by positive (p) or negative (n) axis movement.

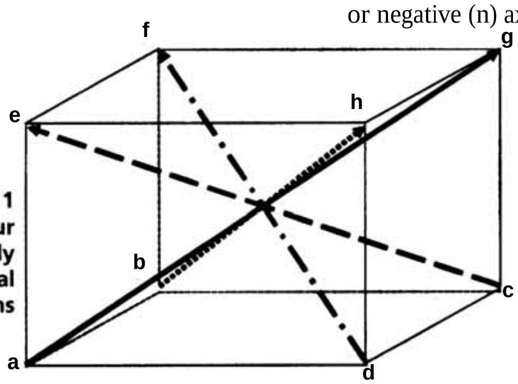

Fig. 1 The four body diagonal directions

The last four body diagonals are the same corners as the first four diagonals, except the directions are reversed. For that reason, there are only four body diagonal directions with forward movement and reverse movement (bi-directional); and only four setups with measurements taken after each simultaneous X, Y, and Z move. The accuracy of each position along the body diagonal depends on the positioning accuracy of all three axes and the machine's geometrical errors.

The theoretical results indicate that the four body diagonal displacement errors are sensitive to all nine linear errors and two angular errors. The error terns in the body diagonal displacement error equation may be positive or negative, and they may cancel each other out. Because 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 four body diagonals is theoretically possible but highly unlikely. Since most of the angular error terms are cancelled and only two angular error terms are left, we concluded the body diagonal displacement errors, including three displacement errors, six straightness errors, and three squareness errors, are not sensitive to angular errors. Accordingly, it is a good and quick measure of the 3D (volumetric) positioning accuracy.

Since there are only four sets of data

and nine sets of errors, not enough information exists to determine the source of errors. This led to the development of the Sequential Step Diagonal Measurement or Laser Vector Technique developed and patented by Optodyne Inc.

Sequential step diagonal measurement

The sequential step diagonal measurement method collects 12 sets of data with the same four diagonal setups. Based on these measurement data, all three displacement errors, six straightness errors, and three squareness errors can all be determined. This allows 3D (volumetric) positioning errors to be measured without high costs and lengthy machine tool down time. What's more, the measured positioning errors can also be used to generate a 3D (volumetric) compensation table for correcting the positioning errors to improve positioning accuracy.

The sequential step diagonal measurement method differs from the body diagonal displacement measurement in that each axis moves separately in sequence and the diagonal positioning error is collected after each separate movement of the X-axis, Y-axis, and then Z-axis. This collects three times the amount of data and allows the positioning error for each separate axis movement to be measured.

In the sequential step diagonal method, the movement is alternatively along the X-axis, the Y-axis, and then the Z-axis. It is repeated until the opposite corner of the diagonal is reached. The trajectory of the target is not a straight line and the lateral movement is quite large (see figure 3). A conventional interferometer cannot make these measurements because it does not tolerate such a large lateral movement. However, such single-aperture laser interferometers as a Laser Doppler Displacement Meter (LDDM) can be used. With a flat mirror as the target, the movement parallel to the mirror does not displace the laser beam and does not change the distance from the source, and, therefore, the measurements are not affected.

Test case on a VMC with Fanuc16i CNC

The sequential step diagonal measurement was tested using a vertical machining center (VMC) with a Fanue 16i controller. The measured volume was X = 55" (1397 mm) to 139" (3530.6 mm), Y = 2" (50.8 mm) to 50" (1270 mm) and Z = 10.5" (266.7 mm) to 34.5" (876.3 mm).

For the error measurements, we used an Optodyne model MCV-500 LDDM with SD-500 sequential diagonal measurement accessory single-aperture laser calibration system with a steering mirror for easy alignment of the laser beam in the body diagonal direction. The laser was mounted on the table of the VMC. A 3"x 4" (75x100mm) axe, Ya, z,) flat mirror was mounted on the spindle with the surface perpendicular to the laser beam. The air temperature and pressure were measured to compensate for changes in the speed of light and the machine temperature was measured to compensate for thermal growth.

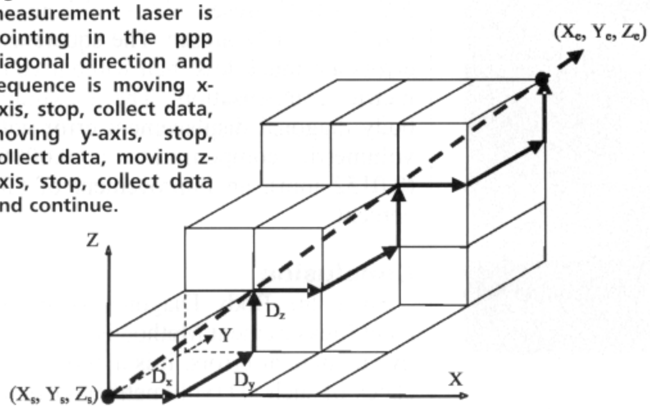

Fig. 3 The vector measurement laser is pointing in the ppp diagonal direction and sequence is moving x-axis, stop, collect data, moving y-axis, stop, collect data, moving z-axis, stop, collect data and continue.

Four setups were required, including one along each body diagonal direction: ppp, npp, pnp and nnp for four directions. The control was programmed to move the spindle beginning at one corner and moving to the opposite corner. The measurement data were automatically collected by the Windows LDDM software at every stop. The software analyzed the data and automatically calculated the errors for each axis.

Two sets of body diagonal displacement data were collected, one without 3D (volumetric) compensation and one with 3D (volumetric) compensation. Linear displacement errors of each axis with the volumetric compensation were also measured. Based on the measured sequential step diagonal data, the 3D (volumetric) positioning errors.

including three displacement errors, six straightness errors, and three squareness errors were measured. This allowed automatic generation of a 3D (volumetric) compensation file.

The measured squareness errors are XY = -5.72 arcsec, YZ = 1.73 arcsec and ZX = 3.47 arcsec. The measured linear displacement errors, vertical straightness and horizontal straightness of X-axis, Y-axis and Z-axis. For the Xaxis, the maximum vertical straightness error (deviation in the y-direction) is +0.00035" (0.009 mm); the maximum horizontal straightness error (deviation in the z direction) is - 0.0005" (0.0127 mm); and the maximum displacement error is - 0.0005" (0.0127 mm).

For the Y-axis, the maximum vertical straightness error (deviation in the x-direction) is 0.0002"/-0.0004" ~0.0051mm/-0.0102mm); the maximum horizontal straightness (deviation in the z-direction) is 0.0035"/-0.004"(0.0889mm/-0.0102mm); and the maximum displacement error is - 0.0013" (-0.0330 mm).

For the Z-axis, the maximum vertical straightness error (deviation in the x-direction) is 0.0005" (0.0127 mm); the maximum horizontal straightness error (deviation in the y-direction) is 0.00055" (0.0140 mm); and the maximum displacement error is -0.0015" (0.0381 mm).

The measured ASME B5.54 or ISO 230-6 body diagonal displacement maximum error without compensation is 0.003" (0.0762 mm). Using the laser sequential step diagonal data and the calculated volumetric positioning errors, the straightness error compensation table was generated for the Fanuc 16i Controller. The linear displacement errors of each axis were measured with the volumetric compensation. The measured maximum errors were 0.0002" (0.0051 mm), 0.0001" (0.00254 mm) and 0.0001" (0.00254 mm) for X-, Y, and Z-axis respectively. These errors are considerably less than without volumetric compensation. With volumetric compensation, the squareness errors are XY = - 0.05 arcsec, YZ = - 3.7 arcsec and ZX = -0.32 arcsec. The squareness errors are much less than without volumetric compensation. The maximum body diagonal displacement error with volumetric compensation is 0.0006" (0.0152 mm), an improvement of 500 percent.

Conclusion

Since the Body Diagonal Displacement Measurement Method is not sensitive to angular errors, it is a good quick check of such 3D (volumetric) positioning errors as the three displacement errors, six straightness errors and three squareness errors. The Sequential Step Diagonal Measurement Method collects 12 sets of data for solving all nine linear errors and three squareness errors. The measured 3D (volumetric) positioning errors can be used to generate the 3D (volumetric) compensation file and reduce the body diagonal displacement error considerably. This makes the calibration and compensation of 3D (volumetric) positioning errors of CNC machining centers or CMM economically viable, practical, and necessary.

For an expanded white paper complete with the formulae for the 3D volumetric positioning errors of CNC machining centers in the four basic configurations derived by using third order translation and rotation matrices, please visit **Optodyne Inc., www.rsleads.com/509-161**