Measurement of 18 positioning errors Using a simple laser Doppler displacement meter

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Abstract

The measurement and compensation of 3D volumetric positioning accuracy becomes more important for quality assurance and to achieve higher accuracy. The introduction of B5.54 and ISO230-6 machine tool performance measurement standards are increasing the popularity of laser interferometer body diagonal, sequential step diagonal or vector technique for the calibration and compensation of machine tool errors. This is because the reduction in calibration time these methods can provide over the conventional laser interferometer based measurement.

To complete the measurement of all 21 rigid body positioning errors, the pitch and yaw angular errors can be determined by 3 linear displacement measurements along the same axis but at different locations or Abbe offset. Hence 18 of the 21 rigid body positioning errors can all be measured by a laser Doppler displacement meter (LDDM). The measurement accuracy is limited by the repeatability of the machine. The performance of these measurements is relatively simple, fast and straight forward.

Reported here are the basic theory, performance verification and comparison of the vector technique and the composite technique. The test results including the test setup and operation, data collection and analysis, results and conclusions will be described.

I. Introduction

The worldwide competition and quality standards such as ISO 9000 and QS 9000, demanded tighter tolerance and regular maintenance of all machine tools. 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 linear encoder and compensation. The largest machine tool positioning errors become squareness errors and straightness errors. Using a conventional laser interferometer to measure these errors requires very complex and expensive optics and is rather difficult and costly.

However, using the new revolutionary laser vector measurement technique developed by Optodyne (US Patent 6,519,043, 2/11/2003), the 3 D volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors, can all be measured in a few hours instead of a few days. Hence the 3 D volumetric calibration and compensation become practical, and enable higher accuracy and tighter tolerance to be achieved. The setup and alignment of the laser vector measurement are easy and usually a machine operator can be trained to perform the measurement.

For some machines, the pitch and yaw angular errors may be large and need to be measured. Instead of using another dual-beam laser calibration system, or add another laser head, the same linear laser calibration system can be used to measure the pitch and yaw angular errors by repeated measurements with different Abbe offsets and data processing software. There is no need for additional hardware, hence it is a cost saving.

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 error measurement

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 measurement of the body diagonal displacement errors is recommended by many standards such as ASME B5.54 [2] and ISO 230-6 [3] for a fast check of the volumetric performance. This is because the body diagonal displacement measurement is sensitive to all of the error components [4].

Briefly, similar to a laser linear displacement measurement, instead of point the laser beam in the axis direction, point 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 to the opposite upper corner. 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 ASME B5.54 body diagonal displacement tests have been used by Boeing Aircraft and many others for many years with very good results and success in determine the volumetric positioning accuracy. Hence, it is a good check on the volumetric positioning accuracy. However, if the machine is not accurate, there is not enough information on where the errors are and how to compensate them.

IV. Vector or sequential step diagonal measurement

The sequential step diagonal measurement or laser vector measurement technique was developed by Optodyne for the calibration of 3 D volumetric positioning accuracy of a machine tool [5, 6]. Similar to the ASME B5.54 standard body diagonal displacement measurement, the laser beam is pointing in the body diagonal direction. 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 as shown in Fig. 1. 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, the setup and alignment is simple and therefore the cost is low.

In the conventional body diagonal displacement measurement, the target trajectory is a straight line and it is possible to use the corner cube as target that can tolerate a small lateral displacement. In the vector method, the movement is alternatively along the x axis, than along the y axis and than along the z axis, and repeated until the opposite corner of the diagonal is reached. As shown in Fig. 1, the trajectory of the target is not parallel to the laser beam direction and the lateral movement is quite large. Hence it is necessary to use a flat-mirror as target as shown in Fig. 2. With a flat mirror as target, the movement parallel to the mirror does not displace the laser beam and do not change the distance from the source so the measurement is not influenced.

Conventional laser interferometers are based on the Michaelson interferometer. There are two laser beams, the output beam and the return beam, which are parallel but displaced about 1", as shown in the top of Fig. 3. Hence, large optics is required. Also, the alignment is critical, 3 elements have to be aligned on two parallel axes. The laser head is large and heavy, and a heavy tripod is needed to support the laser head.

The single-aperture MCV-500C laser system is based on laser Dopplermetry. The laser head is very compact (2” x 2” x 8.5”) and is completed with stabilization circuits, electro-optics, and photo-detectors. As shown in the bottom of Fig. 3, the output beam and the return beam are coaxial and share the same aperture. Hence large optics is not required and also a flat-mirror can be used as a target. The compact size and lightweight of the laser head and optics allows the operator to mount the components to the machine directly with magnetic bases without the use of a tripod.

V. 3 D volumetric positioning error compensation

For a machine tool, as long as it is repeatable, the volumetric positioning accuracy can be improved up to the positioning repeatability of the machine. Many CNC machines with advanced controllers have the capability to perform the 3 D volumetric compensation, such as Fanuc with straightness compensation capability, Heidenhain with nonlinear compensation capability and Siemens with sag compensation capability. For some CNC machines without the volumetric compensation capability, the 3 D volumetric compensation can be achieved by compensate the parts program using the formulae below.

$$Dx(x,y,z) = Dx(x) + Dx(y) + Dx(z) \quad (1)$$
$$Dy(x,y,z) = Dy(x) + Dy(y) + Dy(z) + Øxy*x/X \quad (2)$$
$$Dz(x,y,z) = Dz(x) + Dz(y) + Dz(z) + Øyz*y/Y + Øzx*x/X. \quad (3)$$

Where the Dx(x,y,z), Dy(x,y,z) and Dz(x,y,z) are correction values in the x, y, and z direction at the position (x,y,z). Many software can be used to convert an existing parts program to a new parts program with corrected positions[7].

VI. Linear displacement, pitch and yaw angular error measurement

It is noted that the linear displacement errors are different when measured at different locations due to the pitch or yaw angular errors. Hence, if the machine is repeatable, the measured linear displacement errors can be used to calculate the pitch and yaw angular errors. As shown in [4], in the linear displacement error measurement, the measured error D along x, y, and z-axis at each increment can be expressed as:

$$DX = Dx(x) + m * Ay(x) + p * Az(x), \quad (4)$$
$$DY = Dy(y) + q * Ax(y) + s * Az(y), \quad (5)$$
$$DZ = Dz(z) + t * Ax(z) + u * Ay(z), \quad (6)$$

where Abbe offsets m and p are distances from the measurement line to the reference line in y and z directions respectively, q and s are distances from the measurement line to the reference line in x and z directions respectively, t and u are distances from the measurement line to the reference line in x and y directions respectively.

Theoretically, based on Eq. 4, three linear measurements along x-axis at 3 different locations with known Abbe offsets m1,p1; m2, p2; and m3, p3, can be expressed as,

$$DX1 = Dx(x) + m1 * Ay(x) + p1 * Az(x), \quad (7)$$
$$DX2 = Dx(x) + m2 * Ay(x) + p2 * Az(x), \quad (8)$$
$$DX3 = Dx(x) + m3 * Ay(x) + p3 * Az(x), \quad (9)$$

There are 3 sets of data DX1, DX2 and DX3 and 3 unknowns Dx(x), Ay(x) and Az(x). The solutions are,

$$Ay(x) = [(m3-m1)*(DX2-DX1)-(m2-m1)*(DX3-DX1)] / [(m3-m1)* (p2-p1) - (m2-m1)*(p3-p1)]. \quad (10)$$
$$Az(x) = [(p3-p1)*(DX2-DX1)-(p2-p1)*(DX3-DX1)] / [(m3-m1)* (p2-p1) - (m2-m1)*(p3-p1)]. \quad (11)$$
$$Dx(x) = DX1*(m2*p3-m3*p2) + DX2*(m3*p1 - m1*p3) + DX3* (m1*p2 - m2*p1) / [(m3-m1)*(p2-p1)-(m2-m1)*(p3-p1)]. \quad (12)$$

Similarly for the y- and z-axis errors, Ax(y), Az(y), Dy(y), Ax(z), Ay(z), and Dz(z) can all be determined. Of course, the accuracy of the measurement is limited by the repeatability of the machine and the Abbe offset. For example, for a machine with repeatability of 0.0001”(2.5 µm) and the Abbe offset of 20”(500 mm), the accuracy of the angular measurement is 0.0001/20 = 0.000005 rad, or 1 arcsec which is good enough for most of the machines.

VII. Test setup

The test was performed on a vertical machining center. The working volume is 40” x 20” x 20”. The specified axis accuracy is 0.0002” and axis repeatability is 0.0001”. The controller has the capability of compensate the pitch errors for all three axes. In all the measurement reported here, the pitch error compensation values were all set to 0. A single aperture LDDM laser calibration system was used to perform all the measurement. For all the measurement the laser heads were mounted on the machine bed with magnetic holders and the targets were mounted on the spindle with magnetic holders.

The Air temperature and barometric pressure were measured to compensate the changes in speed of light and the machine temperature was measured to correct the machine thermal expansion. The material thermal expansion coefficient was set at 6.7 ppm per degree F. The material temperature varied from 54 degree F to 70 degree F. The automatic data acquisition, the error analysis and automatic generation of the compensation files, were performed by the Optodyne LDDM Windows software.

For x-axis linear and angular measurement, there were 3 setups. In the first setup, the laser beam was at y = 0 and z= 4.25”. In the second setup, the laser beam was at y = 0 and z = 14.75”. In the third setup, the laser beam was at y = 7.5” and z = 4.25”.

Similarly, for y-axis measurement, in the first setup, the laser beam was at x = 0 and z= 4.25”. In the second setup, the laser beam was at x = 0 and z = 14.75”. In the third setup, the laser beam was at x = 7.5” and z = 4.25”. For z-axis measurement, in the first setup, the laser beam was at y = 0 and x = 0. In the second setup, the laser beam was at y = 0 and x = 10.5”. In the third setup, the laser beam was at y = 10.5” and x = 0.

The setup for the vector measurement is the same as the body diagonal displacement measurement, except the retroreflector is replaced by a 4” x 6” flat-mirror as shown in Fig. 2. Here, the flat-mirror is moving along the x-axis, then along the y-axis, then along the z-axis and repeat the sequence until reached the opposite corner of the diagonal.

The laser was mounted on the machine table and using the steering mirror to aligned the laser beam parallel to the diagonal. The flat mirror was mounted on the spindle with the surface perpendicular to the laser beam. The machine was programmed to move the spindle starting from one corner to the opposite corner. The measurement data were automatically collected by the Windows LDDM software at every machine stop or at each single axis of movement.

It is noted that, the laser vector measurement only took 2 to 4 hours instead of 20 to 40 hours by a conventional laser interferometer. The laser setup is very simple and the data collection is automatic. The data processing and compensation file generation are all automatic without manual compilation to minimize errors. Hence, a machine operator may be trained to perform the laser calibration and compensation without the need of an experienced quality engineer.

VIII. Measurement results

All the measurements were performed bidirectional and repeated 5 times. Based on the ASME B5.57 standard or the ISO 230-2 standard, the accuracy A, the repeatability R, the systematic deviation E, and reversal value B were calculated and tabulated in the tables. Typical results are shown in Table 1 the linear displacement error in x-axis, y-axis and z-axis. For linear displacement error in x-axis, the accuracy A = 0.000409”, the repeatability R = 0.000314”, and the systematic deviation E = 0.000312”. For vertical straightness error in x-axis, the accuracy A = 0.000879”, the repeatability R = 0.000746”, and the systematic deviation E = 0.000657”. For horizontal straightness error in x-axis, the accuracy A = 0.000950”, the repeatability R = 0.000693”, and the systematic deviation E = 0.000764”. These results show that the repeatability of the machines is very good and the straightness errors are not negligible as compared to the linear displacement errors. Hence, only compensating the 3-axis displacement errors is not enough. The straightness and squareness errors should also be compensated to achieve higher volumetric positioning accuracy.

The pitch and yaw angular errors of each axis were determined by measuring linear displacement errors at 3 different locations. The x-axis, maximum pitch angular errors were + 4 arcsec to -3 arcsec and the maximum yaw angular errors were +0 to -6 arcsec. The y-axis, maximum pitch angular errors were + 7 arcsec to -0 arcsec and the maximum yaw angular errors were +0 to -5 arcsec. The z-axis, maximum pitch angular errors were + 0.5 arcsec to -0.8 arcsec and the maximum yaw angular errors were +0 to -5 arcsec. The measured maximum squareness errors were xy-plan -19.65 arcsec, yz-plan -4.19 arcsec, and xz-plan -11.62 arcsec. The 3D volumetric positioning errors, namely, displacement errors, vertical and horizontal straightness errors and squareness errors of each axis were measured by the vector or sequential step diagonal technique. Based on these measured errors, 3D volumetric compensation files were generated for the volumetric compensation.

The measured 4 body diagonal displacement errors without and with volumetric compensation are plotted in Fig. 4a and 4b respectively. The maximum body diagonal displacement errors were reduced from 0.005" to 0.0008" by 3D volumetric compensation, a 625% improvement.

IX. Summary and conclusion

The linear displacement errors were measured at 3 different locations for each axis. With the new software, the pitch and yaw angular errors can be calculated. The **vector** technique or sequential step diagonal technique has been used to measure the 3 D volumetric positioning errors or the straightness errors and squareness errors. The measured 3 D volumetric positioning errors have been used to generate the compensated parts program. The 4 body diagonal displacement errors were reduced considerably with the volumetric compensation.

In conclusion, as manufacturers continue to expand six sigma quality programs to improve products and reduce costs, their vendors are being required to improve the quality of their work. To comply with quality programs, shops should be required to calibrate and compensate machine tools volumetrically instead of just linearly. With 3 D volumetric calibration and compensation, better quality and higher precision parts can be cut.

References

1, R. Schultschik, "The components of the volumetric accuracy", Annals of the CIRP Vol. 25, No. 1, pp. 223-228, l977.
2, "Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers" An American National Standard, ASME B5.54-1992 by the American Society of Mechanical Engineers, p69, 1992.
3, 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.
4, C. Wang and G. Liotto, A theoretical analysis of 4 body diagonal displacement measurement and sequential step diagonal measurement, Proceedings of the LAMDAMAP 2003 Conference, Huddersfield, England, July 2-4, 2003.
5, 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, October 2000.
6, J. Jenecko, B. Griffin and C. Wang, "Laser Vector Measurement Technique for the determination and compensation of volumetric positioning errors. Part II: Experimental verification", Review of Scientific Instruments, Vol. 71, No. 10, pp.3938-3941, October 2000.
7, C. Chung, S. Yeh, J. Liang, and C. Wang, "Design of Volumetric Error Software Compensation Algorithm", Proceedings of the JUSFA 2002 Conference in Hiroshima, Japan, July 15-17, 2002.

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Figure captions

1. The vector measurement, laser is pointing in the ppp diagonal direction and the sequence is moving x-axis, stop, collect data, moving y-axis, stop, collect data, moving z-axis, stop, collect data and continue.
2. Shows the sequential step diagonal measurement using a flat-mirror as target.
3. A comparison of conventional laser interferometer with 2 apertures(top) and MCV-500 with a single-aperture(bottom).
4. Four body diagonal displacement error, a) without compensation and b) with volumetric compensation. The total error was reduced from 0.027 mm to 0.007 mm, an improvement of 380%.

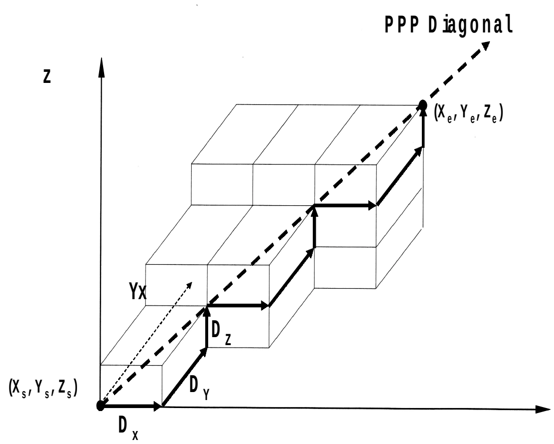

Fig. 1, The vector measurement, laser is pointing in the ppp diagonal direction and the sequence is moving x-axis, stop, collect data, moving y-axis, stop, collect data, moving z-axis, stop, collect data and continue.

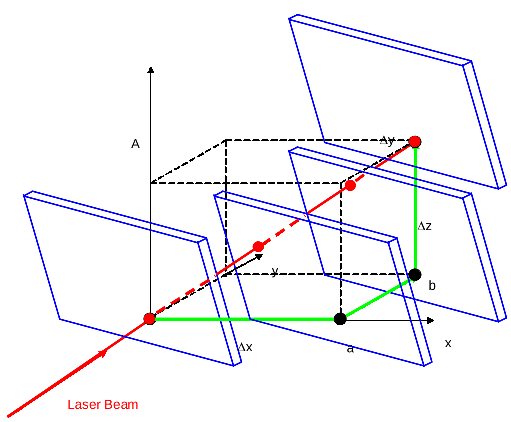

Fig. 2, Shows the sequential step diagonal measurement using a flat-mirror as target

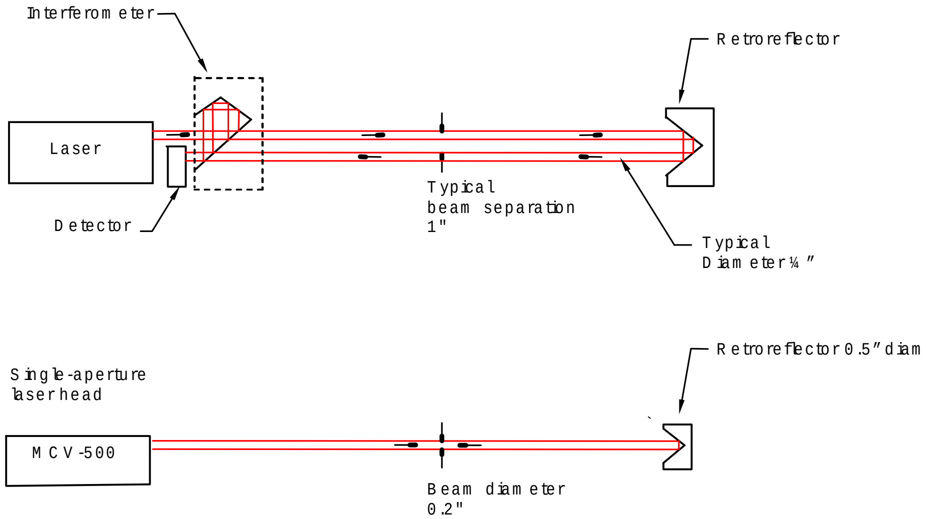

Fig. 3, A comparison of conventional laser interferometer (top) with 2 apertures and MCV-500 (bottom) with a single-aperture.

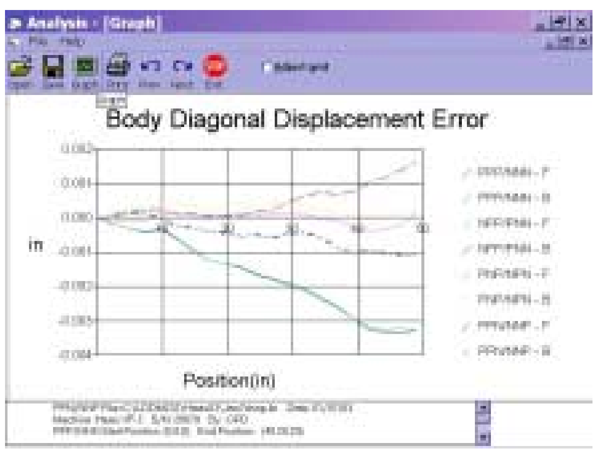

Fig. 4a, The measured 4 body-diagonal displacement errors.

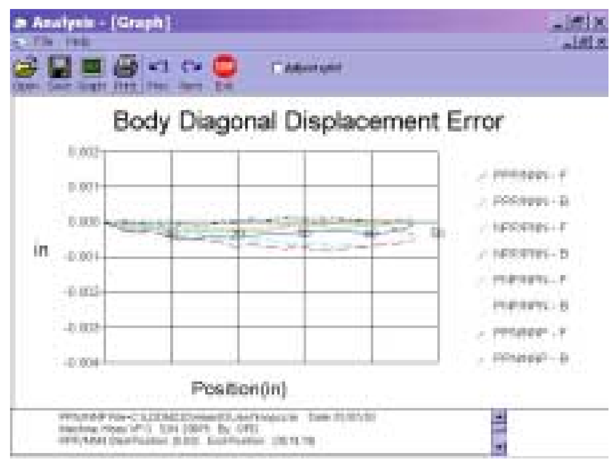

Fig. 4b, The measured 4 body-diagonal displacement errors with volumetric error compensation.

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