High Accuracy On-machine Measurement With Volumetric Error Correction

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Abstract

On-machine measurement is growing widespread application to increase productivity and effectiveness. It yields time, quality and productivity improvement. However, the major objection for on-machine measurement is that the part is measured on the same machine, which made it. Any positioning errors that occurred during machining are very likely to be repeated during inspection. Furthermore, measuring machine accuracy should be at least 4 times more accurate than the parts to be measured.

To overcome these objections, it is necessary to measure the volumetric positioning errors of the machine, and to correct the errors volumetrically. It is noted that only measuring the displacement errors of all 3 axes is not enough. It is necessary to correct the volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors.

Recently, Optodyne has developed a new laser vector measurement technique (patent pending) for the measurement of volumetric positioning errors. The setup and operation is simple. It can be operated by a machine operator and measures the volumetric errors in 2 to 4 hours for a working volume about 1 cubic meter. Using the measured volumetric positioning errors, a lookup correction table can be generated for the on-machine measurement software to compensate the machine positioning errors volumetrically. Therefore, high accuracy on-machine measurement can be achieved.

I. Introduction

A coordinate measuring machine (CMM) can be used to check a part off-line. However, it is very time consuming. It needs additional part handling and another setup, adding to process time. CNC machine tool and CMM have a great deal in common, computer controls, servo-driven moving elements, programmability and sophisticated software based capabilities. To save time and cost, it is more desirable to probe the part while it is still on the machine.

On-machine measurement, replacing the tool tip by a probe to gather dimensional data for part inspection, seems to be very attractive. The concerns are that the on-machine measurement diverts machine time away from making chips, and on-machine measurement may not be accurate enough.

The recent growth of on-machine measurement is being driven by the needs such as shifting to flexible machining, shorter lead times, tighter accuracy specifications and automated processing. The growth is also being driven by the advances in probe technology [1], improved machine repeatability and sophisticated CAD/CAM software [2].

However, the major objection for on-machine measurement is that the part is measured on the same machine, which made it. Any positioning errors that occurred during machining are very likely to be repeated during the measurement. Furthermore, the 4 to 1 ratio of gage accuracy requires that the measuring machine accuracy to be 4 times more accurate than the part accuracy.

II. Inherent Machine positioning errors

The linear displacement errors, straightness errors, squareness errors, angular errors and non-rigid body errors determine the performance or accuracy of a CNC machine tool. The characterization of a machine movement is very complex. For each linear axis of motion, there are 6 errors, namely, 3 linear displacement errors, pitch, yaw and roll angular errors. For a 3-axis machine, there are 18 errors plus 3 for squareness, a total of 21 errors, [3, 4].

For the application here, the major inherent machine positioning errors are the linear displacement errors, squareness errors, straightness errors and thermal distortion errors.

1. Linear displacement errors or lead-screw pitch errors:
   For most CNC machine tools, the linear displacement errors can be measured by a laser system and compensated by the controller.

2. Squareness errors:

The out-of-square condition between the two axes is another inherent machine error. The magnitude of this error grows as the machine travels away from the line of travel along which it was compensated for pitch errors.

3. Straightness errors:
   The guide surface is not perfectly straight; weight shifting and overhanging during axis travel may cause straightness errors. These errors will cause positioning errors.

4. Thermal expansion and distortion errors:
   The material temperature change will cause the lead-screw to grow and the temperature gradient will distort the machine geometry. All these will affect the positioning errors. Hence, it is important to calibrate the machine volumetrically under various temperature conditions to minimize the thermal effect.

III. Volumetric error measurement and compensation

Recently, Optodyne has developed a new laser **vector** measurement technique [5, 6] for the measurement of volumetric positioning errors. Using the measured volumetric positioning errors, a lookup correction table can be generated for the on-machine measurement software, to compensate the machine positioning errors volumetrically.

Conventional laser measurement may measure the linear positioning errors for the 3 axes and generate the lead-screw pitch error compensation tables for the 3 axes. However, just compensating the 3 linear axes is not enough. The squareness errors and straightness errors are usually large and may cause large positioning errors over the working volume of the machine.

Using conventional laser interferometers to measure the linear positioning errors, straightness errors and squareness errors of a 3 axes machine, may take a considerable amount of time and requires an experienced operator to run the complex laser system and to generate the volumetric error compensation table. The equipment is expensive, the setup and operation are complex. Hence it is not practical.

As compare with conventional laser interferometer measurements, the laser **vector** method measures the **vector** errors, namely, the displacement error, vertical straightness error and horizontal straightness error, rather than the displacement error only. With 4 setups, all 3-displacement errors, 6 straightness errors, and 3 squareness errors can be determined, and the volumetric positioning error compensation table generated. The equipment cost is low, the setup and operation is simple. It can be set-up and run by a machine operator and measures the volumetric errors in 2 to 4 hours for a working volume about 1 cubic meter.

IV. Vector measurement technique

The basic concept of the laser **vector** measurement technique [5,6] 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. Furthermore, collecting data with the laser beam pointing in 4 different diagonal directions, all 9-error components can be determined. Since the errors of each axis of motion are the vector sum of the 3 perpendicular error components, we call this measurement a "**vector**" measurement technique.

1. Body Diagonal Displacement Measurement

The body diagonal displacement measurement method, ASME B5.54 standard [7] is recommended for a fast check of the positioning and geometrical accuracy of a machine. 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 as shown in Fig.1a. Mount a retroreflector on the spindle and move the spindle in the body diagonal direction, for example from the lower left corner (X=0 Y=0 Z=0) to the upper right 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 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 body diagonal displacement measurement is a good method for the machine verification, but there is not enough information for the identification of the error sources.

2. Vector or Sequential Diagonal Measurement

The new vector measurement method or *Sequential Diagonal Measurement Method* differs from the traditional method because each axis is moved separately and the positioning error is collected after each single movement of the X axis, of the Y axis and than of the Z axis. For this reason, 3 times more data is collected and also the positioning error due to each single axis movement can be separated. Since each body diagonal measurement collected 3 sets of data, there are 12 sets of data. Hence, there are enough data to solve the 3 displacement errors, 6 straightness errors and the 3 squareness errors.

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(b), the trajectory of the target is not a straight line and the lateral movement is quite large. Hence it is not possible to use a conventional interferometer that cannot tolerate such large lateral movement. A laser interferometer with single aperture [8] is used with a flat mirror as target. It is noted that with a flat mirror as target, the movement parallel to the mirror do not displace the laser beam and do not change the distance from the source so the measurement is not influenced. Hence, it measures the movement along the beam direction and tolerates a large lateral movement of the target.

3. The laser measurement system

The laser calibration system is a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500. It is a newest generation laser interferometer based on Doppler effect with single aperture. The system is completed with an alignment mirror to easily steer the laser beam in the diagonal direction.

The target on the moving part of the machine was a 75×100mm flat mirror. 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 measurement data were automatically collected by the Windows LDDM software at every machine stop or at each single axis of movement. The error data has been analyzed by the LDDM software, by clicking on *4-diagonal* on the analysis section and loading the four collected diagonal data files. The errors for each axis were automatically calculated.

V. Measurement on an JOBS machine and the 3D error table

The measurement was performed on a JOBS-LINKS COMPACT 5AX linear motor machine. The machine working volume is 2 m by 3 m by 1 m (80” x 120” x 40”), and the controller is Siemens 840D. Without any compensation, the volumetric errors were measured by the Vector method or sequential diagonal measurement.

All the errors were measured and automatically generated the displacement errors and straightness errors for the x-axis, y-axis and z-axis as shown in Figs. 3, 4, and 5 respectively. At the end of the error analysis, the Windows LDDM software automatically generated the 3D error table as shown in Table 1.

VI. Probing software and lookup table

There are many CAD/CAM software packages available for on-machine probing. After a part is machined, the cutting tool is replaced by a probe, using the CNC machine as a CMM to collect data; the dimensions of the part can be verified. Since the CNC machine tool is volumetrically calibrated, the volumetric positioning errors can be tabulated as lookup tables or compensation tables. These tables are stored in the memory and are used by the software to correct the measured probe positions. This volumetric error correction eliminates the inherent errors in the machine tool geometry and positioning, and accurate dimensional measurements can be achieved. Hence, with the volumetric error compensation, a CNC machine tool becomes a high accuracy CMM and satisfies the 4 to 1 ratio of gage accuracy.

On-machine inspection becomes a viable process, which allowing a CNC machine to be used to verify the accuracy of a part it machined. This represents a major change in the way inspection is performed. Instead of a post-process check performed off-line on parts after machining, on-machine probing makes inspection part of the process, as well as a powerful process improvement tool for machining parts to specification in the shortest time.

VII. Summary and conclusion

Advances in the CNC machine tools, probing technology, CAD/CAM software and volumetric positioning error mapping, make on-machine inspection a viable process. That is, allowing a machine to be used to verify the accuracy of parts it machined. On-machine inspection becomes a viable process, which is, allowing a CNC machine to be used to verify the accuracy of a part it machined. This represents a major change in the way inspection is performed. Instead of a post-process check performed off-line on parts after machining, on-machine measurement makes inspection part of the process, as well as a powerful process improvement tool for machining parts to specification in the shortest time.

In the age of digital manufacturing and absolute quality assurance, on-machine probing with volumetric compensation, will make its contribution to the improvement in quality, throughput and costs.

References

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Figure Caption

Fig. 1, Schematics of the sequential diagonal measurement. (a) Body diagonal. (b) The working volume is divided into elementary blocks and the measurement is done for three sides of the blocks along the diagonal path.

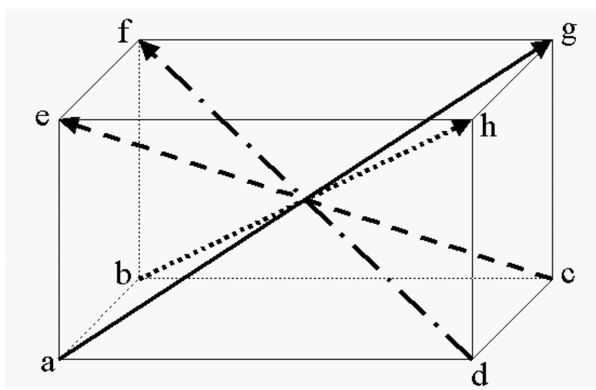
Fig. 2, A photo of the JOBS-LINKS 5-axis linear motor machine with the laser on the bed and the flat mirror on the spindle for the volumetric error measurement.

Fig. 3, X-axis errors, the upper curves are the bi-directional displacement errors, the middle curves are the straightness errors in the y-direction and the lower curves are the straightness errors in the z-direction.

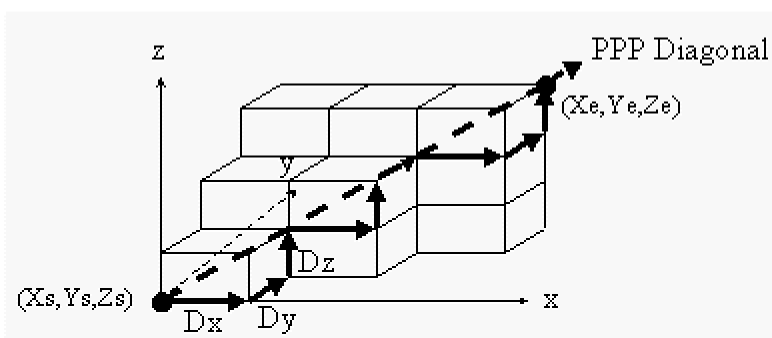
Fig. 4, Y-axis errors, the upper curves are the bi-directional displacement errors, the middle curves are the straightness errors in the x-direction and the lower curves are the straightness errors in the z-direction.

Fig. 5, Z-axis errors, the upper curves are the bi-directional displacement errors, the middle curves are the straightness errors in the x-direction and the lower curves are the straightness errors in the y-direction.

Table 1, 3D error compensation table based on the Fanuc file format.



(a)



(b)

Fig. 1. Schematics of the sequential diagonal measurement. (a) Body diagonal. (b) The working volume is divided into elementary blocks and the measurement is done for three sides of the blocks along the diagonal path.

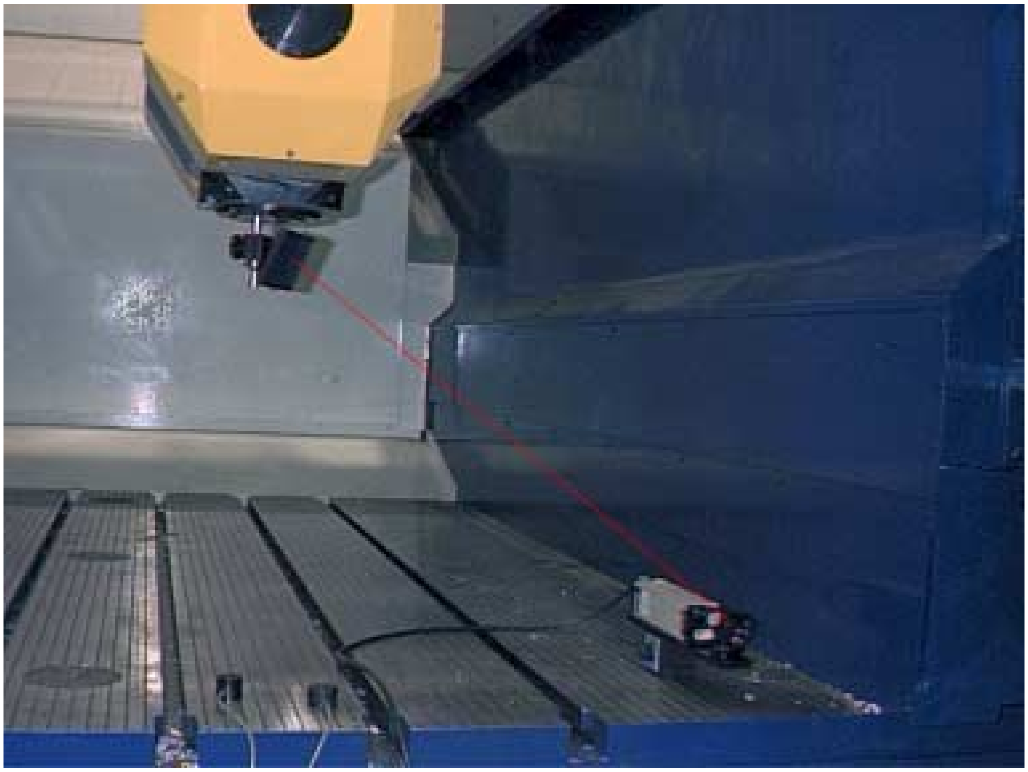


Fig. 2, A photo of the JOBS-LINKS 5-axis linear motor machine with the laser on the bed and the flat mirror on the spindle for the volumetric error measurement.

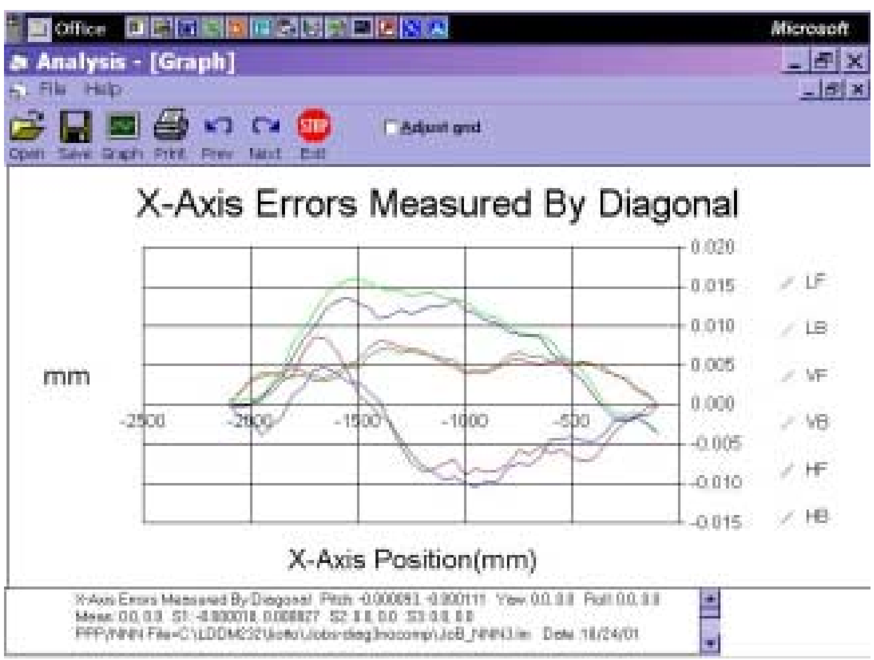


Fig. 3, X-axis errors, the upper curves are the bi-directional displacement errors, the middle curves are the straightness errors in the y-direction and the lower curves are the straightness errors in the z-direction.

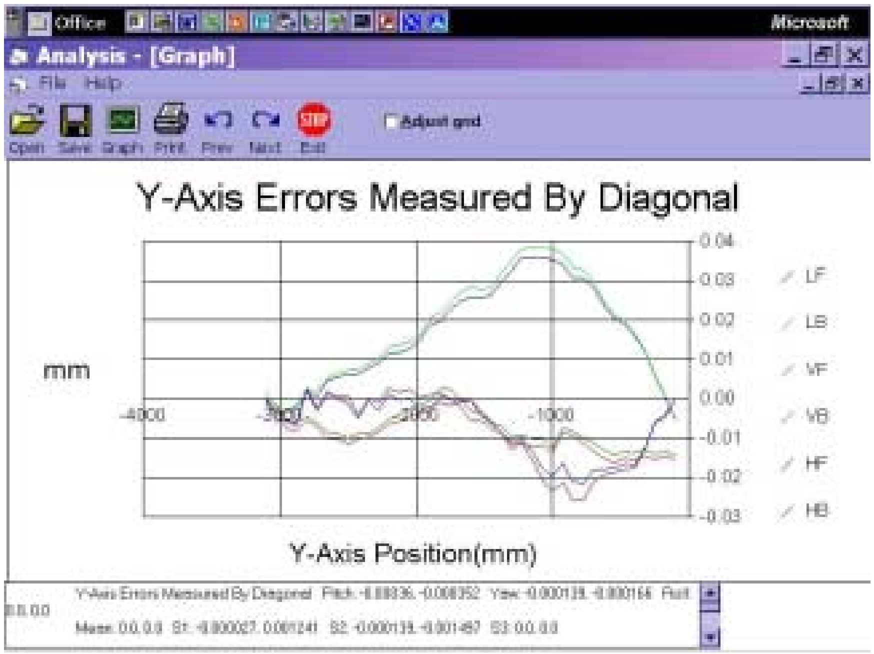


Fig. 4, Y-axis errors, the upper curves are the bi-directional displacement errors, the middle curves are the straightness errors in the x-direction and the lower curves are the straightness errors in the z-direction.

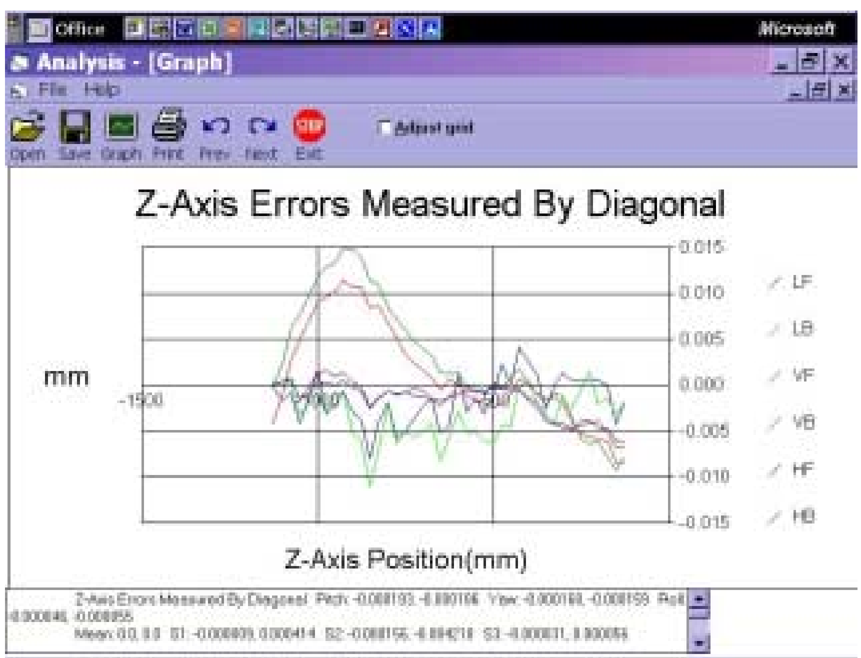


Fig. 5, Z-axis errors, the upper curves are the bi-directional displacement errors, the middle curves are the straightness errors in the x-direction and the lower curves are the straightness errors in the y-direction.

Table 1, 3D error compensation table based on the Fanuc file format

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N5442P3
N5443P21
N5444P16
N5445P11
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N5447P0
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N5453P200
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%
%
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N100003A1P15A2P1A3P-1
N100004A1P11A2P-1A3P-4
N100005A1P5A2P0A3P-4
N100006A1P1A2P-1A3P-5
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