

# **Volumetric Error Measurement and Compensation Using the Vector Method**

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To achieve higher position accuracy of a machine tool, it is important to measure the volumetric errors and to compensate the volumetric errors provided that the machine tool is repeatable. Described here is a vector method developed by Optodyne. Using the vector method, the volumetric errors of a Giddings & Lewis machine, model, RAM 630 machining center have been measured. The measured volumetric errors were used to compensate the machine errors and achieved higher volumetric accuracy. The time required to compensate the machine using the vector method is significantly less than that using conventional measurement procedures.

## **Volumetric Compensation in a CNC Machine Tool**

Competition in the global manufacturing market today requires improving the CNC machine tool performance to achieve higher productivity, better quality and less downtime. With the latest generation of CNC controls it is now possible to achieve higher quality even on a lower cost machine. To do this it is important to measure the volumetric errors of the machine tool and to compensate these errors. Many of the controls available today have this capability but very few take advantage of this technology.

For many years, the machine tool linear errors were measured and compensated by using laser interferometers. However, the linear error is only one of the many volumetric errors. The straightness errors, squareness errors, and the pitch, yaw, and roll angles may all cause poor overall volumetric accuracy, by compensating for just linear errors the overall volumetric accuracy of the machine is not significantly improved.

Most CNC machine controls today have the capacity to compensate the volumetric errors, for example on a typical three axes machine it is possible to compensate, three linear errors (or pitch error), six straightness errors (or cross errors or sag errors) and three squareness errors. The machine accuracy can be improved by measuring all these errors and then to compensate these errors, providing that the machine is repeatable. The key is how to measure all these errors accurately and quickly. There are many methods to measure these errors. However, all of these methods are very complex and the cost is normally prohibitive for smaller companies. This is one of the major reasons these errors are not compensated. The other reason is time, with the cost of machine time most companies are not willing to invest the 16 to 20 hours required to measure all these errors.

Described here is a vector method, it can measure all these errors, using a simple and portable laser interferometer or a Laser Doppler Displacement Meter (LDDM ) with 4 setups and within a few hours unlike possibly days required using conventional interferometer systems.

## Basic Concept of Vector Measurement Technique

For years standards such as the ASME B5.54 and ISO 230-2 have recommended checking the volumetric accuracy of a machine by measuring the body diagonals, this is because the measured linear errors in the diagonal direction are sensitive to all 21 errors on the machine. More precisely, the measured linear errors, are the vector sum of errors, namely, the linear 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). Furthermore, by pointing the laser beam in 3 different directions, all 3 components of the error vector 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” method.

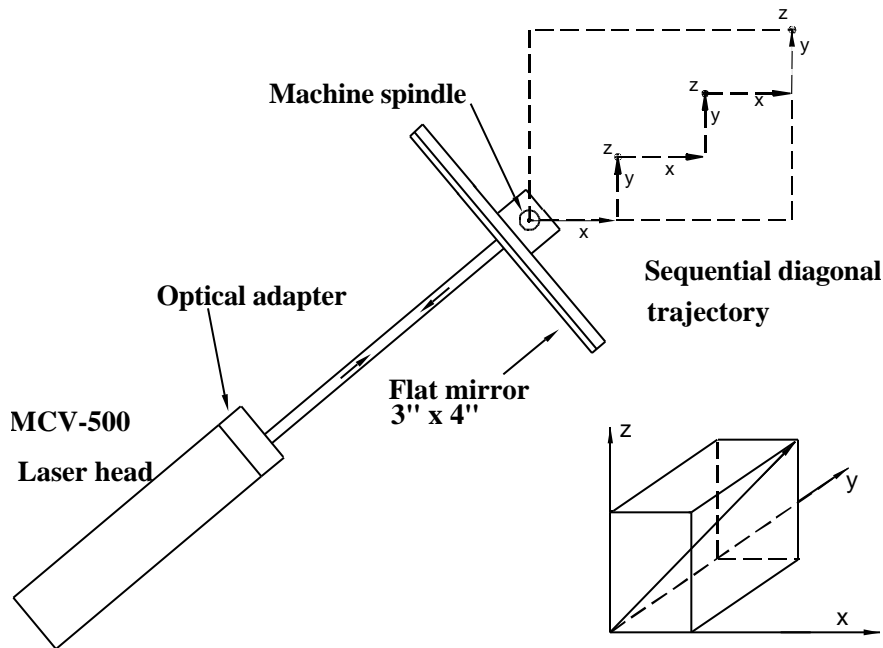
In practice, first point the laser beam in one of the body diagonal directions, same as the standard diagonal measurement. For a standard laser diagonal the machine is programmed to move x, y, and z axes simultaneously to the next increment  $dR$ , stop and take a measurement. The problem with this method is that once the data is collected there is no way to determine what caused the errors. With the “vector” method, the machine is programmed to move the X-axis to  $dX$ , stop and take a measurement, then move the Y-axis to  $dY$ , stop and take a measurement, then move the Z-axis to  $dZ$ , stop and take a measurement. Here  $dX^2 + dY^2 + dZ^2 = dR^2$ .

As compared to the conventional body diagonal measurement where only one data point is collected at each increment  $dR$ , the vector measurement collects 3 data points, one at  $dX$ , one at  $dY$  and one at  $dZ$ , hence 3 times more data is collected. Furthermore, the data collected after  $dX$  is due to the x-axis movement only, and data collected after  $dY$  and  $dZ$  are due to the y-axis and z-axis movement respectively. Hence the error sources due to the x-axis motion, the y-axis motion and the z-axis motion can be separated.

After the first diagonal is completed point the laser beam in another body diagonal direction and repeat the same process until all 4-body diagonals are measured. Since each body diagonal measurement collects 3 sets of data, there are 12 sets of data when all 4 diagonals are measured. Hence, there is enough data to solve the 3 displacement errors, 6 straightness errors, and 3 squareness errors.

For conventional body diagonal measurement, the displacement is a straight line along the body diagonal; hence a standard laser interferometer can be used to do the measurement. However, for the vector measurement described here, the displacements are along the x-axis, then along the y-axis and then along the z-axis. The trajectory of the target or the retroreflector is not a straight line. The maximum deviation from the body diagonal is proportional to the size of the increment. A conventional laser interferometer would be way out of alignment even with an increment of a few mm.

To tolerate such large lateral deviation, a Laser Doppler Displacement Meter using a single aperture laser head and a flat-mirror as the target can be used. This is because any lateral



**Fig. 1 Schematic of Sequential Diagonal Measurement**

movement or movement perpendicular to the normal direction of the flat-mirror will not displace the laser beam, hence the alignment is maintained. After 3 movements, the flat-mirror target will move back to the center of the diagonal again, hence the size of the flat-mirror has only to be larger than the largest increment. A schematic showing the vector measurement setup is shown in Fig.1. Here the flat-mirror target is mounted in the machine spindle and it is perpendicular to the laser beam direction.

### Measurement Data and Results

Using an Optodyne MCV-500 laser calibration system and a volumetric calibration package, the volumetric errors of a Giddings & Lewis, model RAM 630 horizontal machining center were measured.

The measured volumetric errors, linear errors, vertical straightness, and horizontal straightness of X-axis, Y-axis, and Z-axis respectively will be presented and discussed. It is noted that for the X-axis, the largest error is the linear positioning error and for the Y-axis the largest error is the vertical straightness which may be caused by the non-squareness, and for the Z-axis the largest error is the horizontal straightness. Hence, if the machine is compensated for the linear positioning errors only, the large straightness errors in the Y-axis and in the Z-axis will not be compensated.

The measured volumetric errors were used to generate the compensation files. The compensation files were loaded into the controller of the machine. The volumetric accuracy of the machine was checked by the conventional body diagonal measurement (ASME B5.54 standard). The body diagonal errors measured without compensation were about 60  $\mu\text{m}$  and the same measurements with compensation were about 14  $\mu\text{m}$ . Hence an improvement of diagonal accuracy of a factor of 4 is achieved.

## **Summary and Conclusions**

To achieve higher position accuracy of a machine tool, it is important to measure the volumetric errors and to compensate the volumetric errors provided that the machine tool is repeatable. Using the Optodyne MCV-500 laser calibration system and the vector method, the volumetric errors of a machining center have been measured. These errors were then used to compensate the machine errors resulting in higher volumetric accuracy. The time required to compensate the machine using the vector method is significantly less than that using conventional measurement procedures.

In summary, we have shown that the volumetric errors of a machine tool can easily be measured by the vector measurement technique developed by Optodyne. The measured volumetric errors can be used to compensate the machine errors and achieve higher volumetric accuracy. Furthermore, the time required to compensate the machine using the vector method is significantly less than that using conventional measurement procedures making it easier for manufactures to take advantage to the advancements in CNC control technology.