Machine tool errors, measurement, compensation and servo tuning using MCV-5000 Aerospace laser calibration system

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I. Introduction

Twenty years ago, linear tolerances were the most important accuracy measurement, but today most machine tools can hold very tight linear tolerances. The next greatest errors are squareness and straightness errors and dynamic (servo) errors.

The time is fast approaching when linear accuracy is not enough. Buyers of machine tools will purchase machines not based on linear accuracy alone, but on 3D volumetric accuracy. Already, leading machine tool builders such as Mitsui Seiki and Yasda, etc., have published 3D volumetric accuracy of their machine tools and are enjoying a dramatic increase in sales.

The one true test of machine tool accuracy is whether or not it can hold dimensional tolerances. Dynamic servo errors are akin to racing a car, too fast through the curve and it overshoots; too slow and you waste time and may undershoot. It’s the same with a machine tool, how fast can the tool move without undershooting, overshooting or crashing. Overshooting a corner creates a distortion or an anode on the edge of a corner. Undershooting causes distortion and abrupt feed rate changes affect cornering and contouring accuracy.

II. Basic machine static positioning errors

1. Linear displacement error or pitch error,

The linear displacement error used to be the largest error. However, because the improvement in the accuracy of the lead screw and linear scale, the linear displacement errors become much smaller. Furthermore, most CNC controllers have the capability to compensate the repeatable pitch error. Hence the linear displacement error no longer the dominate error of the machine.

2. Errors caused by thermal expansion and distortion,

For most shop floors, the air temperature is not regulated. Hence there are large temperature variations. Most machine tools are steel structure. The thermal expansion coefficient is 12 ppm/°C. That is, an increasing of 1°C of material temperature will cause an increasing in length about 12 µm over 1 m. This is very significant, if the machine is used to cut other than steel material, such as Aluminum. Also, the temperature gradient in the machine will cause some distortion. These distortions may affect the squareness and straightness errors.

3. Axes squareness errors,

The non-perpendicular between axes is call squareness error. Usually, all axes are aligned very well before leave the manufacture. However, during shipping and installation, the squareness may become off. Also, for new installation, the machine leveling will cause some squareness and straightness errors. For some CNC controllers, the squareness errors can be compensated.

4. Vertical and horizontal straightness errors,
The straightness error is the error in the direction perpendicular to the direction of motion. It is caused by the guide way alignment and assembly. It may also cause by shipping, installation or machine crash. For some advanced CNC controllers, the straightness error can be compensated.

5. Angular errors,
The angular errors are pitch, yaw and roll errors. For most machines, the angular errors are related to the straightness errors. It is noted that the effect of angular errors on the spindle positioning error is the angular error times the Abbe off-set. In many cases the straightness error measurement already included the errors caused by the angular errors. For some CMM, the controllers have the capability of compensating the angular errors. But it is very difficult for CNC to compensate the angular errors separately.

6. Non-rigid body errors.
The non-rigid body errors are caused by the non-rigid body motion. There are 45 non-rigid body errors. Of course, not all the non-rigid body errors are important. The most significant non-rigid body errors are caused by weight shifting, improper alignment and assembly of mechanical parts, counter weight or balance, improper leveling, etc.

III. Dynamic contouring errors
1. Backlash and reversal spike,
The backlash may be caused by play in the drive system of the machine, play in the guide ways, excessive strain on the ball screw, encoder hysteresis, and over compensation. The reversal spike may be caused by inadequate amount of torque at axis reversal point; servo response time is inadequate on backlash compensation, and poor servo response at the crossover point.

2. Loop gains Kp, Ki and Kd,
In the PID control algorithm, the proportional loop gain Kp controls the tightness of the control, the integrate loop gain controls the follower error, and the differential Ki acted as damping in the loop. To achieve the best dynamic performance possible, the system must be tuned for the specific application. Load, acceleration, feed rate and performance requirements all affect how the servo loop should be tuned for the best results.

3. Look ahead and feed forward,
For advanced control at high feed rates and small radius of curvatures, the look-ahead and feed forward are very important. The look-ahead is how many blocks of data ahead the current execution. The feed forward is an additional feedback loop for the trajectory. The goal is to minimize the following error at high feed rate.

4. Acceleration/deceleration, resonance vibration, and damping
The acceleration/deceleration is important for the spindle to reach a high speed at a short time. The resonance vibration limits the servo loop time response. Usually, higher resonance frequency means shorter loop response time. The damping is important to reduce the settling time and ringing.

5. Linear interpolation and circular interpolation.
When the spindle trajectory must follow a particular path to get from its starting point to its ending point, the coordination of axis movements is said to be interpolated. The linear interpolation breaks the path to small linear segments and the circular interpolation breaks the path to small circular segments.

IV. How to measure and compensate static positioning errors
Recently, Optodyne has developed a new revolutionary laser vector technique for the measurement of 3D volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors. All these errors can be measured in a few hours instead of a few days by a conventional laser interferometer. Using this technique, the 3D volumetric positioning errors can be measured and the results can be used to generate positioning error maps or to compensate the 3D volumetric positioning errors.

V. How to minimize the dynamic errors
The dynamic errors can be minimized and servo tuning can be performed by non-circular contouring measurement using a MCV-500 plus LB-500, or the MCV-5004. The following parameters can be determined.
1. Servo parameters Kp, Ki and Kd and the feed forward parameters of the digital PID algorithm can be tuned to achieve the best dynamic performance possible.
2. Acceleration/deceleration, feed rate and vibrations can be determined.
3. Stabilizing axis oscillation and the ringing, damping, settling time and following errors can be determined.
4. Minimize the following error or soft loop
5. Linear interpolation and circular interpolation can be measured by circular contouring accuracy at varies radii and feed rates.
6. Circular and non-circular contouring measurement can be used to perform the automatic tuning of servo parameters.

VI. Summary and conclusion
The traditional laser calibration techniques for measuring 3D accuracy, i.e. a Wallenstein prism and a special target and straight-line laser with quad detector are impractical. The Wallenstein prism is very difficult to setup and align. The straight line laser beam with a quad-detector is affected by air circulation and temperature gradients when measuring the center of the beam. Both methods are time consuming, requiring several days to calibrate a machine tool.

The Sequential Step Diagonal technique, patented by Optodyne, can measure 3D accuracy in hours instead of days. The method, using a Laser Doppler Displacement Meter measures three displacement errors, six straightness errors and three squareness errors with only four setups.

Competition in global manufacturing today requires improving machine tool performance to achieve higher productivity, better quality and less downtime. To keep up with the speed and increased accuracy requirements, the machines have to be kept within tolerance, which means 3D volumetric error measurement, error compensation and machine alignment and adjustment are very important.

LDDM laser system can measure both static 3D volumetric positioning errors and dynamic contouring errors. Hence it is a very important tool for the production and development of high precision machine tools.