A Laser calibration system selection guide
By Optodyne

Table of contents

1. Introduction

This selection guide is designed to help you to select the best laser calibration system for your machine calibration and compensation with the highest return on investment (ROI).

2. Why calibrate your machines?

Calibration of your machines is very important for the following reasons.

A. For the production:

Quickly determine the machine performance capabilities.
Assure the process control for machining operation.
Determine the production scheduling based on performance capabilities.
Increase the throughput by optimizing feed rate performance.
Satisfy the on-machine inspection procedure.

B. For the maintenance:

Verify the machine performance for acceptance test and preventive maintenance.
Generate and verify the error compensation files for the controller.
Quickly assess the machine characteristics.
Reduce the maintenance costs and machine down time by rapid diagnosis of these errors.

C. For the quality assurance:

The quick check is comply with ISO 230 and ASME B5.54 standards for CNC machine evaluation.
A quick way to regularly calibrate and certify machines to meet the ISO 9001 standard.
Improve the product quality, while reduce the quality costs.
Reduce or eliminate the costly part cutting tests.

3. What is your need?

A. Measurement of static positioning errors (geometric errors)
   Linear displacement errors and bidirectional repeatability.
   Squareness errors of axes.
   Vertical and horizontal straightness errors.
   Pitch, yaw and roll angular errors.
   Non-rigid body errors such as weight shifting, counter balance, etc.

B. Compensate the repeatable geometric errors.
   Pitch error compensation.
   Squareness error compensation.
   Straightness error compensation.
   3 D volumetric positioning error compensation.

C. Measurement of dynamic contouring errors (CNC controller performance)
   Velocity/acceleration and resonance vibration.
   Backlash and reversal error.
   Servo loop gains.
   Following errors.
   Look ahead and feed forward.
   Linear interpolation and circular interpolation.

D. Optimize the servo parameters
   Set the lost motion and reversal spike parameter.
   Optimize the loop gains, Kp, Ki, and Kd, for displacement, velocity and current.
   Optimize the feed forward coefficient for the real cutting conditions.

E. A quick check of machine performance based on ASME B5.54 standard
   Measure the bidirectional displacement errors and repeatability.
   Measure the body diagonal displacement errors.
   Measure the circular contouring accuracy.

4. What are the machine errors?

The basic machine errors are the **static geometric** errors and the **dynamic contouring** errors.

A. Static geometric errors or 3D volumetric 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/ºC. That is, an increasing of 1ºC 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 times an Abbe off-set. 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.

B. Dynamic contouring errors and servo parameters tuning.
   1. Backlash and reversal spike,
      The backlash may be caused by play in the drive system of the machine, play in the guideways, excessive strain on the balls crew, 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 much 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 and resonance vibration,
   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.

5. Linear interpolation and circular interpolation.
   When the spindle trajectory must follow a particular path to get from its starting point to its stopping 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.

5. What are the differences between LDDM and Michelson interferometer?

Conventional laser interferometers are based on the Michelson interferometer. There are two laser beams, the output beam and the return beam, which are parallel but displaced about 25mm. Hence, large optics is required. Also, the alignment is critical, 3 elements have to be aligned co-axially. The laser head is large and heavy, and a heavy tripod is needed to support the laser head.

The single-aperture MCV and LICS laser systems are based on laser Dopplermetry. The laser head is very compact (MCV, 50mm x 50mm x 225mm) and is completed with stabilization circuits, electro-optics, and photo-detectors. The output beam and the return beam share the same aperture. Hence large optics is not required and a small retroreflector or a flat-mirror can be used as target. Also, since there are only two elements to be aligned, the alignment is not as difficult.

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. Also, there is no need to dismantle the protective machine enclosure, reducing overall setup and calibration time. The Windows™ based data collection and analysis software is simple to operate. Hence any machine tool operator can use the MCV/LICS to calibrate the machine with minimum training.

The MCV-500 is a complete calibration system with air temperature, barometric pressure, and material temperature sensors to compensate any environmental and temperature changes. The laser stability is 0.1 PPM and the system accuracy is 1 PPM. The MCV-500 is based on Optodyne Laser Doppler Displacement Meter (LDDM) technology. Furthermore, both the vector measurement[1] and laser/ballbar technique are invented by Optodyne and patent pending.

6. How to calibrate and compensate machines?

A. Static errors or geometric errors due to mechanical structure and geometry:

1. Linear displacement errors----LICS 100A, MCV-500 [3] or laser interferometer.
2. squareness errors----LICS 200A, MCV-500 body diagonal displacement measurement or using optical square and quad-detector/Wellston prism.
3. Straightness errors----LICS 200A, MCV-500 and Laser vector technique [1] or quad-detector or Wellston prism.
4. Angular errors----Using MCV-5000 or MCV-2002 Dual-beam laser head, or using laser interferometer with angular optics.
5. Non-rigid body errors, such as sag, counter balance, weight shifting etc---- Using MCV-5000 laser vector technique, or multiple laser interferometers.

B. Dynamic contouring errors due to controller parameters and capabilities

The measurement below can be performed with a MCV-500 plus LB-500, or the MCV-5004.

1. Servo tuning principles

   Servo tuning sets the Kp, Ki and Kd and the feed forward parameters of the digital PID algorithm. To achieve the best dynamic performance possible, the system must be tuned for the specific application.

2. Acceleration/deceleration, feed rate and vibrations

   The acceleration plays a significant role in the magnitudes of the following error and the overshoot, especially at start and stop. Asking the controller to change the velocity instantaneously amounts to an infinite acceleration which, since it is physically impossible, causes large following errors and overshoots. The acceleration/deceleration, feed rate and vibrations can all be measured with a MCV-500 plus LB-500.

3. Stabilizing axis oscillation

   If an axis oscillates, this indicates that the gain Kp may be too large.

   After reducing the gain Kp, when the axis stops oscillating, the system response is probably very soft. The following error may be quite large during motion and non-zero at stop. You should continue tuning the PID to tighten the loop. This measurement can be performed by program the machine to move back and forth with an increment of 50 mm and collect the displacement data at 100 Hz to 1000 Hz. The ringing, settling time and following errors can be determined.

4. Following error too large
   This is a case of soft loop. The proportional gain Kp is probably too low and Ki and Kd are zero. Start by increasing Kp. Continue this operation while monitoring the following error until it starts to exhibit excessive ringing characteristics. To reduce the ringing, add some damping by increasing the Kd parameter.

5. Following error during motion
   This is caused by a Ki value that is too low. Use the minimum value for Ki that gives acceptable performance. The integral gain factor can cause overshoot and oscillations.

6. Linear interpolation and circular interpolation
   Linear interpolation is required for multi-axis motion from one point to another in a straight line. The controller determines the speeds on each axis so that the movements are coordinated. True linear interpolation requires the ability to modify acceleration. Circular interpolation is the ability to move the payload around a circular trajectory. It requires the controller to modify acceleration on the fly. The circular interpolation can be measured by circular contouring accuracy at varies radii and feed rates.

7. Contouring
   With contouring, the controller changes the speeds on the different axes so that the trajectories pass smoothly through a set of predefined points. The speed is defined along the trajectory and can be constant, except during starting and stopping. The circular and non-circular contouring measurement can be performed with the MCV-5004 Aerospace laser calibration system.

C. A quick check of volumetric positioning errors and circular contouring errors--- Using a QC-500 to perform a 4 body diagonal displacement measurement, bi -directional displacement measurement, circular contouring measurement with high feed rate and small radius [3].

7. How to select a laser calibration system?

A. Specifications

1. Do I need more that 10E-7 laser frequency stability?
   No, since the laser system accuracy is 10E-6, a laser frequency stability of 10E-7 is more than enough.

2. Do I need more than 10E-6 system accuracy?
   No, in a shop environment, the error due to air turbulence and the uncertainty of the material temperature, the achievable measurement error is much larger than 10E-6 Also, the machine positioning errors are much larger than 10E-6. Hence a laser system accuracy of 10E-6 is more than enough.

3. Do I need more than 0.001 mm resolution?
   No, for a typical machine with working volume of 1 cubic meter, the positioning accuracy is more than a few µm. Hence a resolution of 0.001 mm is more than enough.

4. What is a realistic error budget in a shop environment?
   For a shop environment even with a temperature control of +/- 1 degree C, the measurement uncertainty is already much larger than 10E-6. Hence a laser system accuracy of 10E-6 is more than enough.

B. Capabilities

1. Do I need to measure the linear displacement errors?
   Yes, usually the largest position error is the linear displacement error and the thermal expansion.

2. Do I need to measure the squareness errors?
   Yes, usually the squareness error becomes large due to shipping and new installation and leveling. Hence it is important to measure and to compensate the squareness errors.

3. Do I need to measure the straightness errors?
   Yes, since for most of the CNC machines, the backlash, reversal spike and pitch errors can be compensated, the next largest errors are the vertical and horizontal straightness errors due to the non-straightness of the guide way. ASME B5.54[2] and Boeing ATA recommend to measure the volumetric positioning errors by body diagonal displacement measurement. The vector technique or sequential step diagonal technique [1] measures all the above (items 1, 2, and 3). The measured volumetric positioning errors can be used to generate a volumetric error compensation file for the controller to compensate these errors.

4. Do I need to measure the angular errors?
   For most CNC machine tools, the volumetric positioning errors already included the effect of angular error motions. Hence it is not necessary to measure the angular error. Furthermore, the CNC controllers do not have the capability to compensate the angular errors. For some CMM, the angular errors can be compensated [5].

5. Do I need to measure the dynamic contouring errors?
   For high speed cutting and mold making, the dynamic contouring accuracy is very important. It is important to optimize the servo parameters and to tune the controller properly to achieve the best performance.

6. Do I need to quick check the volumetric positioning accuracy and circular contouring accuracy?
   It is recommended by the ASME B5.54, Boeing Aircraft, and many large corporations, that a quick check to be performed regularly or in need [4].

7. How I compensate these errors?
   Linear displacement errors: for most CNC machines, the linear displacement errors can be compensated. After the linear calibration, the compensation files can be generated automatically by the software for most of the controllers.

   Volumetric positioning errors: for some CNC controllers, the volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors, can be compensated. After the volumetric calibration, the compensation file can be generated automatically by the software for most of the controllers. The software can also generate a 3 D error table for some controllers.

C. Productivity and efficiency
   1. What is the measurement efficiency?
      The measurement efficiency is very important to reduce the number of setups and the measurement time. The vector technique is most efficient. It can collect 12 sets of data in 4 setups.
   2. What are the times for setup, alignment, and operation?
      The setup and alignment time are also important to reduce the machine downtime. Typical setup and alignment time is 5 to 10 minutes.
   3. What is total time of measurement?
      Using the vector technique, for a working volume of 1 cubic meter, the volumetric position errors including 3 displacement errors, 6 straightness errors and 3 squareness errors, can be measured in 2 hours while using a conventional laser interferometer, at least a whole day is required to measure these volumetric positioning errors.
   4. What are the realistic times for these measurements and machine downtime?
      Linear displacement measurement: typical time is 15 to 20 minutes per axis.
      Straightness and squareness: using the vector technique, typical time is 2 to 3 hours for a working volume of 1 cubic meter. Angular errors: typical time is 10 to 15 minutes per axis with on-the-fly data collection.
   5. What are the required operator experiences and training?
      For a machinist, the required training is 1 day or less.

D. Quality of the equipment
   1. What is the warranty period and service support?
      Typical warranty is 1 year and extended warranty of 3 and 5 years are available.
   2. What is the MTBF and the replacement cost?
      The MTBF of the laser tube is 40,000 hours. The replacement cost of a laser tube is less than $2600.
   3. What is the periodical calibration and maintenance requirement?
      The laser system needs to be calibrated every year. There is no other maintenance involved except keep it clean and store in a dry environment.

E. Return on investment (ROI)
   Please estimate the following costs and calculate the ROI for your management.
   1. The cost of machine downtime and scrap.

2. The cost of outside calibration service.
3. The cost of operation, training, storage and transportation.
4. The equipment cost.
5. The ROI is equal to {the annual savings in item 1 and item 2} divided by the {annual cost in item 3 plus the amortized annual cost of the equipment in item 4}.

F. Other considerations
1. How flexible is the need? Can the equipment be upgraded later?
2. How versatile is the need? Can the equipment by used for other applications?

8. LDDM selection table

To help the user to select the appropriate model for his calibration needs, a LDDM selection table is in the next page.

LDDM Selection Table

LDDM model number: \ Calibration functions:	1 Linear displacement	2 Straightness	3 Squareness	4 Angular	5 Rotary axes, Rotary table	6 Surface flatness	7 Squareness & Parallelism	8 Guideway alignment	9 Circular contouring	10 Non-circular contouring	11 Spindle error motion
MCV-500	•										
MCV-500 + SD-500	•	•	•								
MCV-500 + LB-500	•								•		
MCV-500 + SQ-500	•		•				•	•			
MCV-500 + DI-500	•										•
QC-500	•	•	•						•		
MCV-5002	•	•	•	•							
MCV-5003	•	•	•	•	•						
MCV-5004	•	•	•	•					•	•	
MCV-5005	•	•	•	•	•				•	•	
MCV-2002	•	•		•		•		•			
MCV-2002 + RT-100	•	•		•	•	•		•			
MCV-3000	•		•				•	•			
MCV-4000	•	•	•	•		•	•	•			
LICS-100A	•										
LICS-200A		•	•								

9. References (Available in www.optodyne.com or WWW.optodyne-sh.com)

[1] C.Wang, "Laser Vector Measurement Technique for the Determination and Compensation of Volumetric Position Errors, Part I: Basic Theory," Rev. Sci. Instrum. Vol. 71, pp. 3933-3937 (October 2000).

[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] Ap-1104, "Calibration of CNC machines by a machine tool operator"

[4] Ap-1113, "One-day quick-check system"

[5] Ap-1117 "Calibration of a coordinate measuring machine (CMM) by a MCV-5002 laser calibration system.

LaserSelectionGuide.doc
10/7/2013