Lecture 4

Accuracy Inspection & Equipment

The Benefits of Accuracy Inspection

• Increase machine accuracy and repeatability.
• Lower maintenance and production costs.
• Reduce scrap, rework and parts inspection costs.
• Reduce catastrophic breakdowns and increase equipment life.
• Precision machining and greater productivity means increased profits.
Machine Tool Performance

- Machine tool performance is directly linked to the parametric errors within a machine.
- Parametric testing isolates and identifies each of the error sources.

Basic Tests

- Each linear motion in a machine contains 7 parametric errors:
  1. Axial linear positioning
  2. Axial straightness horizontal direction
  3. Axial straightness vertical direction
  4. Roll error
  5. Pitch error
  6. Yaw error
  7. Axial squareness
**Basic Tests**

- From **axial linear positioning** we obtain repeatability, average and maximum reversal error.
- From **axial straightness** we obtain translational lost motion.
- From **roll, pitch and yaw** we obtain angular lost motion.

**Additional Tests**

- Performing additional tests helps to further isolate and identify performance problems such as:
  1. *Periodic error testing of the positioning and feedback device*
  2. *Servo performance*
  3. *Contouring performance using the Telescopic Ball Bar*
  4. *Laser diagonal performance*
  5. *Rotary positioning accuracy, periodic error, repeatability and reversal errors*
  6. *Off axis/Trunion positioning accuracy, periodic error, repeatability and reversal errors*
  7. *Tool change repeatability*
  8. *Pallet change repeatability*
Machine Tools Inspection Equipment

• Measurement Standards
• Inspection Equipment
  ➢ Laser Interferometer System
  ➢ Double Ball Bar (DBB)
  ➢ Grid Encoder (數位盤)
  ➢ Comparator System

Measurement Standards

• ANSI/ASME B5.54-92 (USA)
  ➢ Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers
• ISO 230-2:2006
  ➢ Test code for machine tools - Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes
• ISO 230-6:2002
  ➢ Test code for machine tools - Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)
ANSI/ASME B5.54

- ANSI/ASME B5.54 defines common terms, machine types, machining ranges (workzone), position resolution, and operating modes. It also addresses machine environmental requirements and responses. This standard provides tests for evaluating machine accuracy performance as a machine tool, the machine as a measuring machine with probes in the spindle, machine cutting performance and, optionally, the machining of test parts for the assessment of point-to-point machining capability and contouring capability.

ISO-230-2

- The International Organization for Standardization (ISO) clearly defines the requirements for fully documenting set-up instructions for machine tool calibration in ISO-230-2. These must include:
  1. Location of all (non moving) machine tool axis positions
  2. Location of the laser material temperature sensor
  3. Location of the air temperature sensor.
  4. The effective expansion coefficient used
  5. Starting and ending temperatures of both the machine and its surrounding environment
  6. Location of the pitch line in the machine including:
     - Distance from the spindle face to the pitch line
     - Distance from the spindle centerline to the pitch line
     - Distance form the work holding surface to the pitch line.
• This part of ISO 230 specifies diagonal displacement tests which allow the estimation of the volumetric performance of a machine tool. Complete testing of the volumetric performance of a machine tool is a difficult and time-consuming process. Diagonal displacement tests reduce the time and cost associated with testing the volumetric performance.

• A diagonal displacement test is not in itself a diagnostic test, although conclusions of a diagnostic nature may sometimes be possible from the results. In particular, when face diagonal tests are included, a direct measurement of the axes squareness is possible. Diagonal displacement tests on body diagonals may be supplemented by tests in the face diagonals, by tests parallel to the machine axes in accordance with ISO 230-2, or by the evaluation of the contouring performance in the three coordinate planes as defined in ISO 230-4.
Laser Interferometer System

• Agilent Laser Calibration System
• Renishaw Inspection Equipment
• Optodyne MCV-500C Complete Machine Calibration System
• API 5/6D Laser Measurement System (本校)
Renishaw Inspection Equipment

- Laser Calibration System

Optodyne MCV-500C Complete Machine Calibration System

http://www.optodyne-sh.com
API 5/6D Laser Measurement System

http://www.apisensor.com/PR_XDLaser031805.html

API 5/6D Laser

Rotational axes

+ (YY)

-(XX)

+ Angle A

-Angle A

+ Angle B

-Angle B

+(XX)

-(YY)

+ Angle C

-Angle C

+(YY)
### Laser Calibration

- **Machine Tool Laser Calibration (Pitch Error Compensation)** and Backlash Compensation is a simple and straightforward process only a few things need to be taken into consideration.

1. *Machine Tool Geometry is within tolerance i.e., machine is level, gibs are tight, axes are square to each other, etc.*
2. *Backlash of the axes is minimum.*
3. *Control has the compensation program option installed.*
4. *Machine Control Parameters have been set up correctly.*
Linear Calibration

Along Axis:

1D: Accuracy, Repeatability, Straightness, Backlash, Flatness

2D: Squareness, Pitch, Roll, Yaw

Angular Accuracy (Pitch & Yaw)

2D

One Large "ARC"

Multiple "HIGHS" in Machine Rail
Parallelism & Flatness

- Roll is cross rail leveling. (Parallelism)
- Pitch is top surface leveling. (Flatness)
- These two must be adjusted correctly for precision machining.
- Yaw is positive edge straightness. In most cases this is not adjustable.

Linear Calibration - 3D

3D: Laser Diagonal Test:
Linear Calibration - 3D

Diagonal Interpolation

![Diagonal Interpolation Set-Up](image)

<table>
<thead>
<tr>
<th>Linear Accuracy Characteristics</th>
<th>Linear Accuracy Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Axis</td>
<td>0.000070&quot;</td>
</tr>
<tr>
<td>Y Axis</td>
<td>0.000062&quot;</td>
</tr>
<tr>
<td>Z Axis</td>
<td>0.000074&quot;</td>
</tr>
<tr>
<td>Volumetric Accuracy Characteristics</td>
<td>Volumetric Accuracy Measurements</td>
</tr>
<tr>
<td>Maximum Error</td>
<td>0.000065&quot;</td>
</tr>
<tr>
<td>Total Bandwidth</td>
<td>0.000072&quot;</td>
</tr>
</tbody>
</table>

**FIGURE 2:** The laser diagonal positioning test measures degrees of movement on all three axes.

Rotational Calibration

API Spindle Analysis System

![Spindle Dynamic Analyzer](image)

![Thermal Spindle Analyzer](image)

Double Ball Bar (DBB)

- History
- Hardware
  - Heidenhain DDB
    - [Heidenhain DDB](http://www.auto-met.com/heidenhain/machine_tool/default.htm)
  - Renishaw QC10 System
  - Polargauge DBB System (新勁，HP雷射干涉儀代理商)
  - Optodyne LB-500 Laser/Ballbar
  - API Telescopic Ballbar System (本校)
- DBB measurement steps
- Plots Presentation

DBB - History

- **Double Ball Bar (DBB)** method is one of so called rapid tests for measure the motion error of a milling machine, a machining center or another machine tools which are driven by NC and have circular interpolation motion.
- The measuring equipment records the points on a circular curve, enlarges the extension or contraction of the bar and then shows them in polar coordinates, it is called the motion error trace.
- Then the trace is analysed and the volumetric accuracy is evaluated. Very valuable work concerning the phenomena in DBB measurements was studied in the laboratory of Kakino at late 80's. The most of later studies and work are based on this research.
# DBB - Hardware

<table>
<thead>
<tr>
<th></th>
<th>Heidenhain</th>
<th>Renishaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball bar lengths</td>
<td>150, 200, 250, 300mm</td>
<td>100, 150, 300mm</td>
</tr>
<tr>
<td>(calibrated):</td>
<td></td>
<td>250, 400, 450, 550, 600mm</td>
</tr>
<tr>
<td>(non-calibrated lengths):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement range:</td>
<td>± 5mm</td>
<td>± 1mm</td>
</tr>
<tr>
<td>System accuracy:</td>
<td>± 1 micron</td>
<td>± 1 micron</td>
</tr>
<tr>
<td>Data capture:</td>
<td>IK121 ISA card</td>
<td>RS232</td>
</tr>
<tr>
<td>Max. capture frequency:</td>
<td>100,000 samples/s</td>
<td>250 samples/s</td>
</tr>
<tr>
<td>Calibration:</td>
<td>Internal reference mark</td>
<td>External calibrator</td>
</tr>
</tbody>
</table>

## Heidenhain’s DDB

The **DBB Double Ball Bar**: a telescoping double ball bar linear encoder for performing circular interpolation tests with large radii to inspect primarily the machine tool geometry.

**DBB 110**
Heidenhain’s DDB

Renishaw QC10 DBB System

- Double Ball Bar (DBB)

Ball-bar photo courtesy Renishaw.
Renishaw Measurement Installation

Polargauge DBB System

新勁國際有限公司(Cullam Technologies Co., Ltd.)

Polargauge DBB System

Optodyne LB-500 Laser/Ballbar
Optodyne LB-500 Laser/Ballbar

• Optodyne's LB-500 Laser/Ballbar (Patent Pending) is an add-on package to Optodyne's MCV-500, Linear-Machine Calibration System.

• The combined system can be used to calibrate CNC machine tools, CMM's (Coordinate Measuring Machines), and other precision measuring machines and stages and perform circular test for servo-tuning and dynamic testing.

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Optodyne LB-500 Laser/Ballbar

**Capability (Circular Tests):**

<table>
<thead>
<tr>
<th>Capability</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Stability</td>
<td>0.1 PPM</td>
</tr>
<tr>
<td>Linear Accuracy</td>
<td>1 PPM</td>
</tr>
<tr>
<td>Resolution</td>
<td>1 microinch (0.01 μm)</td>
</tr>
<tr>
<td>Measuring Range</td>
<td>up to 40 inch (1 m)</td>
</tr>
<tr>
<td>Radius*</td>
<td>0.1 to 3 inch (2.5 to 75mm)</td>
</tr>
<tr>
<td>Data Rates</td>
<td>1-1000 data/second</td>
</tr>
<tr>
<td>Maximum Data Points</td>
<td>10,000 per run</td>
</tr>
</tbody>
</table>
## Comparison of Laser/Ballbar and Telescoping Ballbar

<table>
<thead>
<tr>
<th>Performance</th>
<th>Laser/barbar</th>
<th>Telescoping ballbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement sensor</td>
<td>Laser Doppler Displacement sensor</td>
<td>Transducer</td>
</tr>
<tr>
<td>Measurement method</td>
<td>Measures x-coordinate and y-coordinate to generate the circular path. Basically a 2-dimensional measurement</td>
<td>Measures the radius changes along angular positions on a circular path. Angular positions are not measured. Basically a 1-dimensional measurement.</td>
</tr>
<tr>
<td>Sensor Calibration</td>
<td>Linear accuracy is traceable to NIST</td>
<td>Transducer needs periodical calibration</td>
</tr>
<tr>
<td>Sensor range</td>
<td>Up to a few meters</td>
<td>Up to a few mm</td>
</tr>
<tr>
<td>Non-contact measurement</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Radius of circular path</td>
<td>Continuously variable from 1 mm to 150 mm</td>
<td>Fixed radius with increment of 50 mm</td>
</tr>
<tr>
<td>Measures feed rate</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1000 data/sec</td>
<td>250 data/sec</td>
</tr>
<tr>
<td>Maximum feed rate</td>
<td>Up to 240m/min</td>
<td>Up to a few m/min</td>
</tr>
</tbody>
</table>

## API Telescopic DBB System

![API Telescopic DBB System](image)
DBB Measurement Steps

1. Start the measurement session with adjusting the DBB device on the calibrator.
2. Calibrate the DBB device by clicking the calibrate button.
3. Run the machine tool to the zero position and center the socket to its place.
4. Run the machine tool to the measurement position.
5. Start the measurement by clicking the data capturing button.
6. The machine tool starts the CW measurement circle.
7. Change the measurement direction.
8. The machine tool starts the CCW measurement circle.
9. Save the measurement.
10. Close the measurement window.
11. Analyse the measurement data.
Analysis Plots of Measurement Result
Analysis Plots of Measurement Result

Result Report
Ballbar Analysis (Renishaw QC10)

Ballbar diagnostics (in)
XY 360deg 12in 20041011-T1
Operator: admin
Date: 2004-Oct-11 11:57:56

Machine: OKK MC4
Instrument: Dynamic ballbar

Backlash (in)
X: 0.000760 - 0.000791
Y: 0.000315 - 0.000619

Reversal spikes (in)
X: -0.000264 - 0.000244
Y: -0.000657 - 0.000392

Internal play (in)
X: 0.000094 - 0.000035
Y: 0.000055 - 0.000071

Cyclic error (in)
X: 0.000031 - 0.000067
Y: 0.000075 - 0.000043

Other features
Servo mismatch: -0.05 ms
Squaringness: 0.00129 in
Straightness X: 0.000031 in
Straightness Y: 0.0000280 in
Scaling mismatch: 0.0000616 in

Circularity: 0.001469 in

Explanation of Result Plots for Errors Using DBB System
Axis reversal spikes

• When an axis is being driven in one direction and then has to reverse and move in the opposite direction, instead of reversing smoothly it may pause momentarily at the turnaround point. This appears as short spikes that appear on either axis reversal point. This could mean servo response time is poor and excessive friction in axis.

http://www.machinetoolhelp.com/Preventativemaintenance/Ballbaranalysis.html

Scale Mismatch

• Scale mismatch is shown as an oval plot, extended along one axis. One of the machine axes is either over traveling or under traveling relative to the other. One axis could be feeding too far or the other is not feeding far enough, possibly due to overheating or a faulty ballscrew. Servo loop gains may need adjustment.
Backlash

• Backlash- If positive backlash it could be ballscrew end float, worn drive nut, or guide way play. If negative backlash the machine parameter might be overcompensated. If unequal backlash then there could be a wind up in the ballscrew where it becomes stiff on one end of the travel. It also typically occurs on a vertical axis and can also be caused by any counterbalance mechanisms or weight.

Stick-slip

• Stick-slip results when friction causes one axis to stick when it is fed at a very low rate. Left unchecked, this error could prevent the machine from producing an acceptable surface finish.

• Guideways or bearings could be bad or damaged. Improper lubrication or power can be supplied to overcome friction.
Squareness error

- Squareness error is shown in an oval ballbar plot. It occurs when normally orthogonal axes are no longer moving at 90° relative to one another. This may be due to a bent axis or some other misalignment.
- This squareness error oval tilts at 45° with respect to the two axes, and remains in the same position regardless of the direction of travel of the ballbar (CW or CCW).

Servo Mismatch

- Servo mismatch is shown as an oval plot tilted by 45° that does not stay in place - It shifts back and forth by 90° depending on the direction of travel.
- This indicates mismatched servo gains in the CNC, causing the axis with the higher gain to lead the other, and makes precise circular interpolation impossible.
Cyclic Error, Master/slave change over error & Lateral Play

- **Cyclic error** is shown as a plot with waviness that varies in amplitude and reaches a maximum amplitude at axis reversal. This error is caused by a flaw in the axis leadscrew or leadscrew mounting. If only in one half of plot on a vertical axis it may have to do with a counterbalance type problem.

- **Master/slave change over error** often results on CNCs that can only interpolate one axis at a time. Varying the speed of the master axis while the slave axis follows generates arcs. This changeover error produces a plot with 45° steps, and may make precision machining of circular features impossible.

Lateral Play

- **Lateral Play** is caused by looseness in the gibbs or guide ways causing a fish tail effect. When machining interpolated holes you will tend to get an oval shaped hole.
Offset change/Plot discontinuity/Plot rotation/Radius change/Tri-lobe/spiral

- These plots all tend to be setup errors with the ballbar equipment. The tool cup is either damaged, dirty, or walking out of the cup while running the test. It could be an error in the ballbar program you are running. It could also be the joints in the ballbar rods, cup or balls that are loose. It could also be that the computer is slow and not capturing quick enough.

Straightness

- Straightness or Scaling error Lack of straightness in machine guideways. They may be bent, misaligned, worn or poor machine foundation. Scaling error may be caused by scales encoder or drive.
Vibration

- Vibration can be invoked by the machine itself, drive train, servo loop, damaged guideways or surrounding environment.

Rotary Calibrator

- Heidenhain KGM Grid Encoder
  
  ➢ http://www.auto-met.com/heidenhain/machine_tool/default.htm

- Renishaw RX10 Rotary Calibrator
- API Rotary Table Calibrator
Heidenhain KGM Grid Encoder

The KGM Grid Encoder for performing circular interpolation tests with small radii and curved path tests, to inspect primarily the dynamic performance of a control system.

Renishaw RX10 Rotary Calibrator

The RX10 Rotary Calibrator is used for measuring the accuracy of rotary axes in machine tools. It is a high-precision device designed to verify the performance of rotary controls.
Comparator

• Early machine tool calibration techniques used a comparator and mechanical artifacts, such as a mechanical square, to measure static accuracy. But even under optimum conditions, the comparator has low resolution.

• And since any mechanical method is dependent on the operator for accuracy, human skill is still an issue.

• This is why the use of mechanical squares and comparators is limited today.
Heidenhain VM 182 Comparator System

The VM 182 Comparator System for measuring the positioning accuracy, repeatability, and guideway error of linear axes on manual and CNC-controlled machines.


- The VM 182 Comparator System from HEIDENHAIN serves for acceptance testing, inspection and calibration of machine tools and measuring equipment with traverse ranges up to 1520 mm in longitudinal direction and ± 1 mm in lateral direction.
- Machine tool builders and distributors can determine the linear and nonlinear error curves as well as the reversal error of machine axes according to ISO 230-2. At the same time, it also measures guideway error perpendicular to the direction of axis traverse. The resulting error values can then be used in the subsequent electronics (display unit or control) for electronic error compensation. TNC contouring controls from HEIDENHAIN can download the error compensation values directly.
### Specification VM 182 Comparator

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring standard</td>
<td>Two-coordinate DIADUR phase grating on steel</td>
</tr>
<tr>
<td>Signal period</td>
<td>4 µm in longitudinal and transverse directions</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>$a_{\text{therm}} = 10 \text{ ppm/K}$</td>
</tr>
<tr>
<td>Measuring lengths ML</td>
<td>420 mm, 520 mm, 1020 mm, 1220 mm, 1520 mm ± 1 mm</td>
</tr>
<tr>
<td>Reference mark</td>
<td>At beginning of measuring length</td>
</tr>
<tr>
<td>Accuracy grade</td>
<td>± 1 µm in longitudinal direction</td>
</tr>
<tr>
<td></td>
<td>± 1.5 µm in transverse direction</td>
</tr>
<tr>
<td>Evaluation electronics (option)</td>
<td>IK 220 counter card for PCs</td>
</tr>
<tr>
<td>Evaluation software (option)</td>
<td>ACCOM for AT-compatible PCs</td>
</tr>
<tr>
<td>Recommended measuring steps</td>
<td>1 µm, 0.1 µm, 0.01 µm</td>
</tr>
</tbody>
</table>

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### Six Steps to Improved Machine Capability (1/4)

1. **Determine the accuracy you need** - tolerance on the drawing / blueprint determine the machine accuracy required.

2. **Establish baseline**: current performance - run an automated ball bar check. In this simple 10 minute procedure, your machine moves in a programmed circular path. The ball bar detects the machine’s deviations from this path, representing errors in contouring.
Six Steps to Improved Machine Capability (2/4)

3. **Identify and rank error sources** - ball bar analysis software is available that will isolate and rank 18 machine parameters in terms of their impact on your machine’s ability to servo and position accurately (error sources include squareness, cyclic error, stick-slip, reversal spikes, scale mismatch, machine vibration, servo mismatch and backlash). You also get an indication of dynamic positioning accuracy from overall "circularity" or "circular deviation" values in accordance with international standards. Use this information to prioritize maintenance and to determine the best corrective action: compensation or repair.

Six Steps to Improved Machine Capability (3/4)

4. **Eliminate or calibrate errors** - use a laser calibration system to eliminate systematic positioning errors. For example, if the ball bar identifies scale mismatch, just laser the axis that needs to be linear error corrected. Running a laser system on your machines will make them repeatable and accurate.
Six Steps to Improved Machine Capability (4/4)

5. **Establish new baseline** - once geometric error sources have been eliminated or minimised, re-test with the ball bar to set the new baseline for your machine.

6. **Regular health checks** - run regular checks (at least once a month) to detect any deviation from the baseline. By plotting the critical machine performance parameters on a control chart (see example on right) you have a "medical" record for your machine, and you can schedule maintenance before deteriorating machine performance results in scrapped parts. If a crash should occur, run the ball bar to see if your machine is still fit to continue production.