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Improving Process Capability of CNC Machines by Positional Accuracy

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Abstract: *Position accuracy and repeatability accuracy are the result and one of the most key parameter deciding the resultant performance of a CNC machine. It is the net clear image displaying the vision, experience, efforts and professional approach with dedication of working team. It is the performance index of integration of well sized components including CNC system, servo motor, Ball screw, encoder and its coupling and complete kinematics of axis along with software. Working environment especially temperature which affects the position accuracy of machine: needs to be controlled. Process capability and long term results can be sustained only by full in depth concern and care. This paper describes the case study from design up to the stage of live working in a machine with process capability index of 1.875 with position accuracy of ±2μm..*

Keywords: CNC Machine, Mechanical Accuracy, Positional Accuracy.

1. INTRODUCTION

The accuracy of an axis is dependent on performing parameters of ball screw, AC Servo Motor. Encoder, Servo controller, CNC system apart from mechanical design aspects such as alignment, guide ways, load sharing capability of Bearings and support method applied [1]. Further accuracy is result of excellence of assembly of all these elements. It is the capability of complete system and machine. The future and performance of the CNC machine is good so long the resultant position and repeatability is acceptable as per standards [2]. It is necessary to list out all possible variables which need control right from inception. Initial design followed by Care and check at every stage of assembly is the key of success for getting acceptable, sustainable accuracy on long term basis.

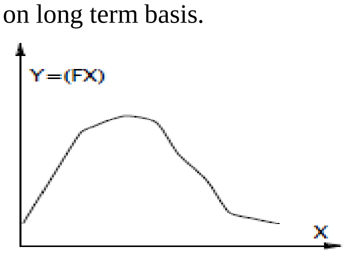

Figure 1 General Function graph

Where all process inputs are deciding the resultant value of variable Y. The ingredients of the process and inter dependency will generate data which shall be arranged in certain format. Here resultant variable may considered as accuracy of the axis under consideration [3]. The input variables may be grouped as below:

Variables as a result of ball screw like:

- Ball screw Pitch or lead
- Surface finish of ball screw such as turned, rolled or ground
- Class of accuracy achieved by manufacturer
- Preload of ball screw and extent of backless error
- Stiffness of ball screw which is again a function of its dimension and mounting arrangement
- Extent of developed sag, deflection buckling, lubrication quantity during run
- Working Temperature

Servo Motor Performing Parameter:

- Motor Inertia as compared to driven load inertia.

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- Acceleration Torque at start and deceleration Torque at stop
- Dynamic performance and response of the motor as per given command
- Coupling behavior between servo motor and encoder

Encoder accuracy

- Resolution based on Pulses per revolution
- Involved gear ratio, if any; depending of machine design
- Repeatability
- Deviation error range

Servo Controller Parameters:

- Feedback error processing gain
- Feed forward gain
- Position error multiplying factor
- Basic creep error adjustment
- Dynamic properties of DC bus at stopping to absorb and dissipate energy in terms of heat in resister or with provision of regenerative braking
- Generation of following error means ability of servo controller to follow CNC commands

CNC System:

- Parameterization values
- Resolution of the whole system
- Width of watch window in microns within which stop declaration is acceptable
- Standstill monitoring behavior
- Energy level required even when axis is at stop position
- Pitch error compensation is executed or not and its measuring process
- Backless error compensation is executed or not.
- Servo Communication sample time after which a new command is generated.
- Application of Brake sequence, its response (brake closing and release time) and its holding torque capability

It is really very complex situation to analyze which variable is unpredictable in deciding the resultant position accuracy.

2. SYSTEM DESCRIPTION

Referring figure 2 below, all axes related motion controls like Single step, jog, slow or rapid velocities are under control with CNC channel. Measuring signal feedback is always being compared with CNC path calculation. The stopping decision is taken by CNC and accordingly it slows down its axes command as per target left out distance. The process repeats several times. At last within specified window; it makes its effort for exact stoppage within it. However if it so happens that it is not able to stop; it will give a reverse command to put back within that window bracket [4]. Within allowed stop time it should be able to control the path completion. If unable to control within this specified time; it will issue a fault message. If it is a casual error say because of hardness of job or misalignment in slide or ball screw deflection

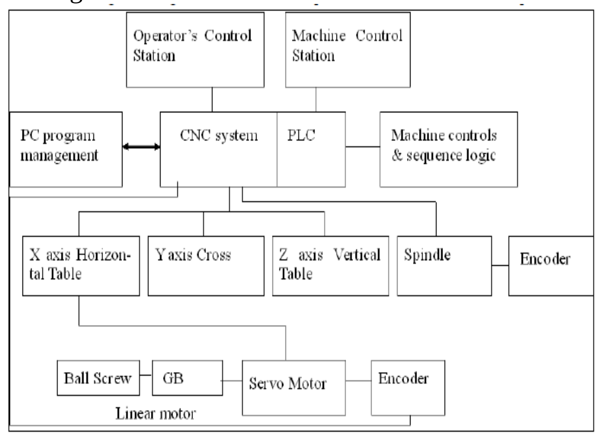

Figure 2 Configuration of System without Adaptive and In-process gauging system

Position Accuracy Determination:

Table 1 gives a guideline to select a desired accuracy class as per application. Ground ball screw are used for machine tool like Lathe Milling ,machine centers, robotics while rolled ones for less accurate machine like wood working etc. In our case it is a precision class from C1,C2, C3 and C4 class [5].

Table 1 International Standard comparison

Standard	Ground						Rolled			
	C0	C 1	C 2	C 3	C4	C 5	C 6	C 7	C8	C1 0
ISO,DIN	-	6	-	12	-	23	-	52	-	210
JIS	3. 5	5	-	12	-	18	-	50	-	210
HIWIN	3, 5	5	6	8	122 2	18	23	50	10 0	210
Axil Play	5	5	5	10	15	20	25	-	-	-
$E_{2\pi p}$	3	4	4	6	8	8	8	-	-	-
E_{300p}	3. 5	5	6	8	12	18	23	-	-	-
Unit of above figure: 0.001 mm(1μm)										

$E_{2\pi p}$:This error is found with one complete rotation of ball screw $E_{300p:}$ This error is a positional error non accumulated over a travel length of 300 mm.

3. MECHANICAL ACCURACY TESTING OF THE SYSTEM

3.1. Static measurement Vs Dynamic Capture Inspection

Conventional inspection and acceptance testing of machine tools is limited essentially to static measurement of the geometrical machine structure without load and on CNC machines for measuring there positioning accuracy. The final results of machining are increasingly influenced by dynamic behavior including step up response and acceleration rates especially during interpolations of slides [6]. Test work pieces are therefore produced and inspected for dimensional accuracy in order to draw conclusions about the dynamic behavior of the machine. Many companies offer, measuring devices for direct capture of dynamic and static deviations [7]. The advantage of this direct inspection method over inspecting only the results of the machining lies in its separation of technological influences from machine influences, and in its capability of distinguishing individual factors of influence.

- Dynamic measurements: Especially at high traversing speeds provide information on contouring behavior that permits conclusions about both the condition of the machine tool as well as the parameter settings of the control loop consisting of the CNC control, drives, and position feedback systems. This information can be used to optimize the behavior of the machine (e.g. kV factor, reversal peaks).
- Static measurements: Such as the measurement of position error in linear and rotary axes using a comparator system, permit conclusions about the geometric accuracy and thermal behavior of the machine.
- Circular interpolation: Tests with very small radii and free-form tests provide information on the dynamic behavior of the control, and circular interpolation tests with large radii provide information on the machine geometry.
- Position accuracy and repeatability: as well as guide way errors of linear machine axes, are determined with a comparator system.
- The position accuracy and repeatability of rotary axes: rotary tables and tilting tables can also be determined. A very precise angle encoder serves as comparator system.
- Machine tool builders use the results of machine measurements to develop design measures for improving accuracy. Such measurements also help them to optimize the commissioning parameters of the control loop wherever they influence the accuracy of a CNC machine.
- Machine-tool users can use the measuring devices for acceptance testing and regular accuracy inspection of their machine.

3.2. Inspection Standards and Software's

The measurement methods for inspection and acceptance testing of machine tools are governed by national and international standards and directives. The ACCOM evaluation software for PCs; is an proven program for measured value acquisition and evaluation according to the DIN ISO 230‑2, ISO 230-3, DIN ISO 230-4 and ISO 10791-6 (K2 and K3) standards, as well as the VDI/DGQ directive 3441. The evaluation software compares the values measured by the grid encoder with the ideal (programmed) circular path, and shows the deviations enlarged on the PC screen [8]. Further it calculates the numerical values, such as circular error, circular backlash and radial error, according to DIN ISO 230-4. The data measured with the circular interpolation tests permit conclusions about the causes of the errors.

3.3. Circular Interpolation Test Complexity

Circular interpolation tests performed over large radii provide information on the machine geometry. On the other hand, circular interpolation tests with small radii provide information on the accuracy of the control under high axis acceleration rates. The influence of the machine geometry on the measuring results of tests with small radii is insignificant. The data measured with the circular interpolation tests permit conclusions about the causes of the errors such as:

- Perpendicularity/Orthogonality errors of the machine axes
- Reversal peaks at quadrant transitions
- Hysteresis, reversal error
- Incorrect error compensation values in the control
- Errors resulting from irregular thermal expansion of machine components
- Tilt and sag in the machine axes Axis adjustments
- Influences of traversing speeds
- Influence of acceleration

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3.4. Measurement of Circular Interpolation

The control and drives, however, have a very strong effect. Circular interpolation tests are performed with the KGM 182 or VM 282 grid encoders depending upon accuracy of the machine from 0.01µm to10µm. The VM 182 comparator system incorporates a scale with a very precise two-coordinate phase grating and a scanning head that moves over the grating without mechanical contact. The scale is embedded in a massive, U-shaped steel profile, and can therefore be mounted directly on the machine table. Along with the measuring position in longitudinal direction, the VM 182 also captures small errors (± 1 mm) perpendicular to the direction of measurement.
The VM 182 serves for acceptance testing, inspection and calibration of machine tools and measuring equipment with traverse ranges up to 1520 mm. Machine tool builders and users, can use the VM 182 to determine the linear and nonlinear error curves as well as the reversal error of machine axes according to DIN ISO 230-2. Along with the position error, it also measures the guide way error orthogonal to the traverse direction of the machine axis.

3.5. Circular Interpolation Test

In the circular interpolation test, the CNC control performs a circular interpolation in the working plane.

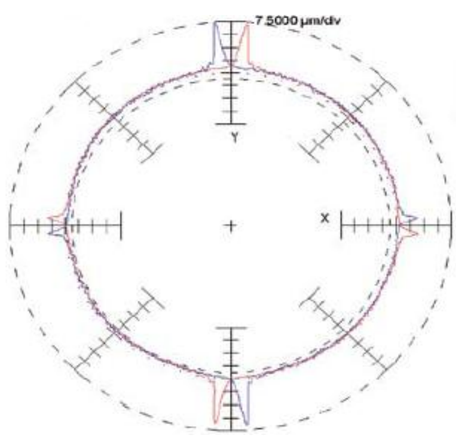

Figure 3 Circular Interpolation with deviation obtained from KM 282

Circular Interpolation performed on X axis and Z axis while Y remains stationary with recorder pen. It is observed in figure 3 above that at each 90^0 movement a jerky deviation is found when axis direction is changing. It is due to cumulative backless and positional error combination. Second reason is difference in value of positioning window of the two axes. Third reason is difference in drive tuning parameters like kV gain, Feed Forward gain, following error and preloading of ball screws.

3.6. Static positioning

In the free-form test, the CNC moves the machine axes in a plane on any programmed path. The KGM282 encoder with its evaluation instrument is used to measure the path actually traversed. The inspection software ACCOM displays the errors in various views. The dynamic behavior of the machine can be evaluated at corners and transitions in the contour.
Free-form paths as per ISO 10 791: Variables like feed rates and interpolation of two axes can be inspected. The free form show following interesting contour transitions:

- Continuous transition from line to arc
- Continuous transition from arc to line
- Abrupt transition from line to arc
- Abrupt transition from arc to line
- Abrupt transition from line to line

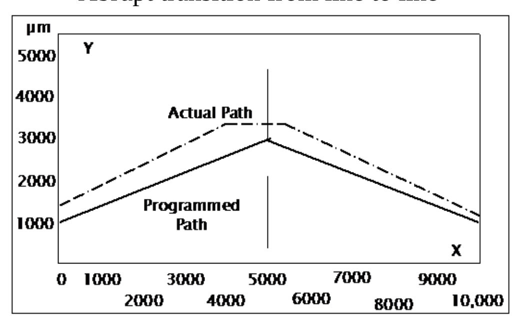

Figure 4 Step response test

3.7. Step response test

The step response test can be used to measure the smallest possible positioning increment (step-response function) and provide information on the influence of static friction and the accuracy with which positions can be held. This test is also intended for high-precision tasks requiring increments of as small as 0.1 µm to 0.01 µm. The graphical representation of distance over time (Xt, Yt) and of speed over time (vt). The step response test is performed with KGM 182 grid encoders as well as with the VM 182 comparator system. The positioning accuracy and repeatability of a machine tool is measured after the machine axis has been moved to certain positions. The figure 4 gives a clear idea how slide deviates from programmed path.

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4. RESULT AND ANALYSIS

Static positioning accuracy of linear axes:

The Linear Comparator unit can be used to determine the positioning accuracy of a machine tool when moving machine axes to specified positions. Besides the positioning accuracy, these devices can also measure the Guide way error perpendicular to the direction of the machine tool's slide. The measuring unit displays the errors clearly according to the respective standards. Small traverse paths up to 230 mm can be measured with KGM 282 grid encoders, larger traverse paths up to 1520 mm can be measured with the VM 182 comparator system. For clarifying the importance few specific parameters of KGM 282 are given in following table 2.

Table 2 Broad Specification of Linear Comparator

Parameters	Range / value/ resolution
Measuring Standard with coefficient Of linear expansion	Two co-ordinate DIADUR phase grating $A_{THERMAL}$:$10X10^{-6}k^{-1}$
Accuracy grade	± 1µm in longitudinal direction ± 1.5µm in traverse direction
Measuring Length	520 1020 1520 mm
Incremental Signal	Sine 1Vp
Signal Period	4µm
Measuring step	≥ 0.001 µm with multiplier electronic unit
Supply Voltage	5V± 5%
Traversing Speed	≤ 80 m/min
Coupling/mounting	Magnetically coupled on a plate

X axis position error:

The figure 5 provides complete data information with marking of standard deviation and linear trend line. This axis is longest one and total span is 1500mm with mounting support at both ends. The backless error is almost nil due to double nut pre-loading. Here most of the points are lying on positive side and total stop is within 3µm; while on negative stop is within 1µm limit. The positioning range is (+3,-1) µm which means a window size of 5µm; which is very good for a long span axis with 10mm lead. The results are acceptable for our kinematics and precision requirement.

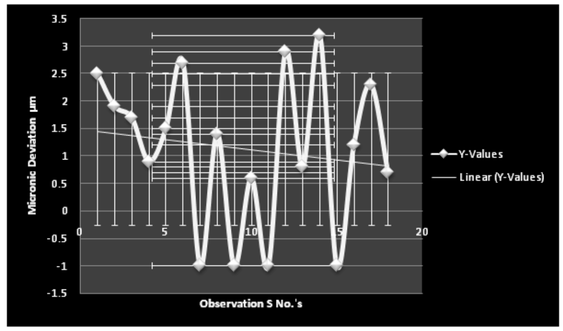

Figure 5: X axis positional Accuracy Assessment

X axis positioning error:

The sample are plotted along with plotting standard deviation limits are described in figure 6.It is observed that most of the points are well within limits of (0-3.5µm and tendency of stop is over the target. However, at least three points; are on negative side. The over shoot is on higher side and system reacts with higher magnitude of command to put back the whole slide back after overcoming complete inertia of driven mechanism. The reason possibility are on axis drive tuning and pitch error compensation. Over all, the positioning capability is well within ± 3µm and it is acceptable for our precision grinding with helical interpolation.

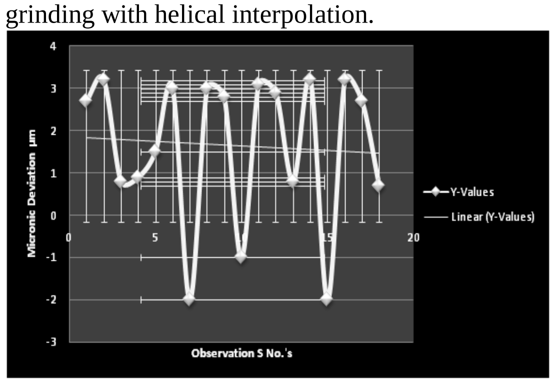

Figure 6: X axis positional Accuracy Assessment

Referring to figure 7 below, most of the point positioning are lying within ±2µm with exception of one scattered point. The window range is(+ 3, -2) and mostly points are covered in(+2, -1); therefore it is concluded positional limit is acceptable as per JIS standard. In our application Y axis purpose is to place grooving wheel on job with precision against gravity. Our sample data are collected on both upper ends and also in the mid of ball screw. As a whole it represents total range of the axis and safely it applies to complete range within ±3µm.

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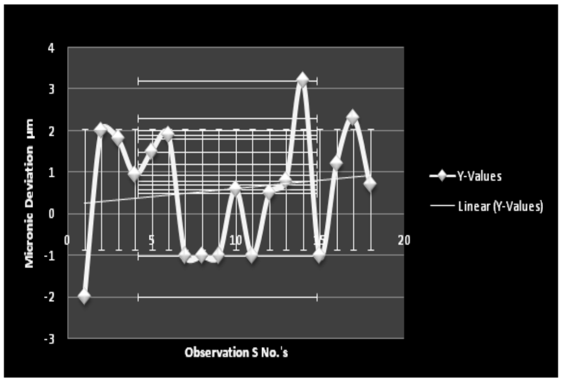

Figure 7: Measurement of vertical Y axis

5. CONCLUSION

The slide Position accuracies of all axes is within ±5µm and Repeatability accuracy of all axes is within ±2µm. The grinding spindle balancing is achieved within 0.4µm.It is ensuring surface finish accuracy within 0.4 rA value. All other accuracies are as required in building a grinding machine. The pitch error compensation application is reflecting its refinement in slide accuracy precision. The machine accuracies so achieved; put this machine built- up; under precision class. The achieved accuracies are a validation of all mathematical modeling, and calculations with applied safety factors.

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