LOCATION DEPENDENCY OF POSITIONING ERROR IN A 3-AXES
CNC MILLING MACHINE


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Abstract

To produce complex components within a close tolerance value, the machine tools are required to be more accurate than the specified accuracy of the components. Generally to achieve better accuracy of machine tools, laser interferometer systems are used to measure the positioning error and thereafter error compensation is done to improve the accuracy. In case of big size milling machines, it is observed that the accuracy of the machine is not always uniform throughout its work table area. This paper presents a study of error distribution across the work table surface that enables to identify the best location for machining close tolerance components. It also indicates the error involved in the machining, corresponding to the various locations of the machine work table.

Keywords: Tolerance, Positioning error, Milling machine.

1 Introduction

Quality assurance of the mechanical components manufactured in industry usually requires that they conform to the tolerance specifications, which may be internal or customer-specified. Quality is inversely proportional to variation and to reduce variation, it becomes necessary to measure variation accurately in the first place. Two steps are followed to enhance the accuracy of machine viz. (i) precision error measurement and (ii) accurate compensation to eliminate the measured errors. The positioning error of the axis of a multi-axes machine is checked either by measuring the dimensions by Coordinate Measuring Machine (CMM) of a component machined on it or by measuring the positioning errors present in the axes by a laser interferometer or by a ball bar system. The errors are then used to correct the coordinates of the nominal cutting trajectory of the machine tools through the error compensation software.

Many times it is experienced that the positioning accuracy of the production machines changes with the location of the work table e.g. the positioning accuracy of X-axis is not constant for every Y-axis location. In case of big size milling machines, the accuracy of the machine is not necessarily uniform throughout its work table area. This is particularly problematic while machining identical components in mass production by mounting an array on the work table of the machine. All the components, being machined on the same machine, are supposed to possess same accuracy, but due to location dependency of the positioning accuracy, the components are produced in varying tolerances. In this document a study of error distribution across the work table surface is carried out and results are presented. The results enable to identify the best location for machining close tolerance components. They also indicate the error involved in machining, corresponding to the various locations of the machine work table.

2 Positioning Accuracy of Machine Tools

Machine tool positioning accuracy is a core descriptor of a machine and indicates its expected level of performance. The accuracy of the components machined is primarily affected by the positioning errors of the machine tools. There are a number of standards and guidelines outlining how to evaluate machine tool positioning accuracy. Standards commonly used worldwide are ISO 230: Part-2, VDI-3441, ASME B5.54, JIS B-6330, BS-4656 etc.

Positioning accuracy is a very complex affair; it has been simplified with various assumptions. The rigid body assumption proposes six errors in each axis of the machine; namely one displacement error, two straightness errors and three angular errors. Hence for a 3-axis machine, there are 18 such individual errors. To achieve higher positioning accuracy, the angular, straightness, and squareness errors must be measured and compensated. The above errors are related to the built-up quality of the machine and to be controlled during manufacture of the machine or improved by mechanical maintenance of machine during periodic calibration.

3 Method of Positioning Error Measurement

Positioning error results in a relative error
between the cutting tool and work-piece which produces inaccuracy on the components. Identification and compensation of these errors are necessary to improve the machine tool accuracy. Various methods of checking the positioning errors of a multi-axes machine are (i) using slip gauges, step gauges or length bars, (ii) by measuring a part machined by it on a precision Co-ordinate Measuring Machine (CMM), (iii) using Laser Interferometer System or (iv) using Ball Bar System etc.

The laser interferometers are commonly used to make extremely accurate measurements of linear displacement and thereafter giving compensation to the machine controller, as the compensation data for positioning and backlash errors are readily available in the system. The basic theory for laser interferometers dates back to the early 1900s with the Michelson Interferometer being one of the earliest devices to demonstrate interferometric measurements of length.

A laser interferometer uses a laser source that emits a focused monochromatic light beam. The normal set-up for a laser interferometer uses a stationary laser source, a beam splitter, a stationary reference reflective target, and a mobile reflective target, as illustrated in Figure 1. The emitted beam is projected through the beam splitter which results in two separate beams of light. These beams are then projected onto the two targets (one stationary and the other movable) and reflected back to the beam splitter which combines them into a single beam again. The resultant combined beam is then examined for fringes created by a mismatch in the phase relationship between the two returned beams. By counting these fringes as the mobile target is moved, the interferometer system can determine linear displacement as a function of the wavelength of the laser beam.

Since the measurement of distances with an interferometer is accomplished by comparing phase relationships between the reference beam and the measurement beam, the accuracy of the system is dependent on the wavelength of light used and the system’s ability to distinguish fringes created by phase mismatches. The system described is called homodyne system. Other systems which work on frequency change and Doppler shift are also available. Those are called heterodyne systems.

In the present work, UK make Renishaw XL-80 Laser Interferometer System with 0.5ppm accuracy, is used for positioning accuracy measurement. The laser system consists of a He-Ne Laser source, XC-80 environmental compensation unit, Renishaw standard air temperature sensor and Renishaw Laser-XL software. Using this system the positioning accuracy of X and Y-axes of Fulland make CNC Vertical Milling Machine (X=600 mm, Y=450 mm, Z=480 mm, Model: FLG 600, controller: FANUC OiMC) were checked. Table movement in the machine, in X and Y directions, is provided by centrally located motor and a ball screw.

3.1 Instrument Set-up

The set up of the laser interferometer consists of arranging the stationary components (Laser Head, Beam Splitter, Stationary Reflector, Temperature Sensors) and mobile components (Mobile Reflector) of the system so that the relative motion between these components accurately reflects the motion of the machine under measurement. Mounting of the mobile reflector is normally done with a magnetic base, and it is mounted to mimic the motion of the cutting tool of the machine. The Laser Head is mounted off the machine, on a tripod, to insulate it from vibration of the machine in motion. For linear measurement the components are aligned so that the emitted beam leaves the laser head from the upper aperture and is returned from the mobile reflector to the lower aperture, throughout the entire range of motion to be measured. Figure 2 shows a view of the laser
interferometer setup on the CNC Vertical Milling Machine.

3.2 Software Set-up

The Renishaw Laser Interferometer system is controlled by software on a standard laptop. Renishaw software package was used to collect information from the laser interferometer system. The software was setup to capture the reading of data from the system with the motion of the machine work table. The motion of the machine table was under automatic control of a part program written for this purpose. Setting up the software for linear motion measurement was done by filling in the entries on the setup screens for the control of the XL-80 laser system. The setup screens are shown in Figures 3a to 3d. The key entries of various setup screens for linear measurement, to determine positioning accuracy, are explained in Table 1.

![Figure 2 Laser Interferometer Setup on Fulland CNC Vertical Milling Machine.](image)

![Figure 3a Setup screen – Target Setup](image)

![Figure 3b Setup screen – Capture Initialization](image)

![Figure 3c Setup screen – Test Information](image)
### Table 1 Key entries for Linear Measurement - Software Menu & Explanation of the Selections

<table>
<thead>
<tr>
<th>(1) Target Setup</th>
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First target and last target positions are fed in the software. If interval size is given then number of target positions are calculated automatically and vice versa. Interval size is the distance between measurement points. Digits after decimal point may be specified in this screen.

‘First target position’ is the starting point of the laser run. For multiple bidirectional runs the machine is expected to move past this position, and then return to this position for the first reading of the next run. ‘Last target position’ is the ending point of the laser run. For a bidirectional run, the system expects the machine to incrementally move to this position in the forward direction, then move past it (outside the Window distance) and then return to this position for the first reading in the reverse direction.

<table>
<thead>
<tr>
<th>(2) Capture Initialization</th>
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After the specified number of runs in this menu, the software will stop capturing data. In bidirectional test, readings are taken in both directions of motion. Therefore the machine is expected to move, by the specified interval, forward from the starting point, and then in reverse from the ending point. A Bidirectional run is complete when the machine has moved from the starting point, to the ending point, and back to the starting point for a final reading.

<table>
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<tr>
<th>(3) Test Information</th>
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This menu contains information about machine, its operator and location of the machine.

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<th>(4) Auto Data Capture Setup</th>
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This menu contains information about data capture by the laser interferometer. In automatic capture enabled mode, machine motion is controlled automatically by a part program. The laser system is set to expect a specified sequence of moves and uses the dwell time to trigger readings.

### 4 Location dependency of positioning error

There are various internal errors, as listed in para 2, in the machine tools. These are related to the built-up quality of the machine and have to be controlled during manufacture of the machine or improved by mechanical maintenance of machine during periodic calibration. Other external factors affecting the positioning accuracy of the machine tools in static conditions are temperature, pressure, humidity, location of job at work table surface etc. Thermal errors are the most detrimental and, if not controlled, cause a lot of variation on the work piece geometry.

In the present work the external factors temperature, pressure and humidity contributing the errors in the work piece geometry were duly compensated. Renishaw XC-80 environmental compensation unit has been used to compensate the effect of environmental temperature, pressure, humidity and material temperature. The compensation unit accurately measures air temperature, air pressure and relative humidity. Up to three material temperature sensors can be attached to the XC-80 compensator to allow linear measurements to be normalized to a standard material temperature of 20°C.

After compensating the above factors affecting the accuracy, the positioning accuracy has been determined at various locations of the work table surface. Positioning accuracy ($P_x$) was determined along 5 paths in the direction of X-axis motion, at various Y axis locations as illustrated in Figure 4. The locations along which the positioning accuracy was determined are indicated as 1, 2, 3, 4 and 5 and corresponding positioning accuracies as $P_{x1}$, $P_{x2}$, $P_{x3}$, $P_{x4}$ and $P_{x5}$. The accuracy of X-axis at location 3 ($P_{x3}$) was determined first. To reach the other locations 1, 2, 4 & 5, machine table was moved in Y direction and Laser Head was kept fixed at one place, only the place of interferometer was changed accordingly.

Similarly the positioning accuracy ($P_y$) was determined along 5 paths in the direction of Y-axis motion, at various X axis locations as illustrated in Figure 5. The locations along which the positioning accuracy was determined are indicated as 1', 2', 3', 4' and 5' and corresponding positioning accuracies as $P_{y1}$, $P_{y2}$, $P_{y3}$, $P_{y4}$ and $P_{y5}$.

Positioning accuracy of X-axis at location 1, 3 and 5 is shown in Figures 6, 7 and 8. The same for Y-axis at locations 1', 3' and 5' is shown in Figures 9, 10 and 11.
Figure 4 Accuracy in X-axis

Figure 5 Accuracy in Y-axis

Figure 6 X-axis positioning accuracy at location 1

Figure 7 X-axis positioning accuracy at location 2

Figure 8 X-axis positioning accuracy at location 5

Figure 9 Y-axis positioning accuracy at location 1'

Figure 10 Y-axis positioning accuracy at location 3', Py3 = 5.0 micron

Figure 11 Y-axis positioning accuracy at location 5', Py5 = 19.0 micron
5 Results and Discussion

All the data collected for positioning accuracy are shown in Figure 12 at the various table locations. The result can be summarized in the following points.

(i) The central portion of table is the area of fine accuracy. The accuracy in this 140mm x 90mm area is found to be 5 micron maximum.

(ii) Next to the area mentioned in step (i) may be called the area of medium accuracy. This area is shown as vertical hatched area in Figure 12. Here the accuracy value is 11 micron maximum.

(iii) The outer area of the machine table may be called as the area of coarse accuracy. This is shown as horizontal hatched area in Figure 12. In this area the maximum accuracy obtained is 19 micron.

6 Conclusion

From the above observations it is clear that if the same component is machined at different locations of the work table, different tolerances will be obtained on the component. It is particularly very relevant when small components are batch produced using a fixture and utilizing the whole area of machine table, in a CNC run. Following conclusions may be drawn from this discussion.

(a) As far as possible the components shall be mounted in the central area of the machine table for machining.

(b) One method to tackle this position dependency of the machine tools may be that only the components which have more tolerance than the positioning accuracy at outer area of the machine table (step iii above) shall be machined on that particular machine.

(c) Other method to deal this issue may be to measure the positioning accuracy of the machine at various locations of the machine table and mount the job according to the tolerance specified.

References

