Accuracy and Tuning in CNC Machine Tools

Introduction:
This article explains how it is possible to achieve a better performance on High Speed CNC Machine Tools. Performance is a general term that needs to be quantified based on the application. Two essential factors for defining the performance of a CNC Machine are Accuracy and Machining Speed. Fine Tuning is to compromise between these two factors. Increasing the machining speed, which is always favorable, could reduce the machining accuracy at the same time, which could be due to an un-tuned servo or excessive vibration. The following ratio is defined as a factor that shows machining overall performance:

$$\text{Performance}(Q) = \frac{\text{Machining Speed}(S: \text{m/min})}{\text{Machining Accuracy}(A: \mu)}$$

Obviously a larger Q is always desirable since it means the Machining Speed (S) is higher or the machine has a tighter accuracy (smaller A). For instance a machine that can run at $S=10\text{m/min}$ and holds the accuracy within $A = 10 \mu$ would have a performance of $Q = 1$. The following chart further illustrates the relation between machining speed and machining accuracy and how they connect to the overall performance of the machine.

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Maximum Programmed Speed</th>
<th>Machining Guaranteed Accuracy</th>
<th>Overall Performance (Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Milling Machine</td>
<td>8 m/min</td>
<td>10 µ</td>
<td>8/10 = 0.8</td>
</tr>
<tr>
<td>High Speed Small Milling Machine</td>
<td>20 m/min</td>
<td>5 µ</td>
<td>20/5 = 4</td>
</tr>
<tr>
<td>Large Router</td>
<td>30 m/min</td>
<td>60 µ</td>
<td>30/60 = 0.5</td>
</tr>
<tr>
<td>Large high Speed Milling Machine with linear motors</td>
<td>40 m/min</td>
<td>10 µ</td>
<td>40/10 = 4</td>
</tr>
</tbody>
</table>

Figure 1

The chart shows different types of machines with various speeds and accuracy. A smaller machine would always have a better accuracy than a large machine. At the same time a large machine may not be able to move as fast as a small machine unless the linear motors are used which are quite expensive items. A machine with a rigid structure can have a better accuracy. That is why a Milling Machine provides a larger Q value than a CNC router. Improving the Q could be very costly since it may require a different servo and feedback systems, calibration, and perhaps different mechanical structure to have larger rigidity.

This Article identifies the major factors and common challenges to improve the performance of the machine. With Fine Tuning and incorporating accelerometer feedback, it is possible to increase the Performance Q.
Dynamic vs. Static Accuracy:

To achieve a better performance, it is crucial to assess the accuracy of the machine in different situations. The accuracy of a CNC machine can be assessed in two ways, Static and Dynamic modes. The Static mode is when the axes of the machine moves to a certain location and their actual position will be measured by an external device (such as an interferometer laser) against the registered values in the CNC. Basically, the CNC moves the axes to a specific position known as command position usually through a part program. After the axes are stopped and they are at rest, a laser would be able to measure this location. The difference between command position (CNC Register) and actual position (what laser measures) can be introduced as “Static Accuracy”. The static accuracy can usually be improved by mechanical alignment, or could be compensated electronically (Linear, Cross or Volumetric Compensation). Accuracy is an expensive item on a machine and the first step to have an accurate machine is to have a tight static accuracy. Modern CNC controllers can compensate the machine’s geometry deviations and achieve this goal.

Dynamic Accuracy can be defined as the accuracy of the axes when they are actually moving or when the machine is cutting a part. It is possible to improve the Dynamic Accuracy by Servo Tuning. There are two major factors that could degrade the Dynamic Accuracy: Servo system positioning error and Vibration both of which are explained later in this article. One of the important factors to define the performance of a machine is the machining speed. A high speed machine is usually capable of executing a part program with almost 20000mm/min. This amount of feed-rate could create a large lag value on the axes servo system as well as large vibrations on the corners due to high acceleration/deceleration. Another source of vibration could be the spindle and the cutting force on the tool tip. An excessive force on the tool tip may cause an unacceptable vibration and in result degrade the overall accuracy.

Axis Lag or Position Error:

A servo system that moves an axis uses feedback devices. An axis could have several types of feedbacks such as position, velocity or current feedback to have a proper performance. Position Feedback is the main feedback source of an axis servo system. A Digital Encoder or Scale is an example of a position feedback that constantly measures the actual position and the CNC constantly compares it to the position command. The difference between the actual and command position is known as lag, following error or position error.

When the CNC sends a movement command to the Servo Drives, the axis would have some inertia against the movement due to its mass and friction. Therefore position error occurs mostly because of the inertia. A heavier axis would have a larger inertia, so the lag of a heavier axis is usually larger than a lighter axis.

The position error is always larger in higher speeds. When the axis moves faster its lag is also larger hence the accuracy tends to get worse in higher speeds. To improve the accuracy in higher speeds one must minimize the lag by increasing the Proportional Gain in Servo Systems however there is a limit for the amount of proportional gain, which beyond that, the axis can oscillate.
Stability is the main objective of any servo tuning. A very tight tuned axis can easily be unstable and go to oscillation mode. To prevent the instability one must reduce the proportional gain of the servo control system. Stabilizing the axis by reducing the proportional gain increases the lag and eventually lowers the accuracy in higher speeds.

When the Proportional gain is adjusted to its maximum value, it is possible to minimize the lag in transient mode by applying Integral and Derivative gains. Therefore the rising time and the overshoot will be minimized as well. It is always desirable to minimize the lag in all conditions. A smaller lag value would lead to a better accuracy. The following factors are defined to quantify the servo tuning performance:

\[
\text{Servo Tuning Performance } (Q_t) = \frac{\text{Maximum Programmed Speed: } \text{m/min}}{\text{Maximum lag: } \mu}
\]

If the Lag value is smaller (a smaller lag means a more accurate machine) the \( Q_t \) will become larger for a specific speed. A tuned machine that is capable of moving with 10m/min and can have maximum 10µ position error would have a \( Q_t = 1 \). The following chart is an example that shows how servo tuning can improve machine performance:

<table>
<thead>
<tr>
<th></th>
<th>Maximum Programmed Speed</th>
<th>Maximum lag</th>
<th>Servo Tuning Performance ( (Q_t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Milling Machine</td>
<td>8 m/min</td>
<td>20 ( \mu )</td>
<td>8/20 = 0.4</td>
</tr>
<tr>
<td>Large Milling Machine with</td>
<td>8 m/min</td>
<td>8 ( \mu )</td>
<td>8/8 = 1</td>
</tr>
<tr>
<td>tuned servo systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Router</td>
<td>30 m/min</td>
<td>20 ( \mu )</td>
<td>30/20 = 1.5</td>
</tr>
<tr>
<td>Large Router with tuned</td>
<td>30 m/min</td>
<td>10 ( \mu )</td>
<td>30/10 = 3</td>
</tr>
<tr>
<td>servo systems</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 2*

**Vibration, another source of inaccuracy:**

One of the major causes of dynamic inaccuracy is the vibration. Even a tuned and stable servo system could experience a structural vibration. The source of these types of vibrations could be because of:

1. Structural deflection due to high acceleration/deceleration.
2. Ballscrew Alignment.
3. Resonance.
4. Loose guide-ways, Backlash in ballscrew nut or, trust bearings.
5. Gears and bearing and spindle run-out.
The structural deflection is usually lower on heavy machines. A heavy machine would have less vibration than a light machine. A well designed body also could have less structural vibration.

If the machine cannot accelerate or decelerate fast enough it would be slow on the corners of the part program and that would increase the cycle time of the program. Obviously a heavy axis cannot move as fast as a light one because of its inertia. **The challenge is to move a large axis in high speed with high accuracy and minimum vibration.**

The vibration on the spindle tip is mostly unknown to the CNC. The CNC servo may simply not see the vibration and therefore it cannot compensate for it. A usual approach to overcome the vibration is to decrease the acceleration and deceleration of an axis. But reducing the acceleration and deceleration would have a direct impact on the machining speed.

Applying a sudden acceleration even with a small value could cause vibration as well. It is always better to apply the acceleration with a specific rate. The rate of the acceleration change is known as jerk.

\[ jerk = \frac{\Delta \text{accel}}{\Delta t} \]

A higher Jerk value means a higher rate of the acceleration change. A good example of jerk is when a person is sitting in a car and the driver suddenly presses the gas pedal. The acceleration would pull that person against the chair and the sudden change in acceleration indicates the magnitude of the jerk value.

**Rigidity**

One of the most important factors to evaluate the quality of a CNC machine is its “Rigidity”. A rigid machine can move faster with lower vibration. The Rigidity can be defined as follows:

Vibration caused by mechanical misalignment:

\[ \text{Velocity Rigidity}(Q_{rv}) = \frac{\text{Maximum Programmed Speed: m/min}}{\text{Maximum Deflection at the tool tip: } \mu} \]

If the mechanical parts such as ballscrews or guide-ways are not aligned properly, the faster the machine moves the larger the vibration would be.

Vibration caused by mechanical deflection:

\[ \text{Acceleration Rigidity}(Q_{ra}) = \frac{\text{Maximum Programmed acceleration: m/sec}^2}{\text{Maximum Deflection at the tool tip: } \mu} \]

\[ \text{Jerk Rigidity}(Q_{rj}) = \frac{\text{Maximum Programmed Jerk: m/sec}^3}{\text{Maximum Deflection at the tool tip: } \mu} \]

A large acceleration or jerk can cause the machine’s structure to bend or vibrate during the stop, start or changing the axes direction. A rigid machine would have minimum deflection.
Vibration due to cutting force on the spindle:

\[
Cutting \text{ Force Rigidity} (Q_{ra}) = \frac{\text{Maximum Material Removal Power (KW)}}{\text{Maximum Deflection at the tool tip: } \mu}
\]

The cutting force on the spindle tool tip could cause vibration on the machine’s structure which could affect the accuracy of the machine.

**Accelerometer Feedback:**

The deflection on the machine structure due to large acceleration is mostly unknown for the CNC Controller. It is possible to use accelerometer feedback to report the amount of vibration back to the CNC and counter act against the vibration. If the body of the machine is modeled properly, the acceleration feedback makes the machine stiffer and allows it to run faster, smoother and with better accuracy. Using accelerometer feedback allows a non-rigid machine to perform as a rigid one. Here is an example:

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<tr>
<td>Large Router equipped with accelerometer feedback</td>
<td>30 m/min</td>
<td>20 µ</td>
<td>30/20 = 1.5</td>
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Figure 3

Using accelerometer feedback can improve the overall performance of a router almost 3 times.

**Conclusion:**

In a CNC machine tool, accuracy and machining speed are two competing factors. To achieve higher accuracy, one may need to reduce the machining speed to decrease the servo positioning error and vibration. On the other hand there is always a demand for higher speed without compromising the accuracy. To achieve this goal, outside of calibrating the machine’s geometry, one can perform Servo Fine Tuning to reduce the position error in the servo system as well as incorporating accelerometer feedback to compensate for vibration.

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