Milling in the "Hot Zone"

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Executive Summary

High-speed machining cannot be rigidly defined because of differences in materials, applications, and the size of the part. ***High-speed is relative.*** Still, the basis is also relative, so the same concepts of acceleration (not speed per se) and faster control functions remain critical to applications at 30 IPM as in applications of 1200 IPM.

The ***"hot zone"*** is the range of feed rates that provide optimal productivity without sacrificing accuracy. The selection of a machine with an appropriate range of feed rates to support ***your*** specific ***"hot zone"*** can make a huge difference in your ability to compete in the world of high speed milling.

While hosts of other factors play a role, two major factors contribute most to performance within that hot zone - acceleration and control intelligence. Selection of the right equipment for your job will give you the best results for your application. Selecting a machine with the right ***"hot zone"*** will give you the best payback on your investment.

Milling In The Hot Zone

[Authors note: The following article can be technically daunting for some of us. A clear understanding of it can pay big rewards for the determined, though, as it will make a dramatic impact on how you evaluate "high speed." Good luck!]

Within specific industry segments, most machining is done within a given range of feedrates. The optimal range is what we refer to as the ***"hot zone,"*** the range where we aren't just productive, but where we are highly productive. This is the range where the longer profit margins are made. This is the ***"hot zone."***

In a world of production machining of aluminum, high-speed might be 1200 IPM (inches-per-minute) feedrates with spindle speeds of 60,000 RPM and 30 HP spindles. Machining EDM electrodes, high-speed feed rates are often 300 to 400 IPM. For mold cavity machining, high-speed feed rates might be 180 IPM. For super-precision laser cutting of delicate medical implants, high-speed might be feed rates of 15 IPM!

Most would respond that 15 IPM is hardly high-speed. My experience has proven otherwise. On a new machine capable of 700 IPM rapid traverse rates, and feed rates to 400 IPM, simply changing the control to a true high-speed control can drop cycle times from 20 minutes per part down to just 10! That was achieved when laser power and accuracy requirements mandated feedrates of only 3 IPM!

"High speed for 3 IPM feed rates?" you ask. That is the heart of this story, the difference between simply machining fast and true high-speed machining. This article explains how to distinguish high-speed from fast milling in order to keep you at the pinnacle of your trade without investing your entire future.

The fastest machines today incorporate various technologies in order to optimize performance. Though the drive mechanism might seem the most apparent limiter/enabler for high speed, the CNC control plays a more important role for all but the simplest of applications. Ballscrew size and pitch, guide way construction and preload selection, machine design stress analysis, spindle design and RPM, and more all weigh in to the optimal machine. Still, the most basic ingredient to enable each of the features to perform to their utmost is the controller itself. It alone is the director of the symphony of components; the head coach of the team, if you will.

At the heart, acceleration

The real separation between high speed and fast milling is the acceleration of the axes and those axes' logical, safe, accurate control. Going at high feedrates and suffering gouges and rounded corners is not high-speed. Rather, that is just going fast (and sloppy)!

The control is the primary enabler of accurate acceleration, not the drives! Surprised? Well, the idea is that since the control orchestrates all the motion in the machine system, the control must be intelligent enough to make the best of any drive system. Therefore, the control is what allows the system to get the most out of the drives, all the while keeping things in control to deliver an accurate part.

There's a lot to this concept of acceleration, and we'll get into some of the nuts and bolts of it later. For the moment, let's take an overview.

Laws of physics state that no mass can accelerate to a speed instantly. Acceleration is the process of changing from a given speed to a different speed. The initial speed might be zero, stopped. The final speed might be slow, say just one IPM (inch-per-minute). Even such a small rate of change takes time. The rate of change is the amount of speed change over a period of time. On the most technical level, we speak of acceleration in terms of inches per second squared, or inches per second per second. Yes, the second "per second" is needed, as we are talking about a rate of change, not just a rate of fixed or constant speed.

For instance, if your machine is moving at 1 IPM and it will take one second for it to get to 201 IPM, you might simply say that the rate of change is 200 inches per minute per second. In other words, the feed rate changes 200 inches per minute in 1 second. This can also be called 3.3 inches per second per second or 3.3 inches per second squared.

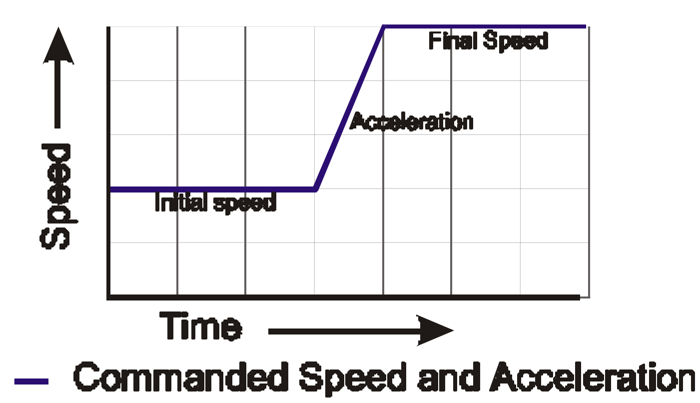


Figure 1, Simple Acceleration

In practice, acceleration today can be much faster. Within the range for CNC machining, we often measure in terms of gravitational force, or "G-force," the rate at which things accelerate toward earth because of the natural pull of gravity. One g-force is generally accepted as 9.80 meters/second² or 385 inches/second².

Most CNC machines using ballscrew drive systems strive for up to about ½G force in acceleration, or nearly 200 inches/second². Unfortunately, this does not mean that today's machines can commonly accelerate to 200 inches/second in one seconds' time. Life is a lot more complicated.

In real-life practice, acceleration varies because of resistance and inertia. From a standing start, there is a sticking effect of the static surfaces in place. There is also the zero inertia that a stationary mass doesn't want to change speed. Once a mass is moving, inertia makes it try to continue moving at that rate, unable to stop instantly.

Historically, acceleration has been fairly simple for CNC. We wanted a faster feedrate and commanded acceleration [in a straight line] to change from the current to the desired feedrate at a constant rate of change.

As we check on the actual machine performance, we find that because of the resistance and inertia discussed earlier, the machine can't actually do all it's told. Rather, we suffer from following error. This is the (inevitable) error between what the machine is commanded to do and the actual movement.

The graph below shows the difference in commanded versus actual acceleration with simple commands as historically used in CNC. The

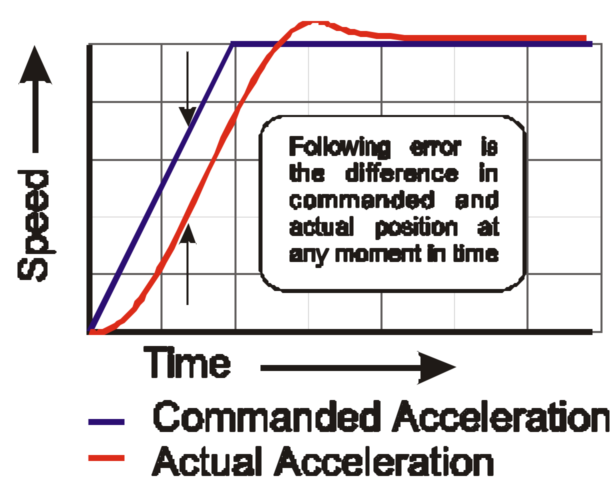


Figure 2, Commanded vs. Actual Accel

red line shows the actual acceleration and speed, lagging behind the commanded acceleration. Even more, once the commanded speed is reached, the machine may actually "overshoot" the commanded speed, causing further inaccuracy. The acceleration rate that is used for commands is based on the evaluation of the machine's acceleration over its entire speed range, not accounting for the variations in performance throughout the range. An acceleration rate that can be achieved throughout all ranges must be used, causing a major compromise in performance.

A Partial Solution

To machine at high speeds with accuracy, some manufacturers now account for these problems in many ways, with "S Curve" or "Bell Curve" acceleration formulae, generically anticipating the physical limitations and commanding accordingly. This helps smooth the machine motion, eliminating some of the "jerk" that might otherwise occur because of following error. Still, even with curved acceleration ramps, there remains the flaw that acceleration is different in different parts of the speed ramp.

The most advanced of systems today use computerized drive tuning online to test the system response and adjust for it. In this way, we can see the drive performance in detail and optimize it. All aspects of the entire machine system's performance then become a part of the CNC program and are anticipated. Thus, motion is commanded in respect to the available performance, getting the most out of the entire machine system, and optimizing the machine's accuracy. This allows for different response of the machine system at different areas on its acceleration curve.

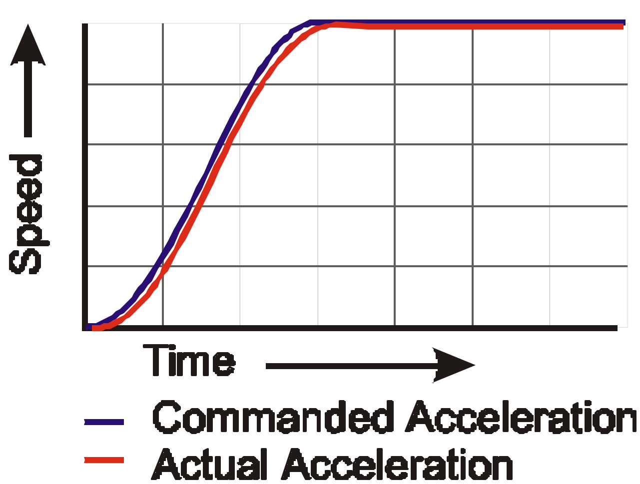


Figure 3, S-Curve Acceleration

The graphs above refer to "following error" or "servo lag." Again, this is the amount that an axis is following or lagging behind where it is commanded to be at any moment in time. Following error of 0.200" is not uncommon amongst CNC machines delivered over the past decade or so with straight-line acceleration as shown in figure 2. Nowadays, that following error is significantly reduced. Through computerized drive tuning, some systems enjoy virtually no following error, peaking at less than 0.001" even at feedrates over 500 IPM.

An additional benefit to the computerized drive tuning and modified acceleration curve is longer machine life. When commanded within its limitations, jerking motion is eliminated, smoothing the machine's motion. Components suffer less strain, wearing more slowly, maintaining more up-time for you.

All of this must be transparent to the machine's operators and programmers. Some systems today require operator tuning when running. This choice creates more for the operator to do and provides a huge opportunity for errors. Machine optimization must be a transparent function.

Top feed rates

So a "faster" machine will be better, right? Well, define faster, please!

Surely, our goal is to get the job done faster, but the point of this text so far is to clarify that a higher rapid traverse rate does not make a machine faster. A machine that is set up for 2400 IPM rapid traverse rates is not likely to get your work done in the least amount of time if your work is 3-D contouring, as found in molds and electrodes, dies and prototypes. Take a look at the following graph of accelerations to see why.

You might well be confused at this point, still stuck on why a machine with higher rapid traverse and feed rates wouldn't be better, or faster to the finish line?

To better convey this message, I often paint the scenario of driving a car with a manual transmission using only the highest gear, 4 or 5. Your car might be very fast once up to speed, but it would surely be slow getting up to that high speed!

What does all this have to do with high-speed milling? Well, your CNC mill does not have variable gears in its drive system. It is stuck with just one gear ratio. The variable speeds arise from control of the motor and its servo control amplifier. As such, it is stuck in whatever gear ratio the manufacturer sets it. If set for a top speed of 2400 IPM, then its acceleration is much slower than if the same motor's top speed is set for 600 IPM.

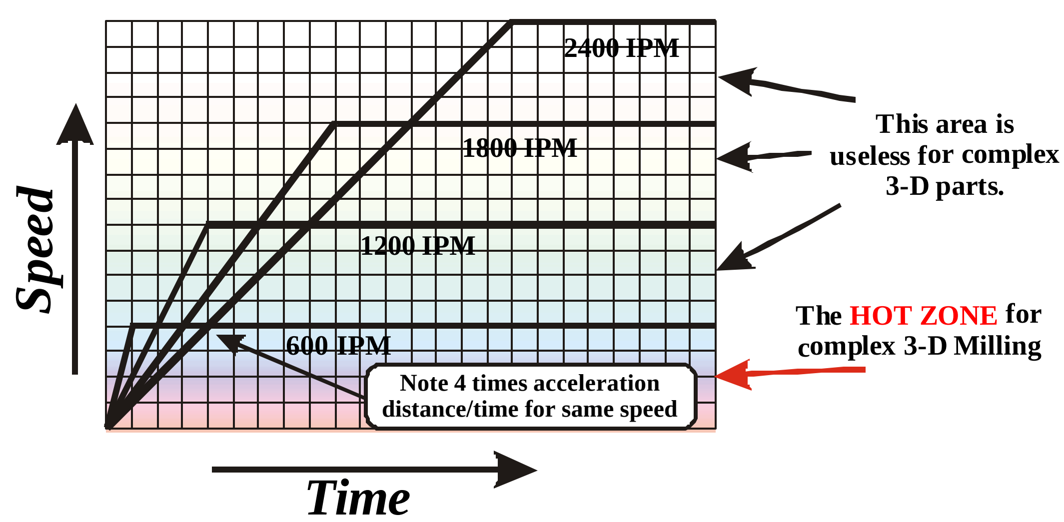


Figure 4, Acceleration Comparison for Various Rapids

This graph is simplified by eliminating the curves that optimize acceleration.

You might think about racing cars. If you were to try using an Indy car on your local county fair's 1/4-mile dirt track, it just couldn't compete. It would be too fast for the conditions, without enough speed control, acceleration and deceleration. Looking closer, a 1/4 mile dirt track requires a lot more cornering, and more acceleration for short straightaways and sharper corners. In essence, an Indy car would be the wrong tool for the job.

Looking at that graph, you will see that accelerating to 600 IPM takes 4 times longer (or more) for a machine set up for 2400 IPM rapids than a machine set up for 600 IPM. This means that in the range of feedrates normally used for 3-D contour milling, the acceleration is dramatically slower. It gets worse if you consider that the deceleration is also 4 times slower!

Use the example of milling a 3-D contour, where the cutter is nearly continually engaged in the material and the cutter is limited to 600 IPM or less. The final result will be finished in much less time on a machine properly geared to peak at 600 IPM than on a machine with the same drive system geared to peak at 2400 IPM! This is simply because its acceleration performance for all the contours and details allows it to navigate those contours faster. Slower can indeed be faster!

More power?

An additional consideration for speed and acceleration is each motor's rated ***full-torque*** speed vs. its ***top speed***, as well as its size. Servomotors are rated for full torque only to a certain speed. Though the motor is generally capable of twice that speed, the power deteriorates the further it goes beyond the full torque peak speed. Thus, once the motor goes beyond its peak speed, its performance is compromised. A machine's complete ***system*** tuning is compromised for each motor's overall performance, not its best performance in the lower range.

Larger motors and drives aren't the answer. Bigger motors are capable of more raw power, but lose their agility. The higher inertia of a bigger motor makes it tougher to get moving. Once it is moving, it is harder to stop. Then there's the issue of price, and ongoing cost of wasting energy, etc. Overall, bigger is not better; bigger drives won't provide the results we want.

When designing a machine for true high-speed performance, the first concern must be its intended "hot zone" for effective contouring. Then the drive systems must be carefully engineered for that need.

Better Acceleration Control, A few of the benefits…

One benefit of better acceleration control is very directly the time it takes to make your parts. The more complex the part, the more of its milling time is spent in acceleration and deceleration time. The better that your machine's acceleration is suited for the job, the higher your ***sustained*** feedrate will be, and thus, the faster your part will develop. You produce more work in less time, increasing your profit.

Another benefit is the accuracy and quality. Precise control of accel and decel with look-ahead makes your part more accurate. Your customer and the end user all benefit by getting better parts. You benefit by becoming your customers' favored source.

A more subtle, yet also significant benefit is better tool life. A more-constant feedrate improves chipload control. This is essential to maximizing cutter life, especially in hard materials with exotic cutters.

Getting The Speed Under Control

"Speed is the skill, control is the art!" says Chester Borucki, an old-school patternmaker. Though originally spoken in regards to manual trades used for patterns, this applies today in CNC as well. All the speed and acceleration possible is worthless unless channeled and controlled properly. This is the CNC controller's job.

In a quest for faster CNC, manufacturers began using faster drive systems without improving the control technology. The result is that most machines today can rapid-traverse fast, but gouge and overshoot. Both performance and accuracy are compromised.

As an option, though, a number of CNC and machine builders offer special logic for high-speed, known as look-ahead or geometric intelligence. The key here is that they offer it as an option! When it comes to accurate machining of complex contours, look-ahead is not an option, it's a necessity. Dave Long of Pro Mold and Die in Roselle, Illinois says "You need high speed and you need look ahead, you can't have one without the other." Look ahead is the logic that evaluates the contour before machining it, keeping the commands within the limitations of the machine for highest performance with accuracy.

(Look ahead is one of the key concepts for effective high-speed machining of 3-D contours. **A Closer Look At Look Ahead** covers the topic in detail at
http://www.creat.com/referen/lkahd3.htm.)

Just to review, the drives establish the potential and the limits for what can be done. The control has to command those drives properly for the best performance. That's why our commands can't be simple straight lines, as shown in figures 1 and 2, but rather must be the more complex curved commands, anticipating what the machine system is really capable of to minimize following error, and yet to push acceleration to the limit.

High Speed CNC

Before the CNC commands any motion to the drives, the CNC must receive and process the data. This is a key element in the process, for as we have seen, the CNC is what determines how to best utilize the speed and acceleration offered by the drive system.

Speed can be measured several ways in CNC. ***One way you can not measure a CNC's speed though, is by the rapid traverse rate!***

There are three crucial time specifications used in a CNC, the Block Transfer Time, Interpolation Time, and the Servo Cycle Time. Each is distinctly different, and each has the potential of limiting your CNC from meeting your needs. All three need to work in harmony to enable the best possible performance from your machine.

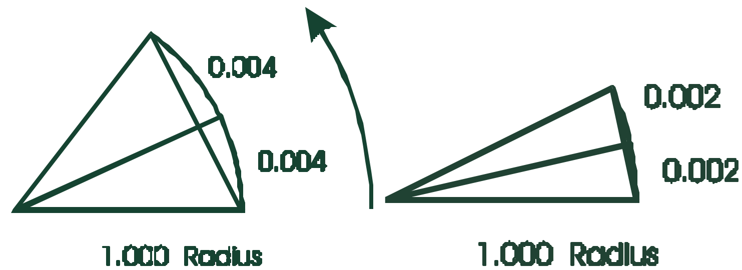
The Block Transfer Time (BTT) is the time that the CNC takes to absorb a single block of program information. If the BTT is 3 milliseconds (ms.), or thousands of a second, then the CNC is capable of absorbing 333 blocks-per-second (bps). The ability to absorb program information quickly is very important to making the CNC run smoothly.

The BTT is the most commonly discussed timer in controls. On a more generic level, many discuss the number of blocks-per-second their CNC can run. A major problem with discussions of BTT is that many controls are capable of reading, but not executing at those speeds. They end up combining or ignoring some distinct commands when the data saturates the system.

The number of blocks-per-second that a system can read can also be misleading in the world of DNC, commonly used to feed information to controls with inadequate program storage. While DNC is still prolific today, it is gradually being replaced by DCN, Direct CNC Networking as described on the Internet in **The Ultimate DNC; Direct CNC Networking (DCN)** at http://www.creat.com/referen/ultmtdnc.htm

The Interpolation Time (IT) is the time the CNC works with to create interpolation segments. Although you may see a single straight-line or circular move as you watch your machine, the CNC control is breaking those moves into small segments based on this timer, in order to coordinate the machine movements as accurately as possible. Although arcs and circles are often entered as single-line commands, the CNC control breaks them into small, linear movements to create the illusion of a circle using axes that are perpendicular and can't actually rotate at all! The IT is the limiting factor for how small the increments can be at any given feedrate for any given interpolation.

The interpolation timer is especially important to accuracy! Twice the speed for the interpolation timer does not simply yield twice the accuracy, but rather 4 times the accuracy for curves! Look at the following two diagrams. Simple algebra demonstrates the concept.



$$1-(1^2-.002^2)=.000008$$

$$1-(1^2-.004^2)=.000032$$

Figure 5, Interpolation Accuracy

The Servo Cycle Time (SCT) is the time that the controller takes to command the axes and verify the axis positions. This is the lowest level motion timer in the bowels of a CNC control, the bottom line in performance!

The chart below shows a sample listing of CNC timer speeds. It lists the distance the axes move in a given time slice at three sample feedrates, 100, 400 and 1200 IPM (inches-per-minute).

As you can see in the chart, if a CNC machine controlled by a CNC with a 3 ms. SCT is traveling at 400 IPM, it will move 0.0200" between measurements of the axes. This does not infer that the results will have a 0.0200" tolerance. This chart makes it obvious that since the positions of the axes are checked at fairly coarse increments, the machining will not be to the tolerance that might be expected with a faster control that checks more often and at closer increments. In contrast, with a control operating at .4 ms. servo cycle time, the distance between measurements is only 0.0026", a 7.7 times improvement!

Time Ms.	Cycles/ Second	Distance Traveled		
		100 IPM	400 IPM	1200 IPM
20	50	.0333"	.1333"	.4000"
10	100	.0166"	.0667"	.2000"
3	**333**	**.0050"**	**.0200"**	**.0601"**
1	1000	.0016"	.0066"	.0200"
.4	**2500**	**.0007"**	**.0026"**	**.0080"**
.1	10000	.0002"	.0007"	.0020"

Figure 6, Distances traveled for various CNC time cycles

Within the CNC industry, there is an effort to define 3-D cutterpaths by NURBS or other curves rather than by the simple historic method of point-to-point. Objectives commonly stated are lower data throughput requirements and faster part cycle times. In both cases, the results still rely entirely on the CNC control's interpolation time (IT) and servo cycle time (SCT). At the lowest level, the CNC must still break any curve into a series of straight lines. NURBS or other curves limit the CNC to known and defined curves, supported by both the CAM and the CNC manufacturer. With a sufficiently fast control, NURBS or curves become non-issues, with the greatest flexibility for the CNC and the CAM package resulting from point-to-point interpolation with faster part cycle times!

Complex control

One of the greatest, yet most intangible and mysterious functions of a faster control is its drive interface and acceleration algorithms. The more processor speed the control has, the more that can be available for these math-intensive functions. Earlier, we discussed acceleration as basics with straight line or s-curve commands. The reality is that it is more complex still, perhaps a topic for another article in the future.

At different feedrates, acceleration potential varies. Again, your drives must be matched to your needs, your "hot zone," in order to maximize the machine system's performance and thus, your productivity. Ideally, this is done through computerized and graphical tuning procedures that not only analyze the drive system, but rather the entire machine system. With this capability, the control can anticipate each axes specific performance to maximize productivity.

In the end, capitalizing on a machine's acceleration relies entirely on the control to coordinate all axes for the best performance without compromising accuracy. In high speed CNC, the control surely is the art!