Achieve Superior Servo Performance, Quickly, with Auto-Tuning

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White Paper

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Servo systems are well-known for their superior performance in demanding motion applications. When system designers want to wrap candy, polish semiconductor wafers, form an aspirin tablet, or lay thin coatings on a roll of plastic, servos do it faster, smoother, and more accurately than just about any other technology.

Unfortunately, getting the superior performance of servos isn't always easy. For example, servo systems must be "tuned," a process where many parameters are set to values that depend on the particular motor, drive, controller, and mechanical load. Tuning the highest-performing motion systems can be challenging.

In this article we'll discuss tuning: why it's required, how it's done, and what happens when it's not done well. We'll also discuss the process of automatically tuning or "auto-tuning." In the past, auto-tuning was effective for a narrow set of conditions: highly rigid mechanical loads and applications that didn't demand top performance. Today, auto-tuning has improved and the best auto-tuners are better at tuning than most people. The goal of this article is to help you better evaluate servo systems and auto-tuning capabilities so you can select the motion components best suited for your application.

Configuration vs. Tuning

Complex configuration processes are common in industrial equipment. However, for most equipment, configuration involves setting up a controller for length of stroke, the number of motor poles, and other concrete parameters that have easily-understood physical meaning. Part of a servo drive's configuration process fits this description—for example, the resolution of a feedback device or the number of magnetic poles for a given motor. But in servo systems, the feedback loops also must be tuned.

Tuning loop gains is the process of raising the value of those gains as high as possible while maintaining an adequate margin of stability. Raise the gains too high and the system will overshoot and ring; it may even become unstable – a condition where the motor oscillates uncontrollably. Keep the gains too low and you can lose the benefit of servos – the system can be sluggish. *Figure 1* shows the step response of a servo velocity control for three cases.

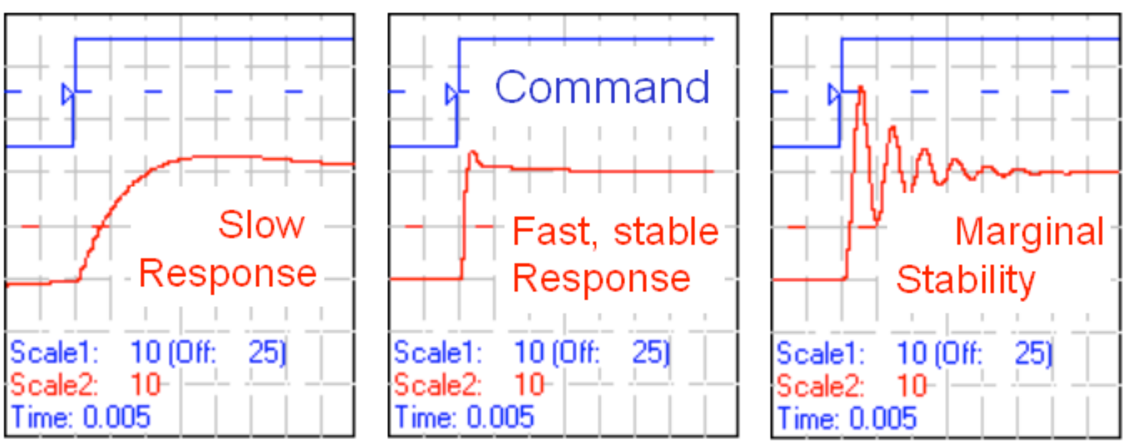

Figure 1. Three ways to tune a servo system.

Case 1. A poorly-tuned velocity controller with gains too low, yielding sluggish performance.

Case 2. A well-tuned velocity controller. Notice the system responds in a few milliseconds with little overshoot.

Case 3. A poorly-tuned velocity controller with gains too high, yielding inadequate margins of stability.

Most engineers find the need for high gains easy to understand. Servo loops calculate error – the difference between the command and the feedback signal. They then scale the error by a "gain," and the output becomes the command to the next stage of the system. The example in Figure 2is a simple position loop: position error is scaled by "position gain" to create a velocity command for the velocity loop. Higher-gain loops are more reactive to error. For example, in Figure 2, double the position-loop gain and the position loop will command twice as much velocity for the same error. As a result, error will be removed more rapidly.

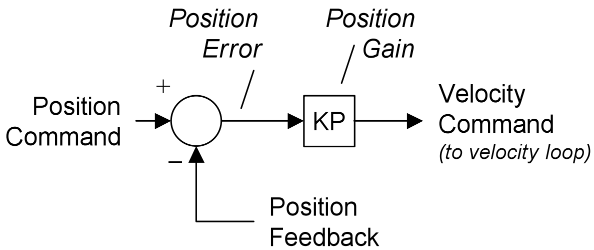

Figure 2. A simple position loop.

Stability, the upper limit on servo gains, is more difficult to understand. The phenomenon of instability is unfamiliar to many people because it rarely occurs in most walks of life. It derives from the delays that accumulate in a control loop – for example, the time to execute calculations in a microprocessor or the time delay of a filter used to quiet a noisy signal. Those delays add up as a signal traverses the loop. *(see Figure 3)* For example, if the delay around a loop is 500 micro-seconds and the gain is too high, the system will oscillate at about 1000 Hz (the frequency of oscillation has a period of twice the delay). This occurs because at that frequency the signal feeds around the loop and back on itself, adding to itself over and over again. The loop greatly amplifies at that one frequency.

While stability itself can be difficult to comprehend, accommodating delay in a loop is simple enough: keep the gains low enough to avoid instability. For the short delays that occur in modern servo systems, that turns out to be fairly easy. In fact, if delays were the only problem servo designers had to deal with, tuning would be an easy process. Unfortunately, the complex mechanical loads that are typical in modern machines make stability problems much more difficult to deal with.

If servo systems controlled rigid loads – that is, loads firmly coupled to the motor – tuning would be simple. But most mechanisms have mechanical compliance, flexing when the motor applies torque. Transmissions add compliance between the motor and load through belts, ball nuts, shaft couplings, and gear teeth that flex when loaded. As a result of this flexing, the mechanical load varies with frequency. At low frequencies, the servo system "feels" the reaction torque from all the mechanical components. At high frequencies, however, the load seems to almost disappear because of flexibility in the transmission.

To better understand how inertia seems to "disappear," consider a simple example. If you hold an office stapler at the end of a large rubber band and move your hand up and down slowly, your shoulder feels the reaction of the whole system from hand to the stapler. But if you move your hand rapidly, the rubber band stretches in and out, and the stapler remains almost still. In that case, your shoulder feels only the reaction of your hand while the inertia of the stapler almost disappears.

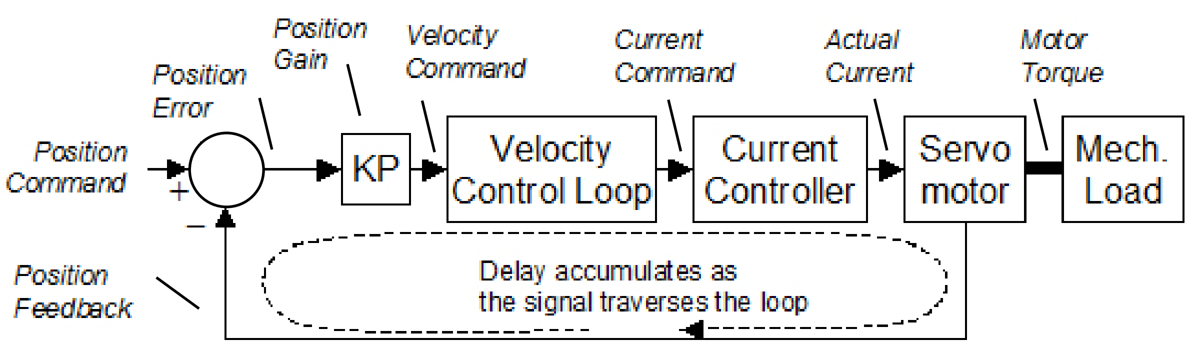

Figure 3. Delay accumulates as a signal traverses a loop.

The same thing happens in servo systems, albeit at much higher frequencies. As gear teeth and belts flex in and out, the elements on the end of the drive train seem to almost disappear. As a result, the apparent inertia of a compliant system becomes smaller as frequency increases. Since the effect of inertia is to lower the gain of the whole loop, this phenomenon is destabilizing at high frequencies. At low frequencies the inertia is high, making the loop gain low; at high frequencies the load inertia virtually disappears, causing the loop gain to increase – often dramatically. Worse, the gain variation is difficult to predict. It varies in complicated ways depending on the mechanical resonances of the motor/load mechanism.

The effect of compliance can be seen in *Figure 4*. The dashed red line shows an ideal load – that is, one that is perfectly coupled to the motor. As frequency increases, the effect of the inertia is to lower the gain due to the fact that is takes more torque to move mass at a higher frequency. So, the red line declines steadily as frequency increases. A compliant load is shown in purple. It tracks the ideal line well until the frequency nears the point of mechanical resonance. At about 700 Hz, the load starts to “disconnect” from the motor. Above the resonant frequency of 1200 Hz, it disappears and the gain increases well above the ideal load.

It’s not possible to fully accommodate the behavior of complicated mechanical structures with a simple loop gain. Instead, various filters must be used to modify the gain and delay as frequency increases. Herein lies the complexity of tuning for optimal performance: it requires the design of multi-pole filters to modify the phase and gain according the system’s mechanics. Of course, it’s possible to attain stable operation by simply adjusting a few gains as well as possible and adding perhaps one or two low-pass filters. But this generally results in low gains and sluggish performance. Achieving optimal performance requires a much broader approach: full-frequency tuning.

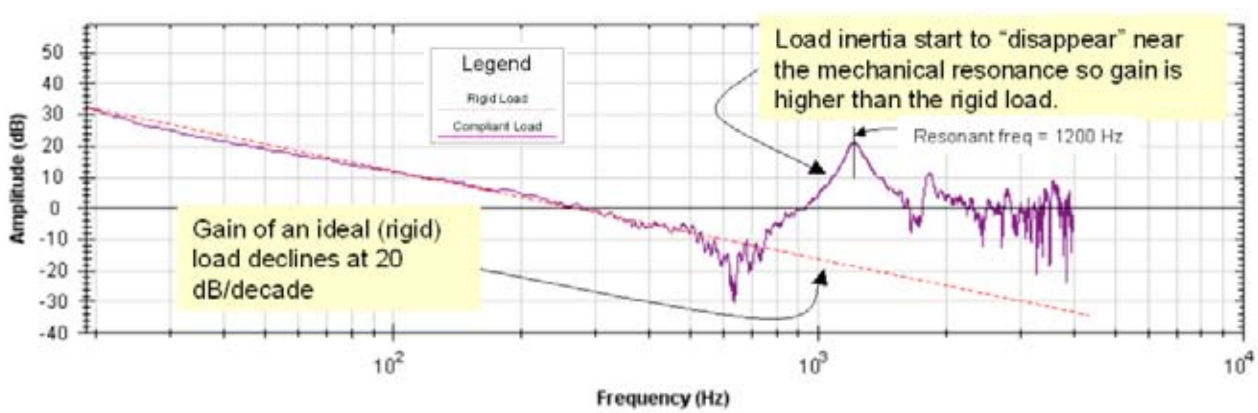

Figure 4. Variation of reaction torque from a typical mechanical system.

Full-Frequency Auto-tuning

Full-frequency auto-tuning is the process of setting loop gains automatically. It relies on the computational power of a PC to execute the calculations required at many frequency points. Originally, auto-tuning was done at low frequency – shake the motor at, say, 10 Hz to sense the inertia and then set gains accordingly. Today, many auto-tuners operate on that same principle. However, such an approach ignores the primary complicating factor of tuning: the variation of apparent inertia with frequency. That accounts for the poor reputation of early auto-tuning systems – they worked well in a laboratory, where loads are rigid, but poorly in the field, where loads are usually compliant.

Full-frequency auto-tuning measures the system at all frequencies of interest – hundreds of points between, say, 10 Hz and 2000 Hz – to ensure stability at every frequency of concern. The starting point is the excitation. Rather than simply shaking the motor at low frequency, a rich signal is injected that excites the system at many frequencies simultaneously. Data is collected across the frequency spectrum over a period of several seconds so that the entire frequency signature of the motor and mechanical load is collected in a short period of time.

The second step is configuration of the filters. When auto-tuning, more complex filter structures can be used than are practical for manual tuning. For example, in Kollmorgen's AKD™ servo drive two four-pole filters are used *(Figure 5)* where perhaps one or two single-pole filters might be common on drives that rely on manual tuning. That's because the configuration of four-pole filters requires up to 16 parameters each, much more than most people can manage manually. However, the large number of filters gives great flexibility to the tuning algorithm in dealing with mechanical compliance and so makes sense for full-frequency auto-tuning algorithms.

The AKD servo drive provides a full-frequency auto-tuning algorithm called the Performance Servo Tuner (PST). In order to compare PST to other auto-tuning algorithms, we used a compliantly-coupled load *(Figure 6)*: a load wheel with inertia about 10 times that of the motor rotor connected through a slotted PVC tube to represent a compliant transmission. Our frequency analysis demonstrated that the configuration was a good representation of many servo machines.

Figure 6. Compliant coupling and load used in servo comparison tests.

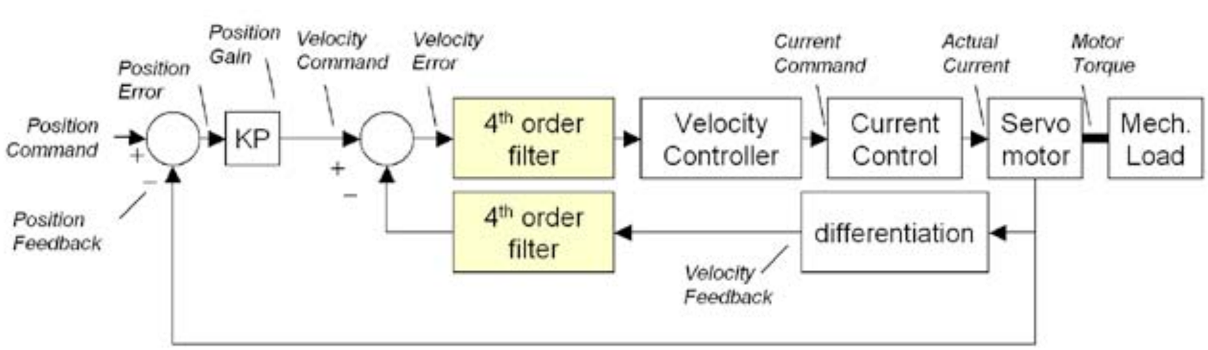

Figure 5. Full-frequency auto-tuning can take advantage of high order filters such as the Kollmorgen AKD™ servo drive's dual 4th order filter system.

We then compared auto-tuning methods on that configuration to several competitors. Some competitors were unable to produce any stable set of tuning parameters, while PST produced tuning superior to all the tested systems with both faster settling times and better margins of stability. For example, *Figure 7* shows the response to a high-acceleration velocity command: compared to the best competitive system, PST cut settling time to less than half and did so with half the overshoot.

In conclusion, tuning can be a complicated process, especially when trying to get high-performance from the compliant load/motor mechanisms commonly seen on modern machines. Auto-tuning can provide superior results quickly, but only when it uses information from the full frequency range of servo operation. Full-frequency auto-tuning algorithms can also support higher-order filter structures than are practical for manual tuning. Full-frequency auto-tuning algorithms together with flexible servo loop filtering can provide outstanding servo performance even for compliant loads, and you don't have to be a servo expert to use them.

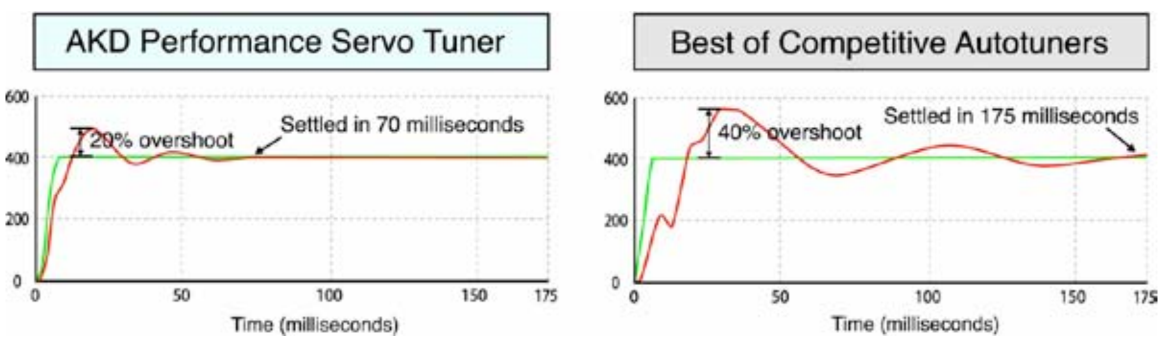

Figure 7. Step response showing superior results of full-frequency auto-tuning: settling time is less than half (75 ms vs. 175 ms) and stability margins are significantly improved (20% vs. 40% overshoot).

ABOUT KOLLMORGEN

Kollmorgen is a leading provider of motion systems and components for machine builders around the globe, with over 70 years of motion control design and application expertise.

Through world-class knowledge in motion, industry-leading quality and deep expertise in linking and integrating standard and custom products, Kollmorgen delivers breakthough solutions unmatched in performance, reliability and ease-of-use, giving machine builders an irrefutable marketplace advantage.

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