How to Improve a Servo Machine

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Today's servo-controlled machines are faster, smaller, and smarter than ever. As a result, machine users demand more and more performance, and this forces designers to keep improving their machines.

Improving the servo performance of a machine can be challenging because so many factors come into play including the servomotors, the feedback sensor, the servo drives, and the mechanical transmission. This white paper is for designers who want to improve servo performance. It will walk you through the decisions you'll need to make, starting with understanding how the servos affects the machine, which components have the dominant effects, and what changes are likely to make substantial improvements.

Servo performance directly affects the quality of the parts a machine produces and the time it takes that machine to produce them. For example, positional inaccuracy in a servo often translates into dimensional variation of parts produced in cut-to-length applications, and registration accuracy in printing applications. Smoothness of the servo system affects the variation of coating thickness in coating machines and the part finish in polishing applications. Response time affects the rate of production: the fastest servos cut more plastic bags, print more labels, test more blood samples, and assemble more printer cartridges in an hour.

While servos clearly affect machine performance, it's not always easy to translate "what the servo does" to "how the machine operates." Designers can evaluate servos with three key measures:

- Accuracy—how close moving parts settle to the commanded position or velocity
- Response—how fast the motion tracks the command
- Robust stability—how reliably the motion tracks the command under various operating conditions

Accuracy

Accuracy is usually quantified in two ways: settled-position error and cyclical error. Settled accuracy, the positional accuracy of the servo when it's settled to a commanded position, is straightforward: errors in the servo system position translate to dimensional tolerance buildup. If the cut-to-length servo in a bag machine has a position error of +/-0.01in. (0.254mm), it will probably contribute a variation of 0.01in. to the bag length. The settled accuracy is often largely determined by the feedback device. Sine encoders are the most accurate feedback devices with errors measured in arc-seconds. Unfortunately, sine encoders are expensive. On the other hand, resolvers and digital encoders are less costly, but have position errors an order of magnitude larger.

The second type of accuracy is more complicated: cyclical error. When a motor turns at constant speed, position errors translate into an apparent velocity ripple. This ripple repeats every revolution of the motor, hence the name, "cyclical." The apparent velocity ripple on the feedback signal feeds the velocity loop, which creates current to compensate for that ripple. Unfortunately, that current creates actual velocity ripple. The result is often a loss of smoothness at speed and an increase in audible noise and motor heat. Cyclical error is cured by higher-accuracy feedback devices. Sine encoders have so little cyclical error that they often produce no measureable effects; the same cannot always be said of resolvers and digital encoders. The key to for machine designers is selecting the right feedback device for each axis of motion. The best starting point is a motor family with a wide range of feedback options such as Kollmorgen's AKM™ servomotors (Fig 1).

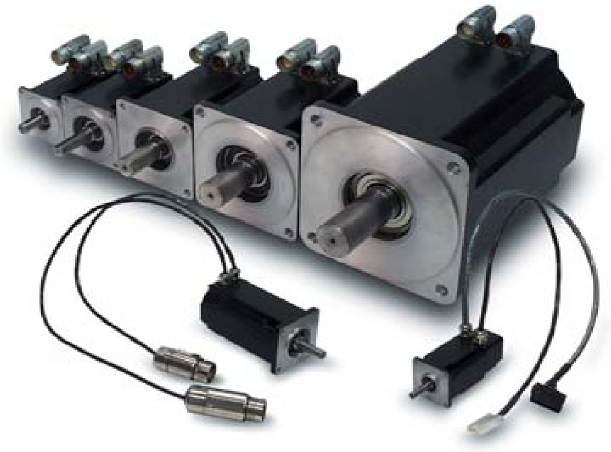

Figure 1 - Kollmorgen's AKM servomotor family supports a wide range of feedback devices.

The mechanical transmission also can contribute to accuracy problems. This is because most machines rely on motor feedback as the primary position signal. If a motor connects to the load through a gearbox, the positional error of a gearbox will cause the motor feedback signal to vary from the load position.

Transmission components such as lead screws, gearboxes, and belts and pulleys all contribute error between the motor and the load. Many of these problems can be adequately addressed by selecting high-quality transmission components. However, for machines that demand the highest accuracy, designers can look at two other solutions.

First, a secondary feedback device can be placed on the load side of the transmission. For example, a linear glass scale can be added to a screw-driven gantry to eliminate accuracy problems in the screw. The motor feedback device can still be used to improve performance if the servo drive supports "dual loop," a servo configuration where both motor and load feedback are used simultaneously. The need for dual loop (as opposed to using only the load position) is created because the mechanical compliance between motor and load can severely limit the servo performance when only a load-side position sensor is used.

While dual-loop solves many problems caused by load inaccuracy, the ultimate solution is a "direct drive" system, which eliminates the transmission altogether. In direct drive systems, the motor (see Fig 2) directly drives the load. The accuracy of direct drive systems is 10x better than traditional systems; audible noise can fall by 40 dB. Other measures such as servo response, acceleration rates, and reliability also can improve dramatically. For the most demanding servo applications, direct drive is the final step of evolution for the mechanical design.

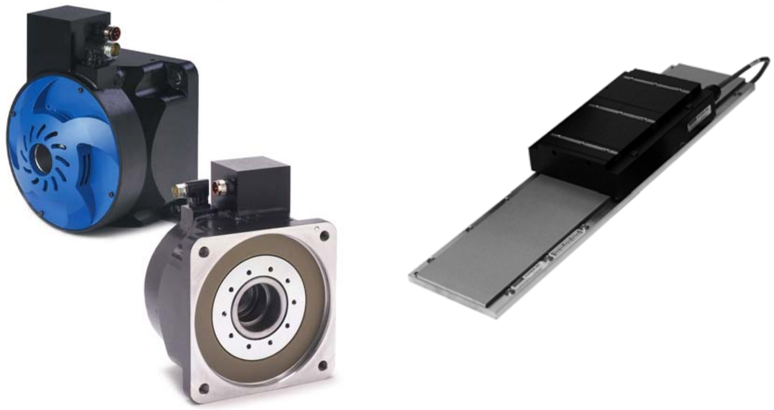

Figure 2 – Kollmorgen's DDL and DDR direct drive motors eliminate the need for a transmission.

Many of the alternatives discussed here have implications on the servo drive. When solving accuracy issues you will want to look at many components: feedback device families, motor type (standard or direct drives), and the servo loop (support of dual loop). So, when you build your servo system, start with a family of servo drives that give you flexibility regarding the many options available to designers.

The Servo Drive

When you want to improve system performance, you also need to consider the drive. Flexibility is a key characteristic. As discussed above, flexibility in support of feedback types and motor types will give you more options for accuracy issues. Other areas of flexibility are: a wide range of servo algorithms, support of multiple communication buses (EtherCAT® and CANOpen®, for example), and a large range of voltage and current models. By choosing a family of drives that can support the widest range of options, you'll be able to operate your servo system in the largest number of applications and you'll have the biggest toolbox possible when it comes time to deal with servo performance issues. For example, Kollmorgen's AKD™ servo drive family (Fig 3) supports a wide range of feedback devices, servo algorithms, communication buses, and power ranges.

Figure 3 - Kollmorgen's AKD servo drives supports a wide range of options for improving servo performance.

A key function of the servo drive is, of course, the execution of servo algorithms. There are multiple position/velocity loop architectures used in modern servo systems such as integrating position loops vs. integrating velocity loops. In both cases, high servo gains generally contribute to faster response to both commands and disturbances. However, the placement of the integrator can favor different applications. For example, integrating position loops are often used when following error (the position error during a move command) should be minimized. On the other hand, integrating velocity loops are often used when the fastest response is needed.

Another family of functions that can help improve servo systems is feed-forward. Feed-forward gains are added paths that speed response to command signals. Servo loops function by minimizing error—more position error generates a larger velocity command, which closes the error more rapidly. But loops take time to respond. By contrast, feed-forward is nearly instant and so allows the servo machine to respond much faster. Consider the effects of gravity on an overhung load such as an unbalanced vertical axis with a brake. If you enable the servo loops without feed-forward and release the brake, initially the current command will be zero, so the load will fall a little. As the servo has time to react, the current will increase and the axis will eventually be restored to the position where it was when the drive was enabled. However, the observer will see a momentarily drop. With "offset feed-forward", you tell the drive how much current is required and the servo loops can be preset to that value before the brake releases. That way, when the brake does release, the load will barely move.

Current offset is just one type of feed-forward; other types include acceleration, velocity, viscous damping, and Coulomb friction feed-forward. All of these functions share a key characteristic—the drive calculates the ideal response and adds auxiliary signals to the loop paths so the output responds much more quickly to expected disturbances than a servo loop without feed forward. Of course, feed-forward gains are no substitute for high servo gains—all demanding applications require high gains to achieve rapid response. However, feed-forward improves even the best-tuned servo loops, working together with the loops to give the most rapid response possible.

Compliance and Stability

One area that limits many servo systems is mechanical compliance. Mechanical compliance describes the flexibility between the motor and the load. Transmission components such as gear boxes and lead screws are not nearly as rigid as they seem (at least not when viewed from at the high frequencies where servos operate). In fact, they act very much like a damped spring between the motor and the load. That spring makes high servo gains hard to achieve. This is because, from the perspective of the motor, the load looks different at low frequency than it does at high frequency. Since the topic is unfamiliar to most people, I like to use a simple example to demonstrate the problem.

Imagine you are suspending an ordinary office stapler with a large rubber band. If you move your hand up and down slowly, the stapler follows your hand and the inertial load your shoulder feels is your hand plus the stapler. But if you move your hand rapidly, the stapler will become almost stationary and the inertial load your shoulder feels will be, more or less, your hand. In effect, your hand disconnects from the stapler at high frequency. For a servo system, that same thing happens when the motor (like your hand) tries to move the load (the stapler) through the transmission (the rubber band). At low frequencies, the total inertia is the motor plus the load; at high frequencies, the motor disconnects from the load and the inertia is, more or less, the motor.

This disconnection causes serious problems for servo loops. The standard PI or PID servo loops are constructed to control a fixed inertial load. When the load varies with frequency, the loop gains often must be reduced just to achieve a stable response. When that happens, the loop performance falls, sometimes dramatically.

The initial solutions to compliance are mechanical. There are two main alternatives: the first is to reduce compliance by using stiffer transmission components. Use servo-quality gearboxes, lead screws, and couplings to minimize these problems. The second is to match the inertia of motor and load—that way, when the load does disconnect from the motor, the total inertia changes only by a factor of 2:1. (If the load is 10x the motor, the total inertia goes down by a factor of 11:1 at high frequency!) These solutions are good, but they have limitations. You can only make a transmission so stiff before costs start getting out of hand. And increasing the motor size reduces acceleration and increases cost (by using a larger motor). At this point, designers turn to advanced anti-resonant servo algorithms to improve performance further.

Anti-resonant algorithms are velocity-loop filters configured to vary the response of the servo loops across the frequency band. Remember from the discussion about the stapler where the servo loop “sees” a total inertial that varies with frequency: large at low frequencies and small at high frequencies. The filters change the frequency response of the loop to compensate for that variation. There are many alternatives for filter construction and placement in the loop. The simplest structure is to have a low-pass filter or two in the feedback path. Such filters are easy to use, but limited in the amount of improvement they can provide. More advanced filters include notch filters (filters that attenuate a narrow band of frequency) and higher order filters, which attenuate more rapidly with increasing frequency. The most flexible filter is the bilinear-quadratic (bi-quad) filter, a filter that can be configured as a low pass, notch, or any number of other filter types. For example the Kollmorgen AKD filter structure includes four bi-quad filters, two in the forward path and two in the feedback path. Such filter structures are highly flexible, allowing designers to deal with a wide range of resonance issues (Fig 4).

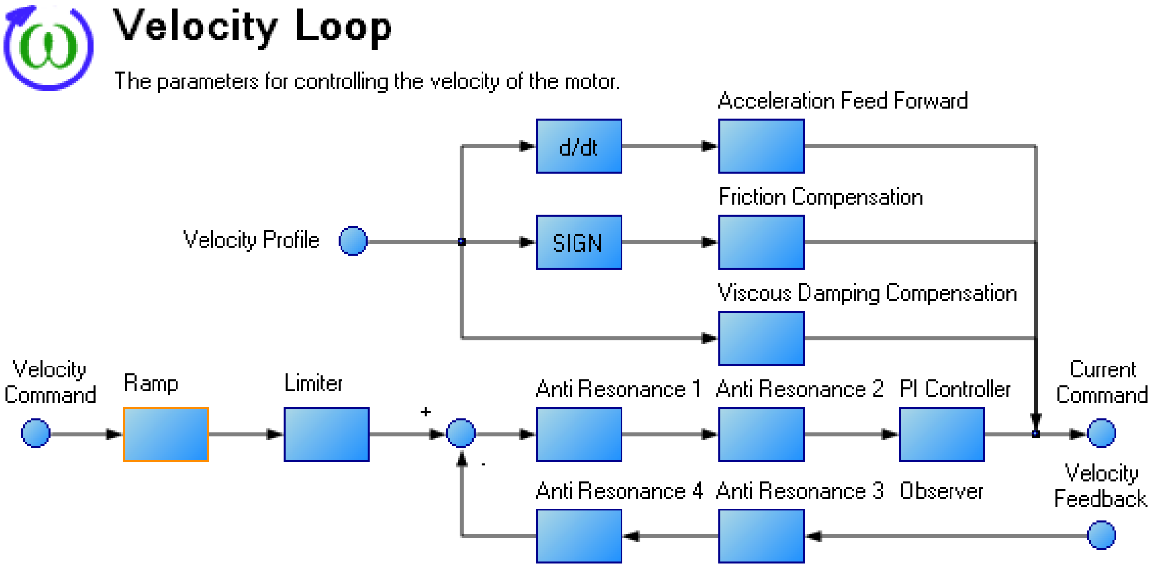

Figure 4 - Example of a highly-flexible servo loop from Kollmorgen's AKD servo drive family.

Bode Plots

In addition to advanced algorithms, servo drive users should specify advanced servo tools. The four bi-quad filters of Fig. 4 create a wide set of options, but configuring those filters can be difficult. Many drives provide only the most basic diagnostic tools, often just a software oscilloscope that shows response in the time domain. However, resonance is more easily comprehended as a frequency domain problem so designers need tools that show the response of the system in the frequency domain. The display of choice here is the Bode plot. For years designers have been able to create Bode plots using “Dynamic Signal Analyzers” or DSAs, instruments that were similar in size and complexity to oscilloscopes (and usually a lot more expensive!). Today, some servo drives such as Kollmorgen’s AKD have DSAs built in so designers can easily view the frequency domain signals (Fig 5). These signals can display resonances making the offending components easier to identify and ultimately correct.

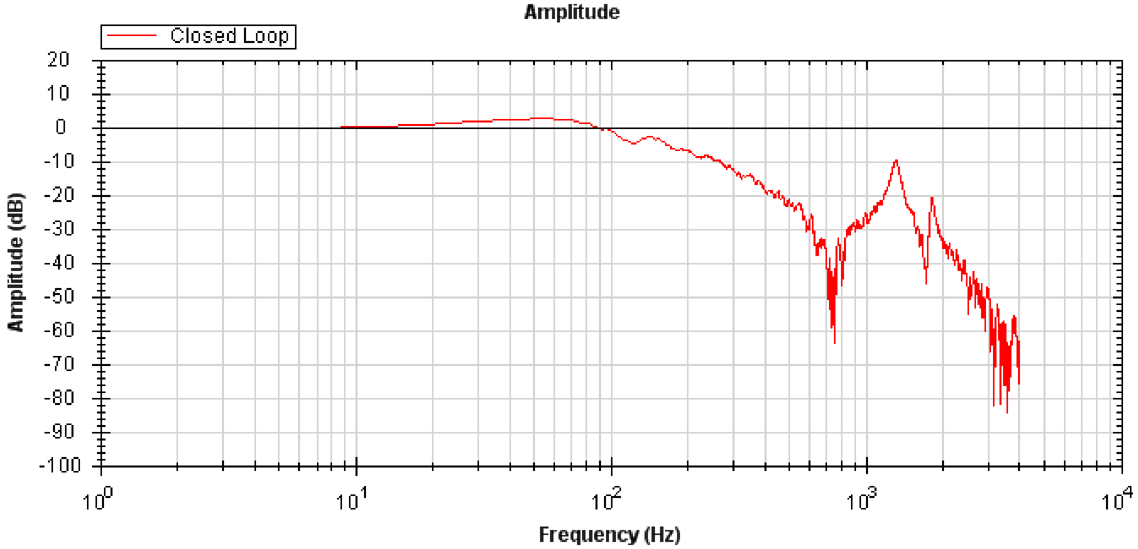

Figure 5 - Typical Bode plot of a servo system showing gain (in dB) vs. frequency.

Auto-tuning

Even with built-in DSAs, it can be difficult to find the optimal configuration for anti-resonant filters. Another tool that servo machine designers need is auto-tuning. Auto-tuning sets the servo gains automatically, providing fast, reliable servo tuning even for complex mechanics. However, not all auto-tuning algorithms are created equally. Many don't configure anti-resonant filters or feed-forward gains. In fact, the simplest auto-tuning algorithms excite the load at low frequency and then set up the servo loops assuming the complete absence of compliance. That works well in a lab, where motors might be driving a steel wheel, but the results in real applications are usually disappointing.

When selecting a servo drive, select one with an auto-tuning algorithm that will cover all the applications where the drive will be used. If the algorithm is robust, it will save a lot of time and it will provide the high gains that give superior servo performance. For example, Kollmorgen's AKD auto-tuning algorithm (patent pending) excites the machine across the full range of frequencies so that compliance can be thoroughly characterized. Then it configures a complete servo loop including position- and velocity-loop gains, multiple anti-resonance filters, and many feed-forward gains.

Conclusion

Servo systems provide outstanding performance, and today's machine users demand more than ever. When machine designers need to improve their servo performance, there are a number of alternatives they can look at (see Table 1). Start with flexible servo components allowing the use of different feedback devices, motor types, and servo algorithms. Configure your servo loops to response rapidly, even in the presence of mechanical compliance. And choose servo drives with advanced tools so you can diagnose problems quickly and reliably.

Table 1

Improve accuracy	**Improve response time**	**Achieve optimal tuning**	**Improve resonance problems**
Select a more accurate feedback device	Increase servo gains	Select a drive with advanced tools such as a DSA to create Bode Plots	Make the machine stiffer, either with better transmission components
Put a secondary feedback sensor on the load side of the transmission	Use advanced servo algorithms	Select a drive with a capable auto-tuning algorithm	Eliminate the transmission by using direct drive motors
Use direct drive motors	Use feed-forward algorithms		Use advanced anti-resonant filters

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