As servo drives become more prevalent in industry, they are being applied in a wider range of applications. A common complaint with servos is that they sometimes make an undesired “growling” noise. This problem can be eliminated by reducing the gain on the speed controller. However, lower speed controller gains can lead to an increase in position error and a decrease in needed performance. This paper looks at the problem of servo instability and methods that can be used to eliminate this problem.

It is best to begin by defining instability. Instability in a motor is uncontrolled and unintended motion at the motor shaft. It can occur at low or high frequencies, with the higher frequencies often becoming audible (i.e. growling). Instability is caused by excessive gain in the speed controller of the drive. The gain setting of the speed controller determines how much torque the drive will generate. For this reason, the gain value should be directly proportional to the inertia of the connected load that is seen by the motor shaft. Remember the phrase “load seen by the motor shaft”, as we will examine what this means later in this paper and how it affects stability.

Some may wonder why they have never had instability problems with AC vector drives. It should be made clear that vector drives can also reach unstable conditions. In practice, most servo applications are more dynamic than speed-only applications. The more dynamic applications require higher gains in the speed controller, which increases the chance of instability.

There are several factors that can contribute to the likelihood of a drive experiencing instability. These include:

- excessive gain in speed controller
- lower resolution feedback device on motor (i.e. resolver or pulse encoder)
- gearing backlash and mechanical “decoupling” of the load from the motor

Most drive engineers are taught that the proper tuning of a speed controller is done with the step response method. This involves running the motor typically at 10-20 percent speed and introducing a step change in the speed set point of 5-10 percent. This step change creates a disturbance that the drive must respond to. By tracing the drive’s response to the step change, it can be measured how much the drive overshoots the new speed set point and how quickly the drive returns to a steady state speed value of under +/- 0.5 percent. Many engineers are taught to increase the speed controller gain gradually until they record signs of instability in the step response and then to reduce the gain slightly from that point to avoid the instability.

The mistake is that often this test is only done at one speed or at speeds above 10 percent of full speed. In some cases, this speed controller gain setting will seem stable at 10 percent speed but may result in instability at lower speeds. Many machines enable servo drives at zero or near-zero speed and may remain at this low speed prior to starting production. This is the point where instability or “growling” is sometimes reported.

Another factor is that drive tuning is done during commissioning when the machine is new and the mechanics are tight. Over the next few months, the machine will run for hundreds of hours and the mechanics will loosen up. This additional compliance in the mechanics is different from what the drive was tuned with during commissioning. This is why the instability often occurs several months after the machine is running.
Adaptive Speed Controller Gain
Adaptive gain in the speed controller offers the ability to automatically lower the controller’s gain at low speed and increase the gain as the motor RPMs increase. Most servo drives offer this feature and the diagram shown below provides what a typically speed controller with adaptive gain might look like.

![Diagram of Adaptive Speed Controller Gain](image)

The gain value for a speed controller is often referred to as Kp. When adaptive Kp is enabled, the Kp has the ability to change with motor speed. As an example with the above diagram, Gain 1 = 30, Gain 2 = 100, Speed 1 = 100 RPM and Speed 2 = 500 RPM. With these settings, the Kp that the speed controller will utilize will be 30 for speeds below 100 RPM. The Kp will be 100 for speeds above 500 RPM. The Kp will linearly ramp between 30 and 100 as the motor RPMs increase between 100 and 500. This would result in a Kp=65 at 300 RPM.

Adaptive Kp is a good feature to use in order to avoid the problem of instability at near-zero speeds after the machine’s mechanics have loosened up. Since most machines do not produce material at very low motor speeds, why keep the gain at high levels when it is not necessary? If the servomotor always accelerates to a high RPM immediately after it is enabled, then adaptive gain may not be as critical. However, for motors that might be enabled at very low speeds and run at crawl speeds or homing speed, adaptive Kp can help avoid instability issues.

Resolution of Encoder Feedback
Another factor that can cause instability at low speeds is insufficient resolution on the motor’s feedback device. Since servomotors do not usually use pulse encoders, the low resolution feedback device of choice is the resolver while the high resolution feedback device is the optical encoder also called sin/cos or incremental. Resolution is defined as the ability of a feedback device to detect small changes in angular position of the motor shaft.

Some people may disagree with the classification of a resolver as a low resolution device since it has an analog output which in theory should have infinite incremental values for one revolution. While this may be true, the reality is that in today’s servo drives, analog signals have to be processed by analog-to-digital devices (A / D converters) in order for the positional information to be utilized. This limitation results in most resolvers have < 10,000 increments / revolution.

In contrast, sin/cos optical encoders transmit 2048 sine waves and 2048 cosine waves for every revolution. The drive’s electronics take multiple samples of each wave which can result in the processing of > 1,000,000 increments / revolution. This factor of 100 in difference of resolution can have a large impact on your ability to properly tune your motor for an application.
In order to understand why resolution is critical, it is important to review how the speed controller works. The speed controller is typically a P-I controller, whose input is the difference between the speed set point and actual speed (encoder) values. The output of the speed controller generates the torque set point, which determines how much force the motor shaft will exert on its load. Therefore, the torque command to the motor is directly proportional to the difference between actual speed and speed set point. In order to smoothly control the motor’s load, you never want the input to the speed controller to instantly have a large value.

Current servo drives have speed controllers that are updated in the 100-200 µsec range. For the example shown below, we will assume a 125 µsec speed controller on a motor that is running at 30 RPM.

<table>
<thead>
<tr>
<th>Motor RPM</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deg / sec</td>
<td>180</td>
</tr>
<tr>
<td>Deg / 125 usec</td>
<td>0.023</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feedback resolution</th>
<th>Resolver</th>
<th>Sin/cos</th>
</tr>
</thead>
<tbody>
<tr>
<td>pulses/deg</td>
<td>10,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>pulses / 125 usec</td>
<td>0.625</td>
<td>62.5</td>
</tr>
</tbody>
</table>

The calculations show that, at this low speed, the resolver feedback is so low that consecutive scans of the speed controller can actually occur without the resolver registering a difference in angular position. Since actual speed is defined as $\Delta$ Distance / $\Delta$ Time, this registers with the drive as zero speed over the previous 125 µsec. This causes the speed controller to immediately generate a large output to try and reduce the perceived difference at the input. During the next scan of the controller, there is an incremental change and the controller then reduces its output because the perceived difference at the input is gone or greatly reduced. It should be obvious how this behavior could cause erratic movements at this low speed. To avoid this undesired consequence, the engineer tuning the drive is forced to keep the gain of the speed controller very low. A low gain slows the response time of the controller so that when two scans occur on the same encoder increment, the controller delays its response time long enough to see the new pulse during its next scan. This stops the erratic movements but in some cases causes a new problem.

Suppose the motor needs to stop the load quickly. An example might be a machine where the inch button causes the machine to move at a low speed, but the operator needs the machine to stop the instant the inch button is released. Dynamically stopping a heavy load requires a fast injection of negative torque and this requires a speed controller with a fast reaction time. If the feedback device is limiting the controller’s gain, this abrupt stop may not be possible. Changing the encoder to a sin/cos can allow for the speed controller gain to be increased by as much as 300 percent.

Resolvers are less expensive and more durable than optical encoders, so there will always be a need for them with servomotors. However, when specifying the servomotor for an application, make sure all operating scenarios are considered before deciding on the feedback device. A good rule-of-thumb to use is to select a feedback device that can deliver 5-10 pulses at the lowest RPM required for the application for the scan time of the speed controller.
Mechanical Decoupling between Motor and Load
Decoupling happens when a section of the mechanical linkage changes in a way that causes the motor to sense variations in the inertia of the load. Examples of decoupling include:

- twisting of a shaft
- flexing of a mechanical coupling
- elasticity of a timing belt
- gear backlash

As the gain of the speed controller is increased, the drive's commands and the motor's responses become more rigid or synchronized. The “stiffness” of this command-response between the drive and motor is very similar to mechanical stiffness. In fact, once this drive-motor stiffness surpasses the stiffness of any of the mechanical linkages, those linkages “decouple”. The Bode plot below shows three separate decoupling events. The 29-53Hz valley-peak is one, the 180-210Hz valley-peak is another and the 320-350Hz valley-peak is the third.

As the frequency increases logarithmically from left to right, a valley is observed at 29 Hz. This is known as the natural or “locked rotor” frequency. At 53 Hz a peak, known as a pole frequency, is shown. If these were the only peak and valley in the entire Bode plot, this system would be known as a “2 mass system”, where the two masses would be the inertia of the motor’s rotor and the inertia of the load. The plot line below 29 Hz would represent the characteristics of the motor and the plot line above 53 Hz would represent the characteristics of the load. The plot section between 29-53 Hz represents the decoupled region. The drive is unable to control these frequencies, so ideally it is best if these decoupled frequency regions are kept to a minimum.
In this example, the decoupling frequencies are minimized because the slope of the line running from valley to peak is close to vertical. Obviously, the larger the frequency gap between the valley and peak, the more horizontal the slope and the greater the range of frequencies the drive cannot control. This gap is controlled with the inertia ratio. In the equation below, \( F_v \) is the frequency of the valley and \( F_p \) is the frequency of its corresponding peak. The larger the ratio of motor inertia to load inertia, the further apart the valley and peak become.

\[
F_p = F_v \times \sqrt{1 + \frac{J_{\text{load}}}{J_{\text{motor}}}}
\]

where \( J \) are inertia values of motor and load. \( J_{\text{load}} \) is the reflected inertia of the load as seen by the motor.

If you are having trouble visualizing the concept of decoupling, perhaps this analogy will help. Imagine you have your hand outstretched holding one end of a rubber band. At the other end of the rubber band is a one pound ball hanging from gravity. If you gently move your hand up and down, you will sense variation in the load as if the weight of the ball is changing. When the band is being stretched, the mass seems higher and when the band is contracting, the mass seems less. This is similar to what the motor experiences when a shaft twists or a coupling flexes or a belt stretches. These changes are linear and don’t seem so abrupt to your senses. However, gear backlash is non-linear and the above analogy is not adequate.

To imagine gear backlash, we start with the same scenario of a one pound ball at the end of a rubber band. However, this time the rubber band is being cut so that we instantly sense a change from one pound to zero. Our hand might actually jerk up for an instant until we adjust our arm muscles to the fact that there is no longer a weight to hold up. Just as we adjust to this no load condition, the band is magically restored to its original condition and we instantly sense the one pound ball again. This time, our hand might drop down until we adjust our arm muscles to compensate for the new weight.

No matter if the decoupling is linear or non-linear, the result is the “load seen by the motor shaft” changes. Remember this phrase from the first section of this paper? Stability of a drive controller exists when the gain of the speed controller properly matches the inertia of the connected load. When sections of the mechanical load decouple, the motor shaft senses less inertia. The controller gain is no longer properly matched because the perceived inertia is less. If enough of the load decouples, the gain-to-inertia ratio can reach a level that creates instability. Non-linear decoupling (gear backlash) is the worst type of decoupling because the perceived inertia value changes so drastically.

Summary
As we have seen, excessive speed controller gain causes instability in a servo system. However, lowering this gain is often not a viable option, so a systematic approach should be used to determine the best remedy of the instability.

Reducing gain or implementing adaptive gain in the speed controller is probably the most common method to attack instability. There is very little benefit to increasing the gain beyond the value that achieves the specifications of performance. If the drive achieves its goal with a gain value of 80, why increase the gain to 110 even if the system is still stable? This additional gain only stresses the mechanics of the system.

Low resolution feedback devices are popular for servos when cost reduction or durability is desired. If the motor is always going to run at high RPMs and the current gain settings are sufficient for the application, this may be acceptable. However, keep in mind that the lower resolution can limit your gain settings and cause instability at low RPMs.

Inertia ratios are not just some number that servo motor manufacturers created to scare you into buying bigger motors for your application. The ratio value you should use when selecting your motor depends on the application and the motion profile the motor will be expected to perform. Selecting a goal of 10:1 for all applications can be very expensive and unnecessary, so make sure the motion profile is known.
before selecting the motor. One benefit a low inertia ratio does provide is to reduce the chances of encountering problematic resonances in your system.

About the author —
Marcus Schick is the industry business developer for the motion control business of Siemens Industry, Inc. He has worked as a design engineer, account manager and business developer primarily working with OEMs in the printing and converting industries. His areas of particular expertise are commercial printing presses and corrugated box machines. Schick graduated from Auburn University with a bachelor's degree in electrical engineering.

For more information on reducing servomotor instability, please contact:

Siemens Industry, Inc.
Drive Technologies — Motion Control
390 Kent Avenue
Elk Grove Village, IL 60007
Phone: 847-640-1595
Fax: 847-437-0784
Web: www.usa.siemens.com/motioncontrol
Email: SiemensMTBUMarCom.sea@siemens.com
Attention: John Meyer, Manager, Marketing Communications