Application Note #3413

Manual Tuning Methods

Tuning the controller seems to be a difficult task to some users; however, after getting familiar with the theories and tricks behind it, one might find the tuning procedure simple and fun. This application note explains the basic ideas behind the feedback control system, introduces the DMC commands related to tuning, and offers some tips on how to use these commands.

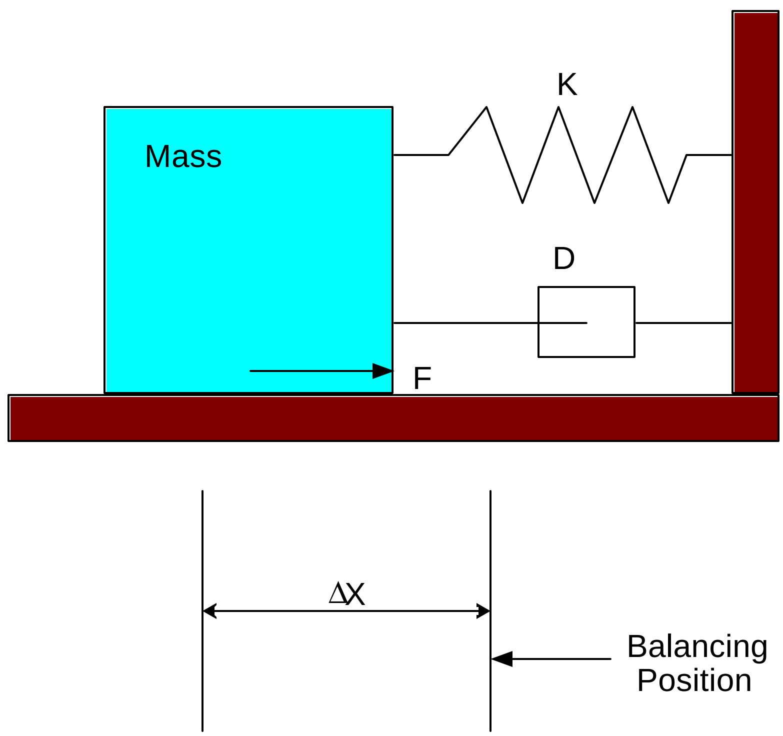

Figure 1. Spring-Damper and Mass

A simple physical model:

Begin with a very simple physical model: a spring-damper and mass system (see Figure 1). K is the spring constant, and D is the damping ratio. If the mass is pulled away from the balancing position, the magnitude of the combined force exerted by spring and damper on the mass should be:

$$F = \Delta X * K + V * D$$

where ΔX is the distance of the mass from the balancing position, and V is the velocity. The further the mass is pulled away from its balancing position, the greater the force the

Galil Motion Control, Inc. • 3750 Atherton Road • Rocklin, CA 95765 USA • 800-377-6329 • Ph: 916-626-0101 • Fax: 916-626-0102 • www.galilmc.com

spring will exert on it; the faster it is pulled, the greater the force the damper will exert to prevent motion. Also, the stronger and tougher the spring is, or the greater the value K (spring constant) is, the spring will exert greater force to the mass, and likewise for D (damping ratio).

How the DMC Controller controls the motor:
Now, look at the system block diagram of the controller-amplifier-motor displayed in Figure 2.

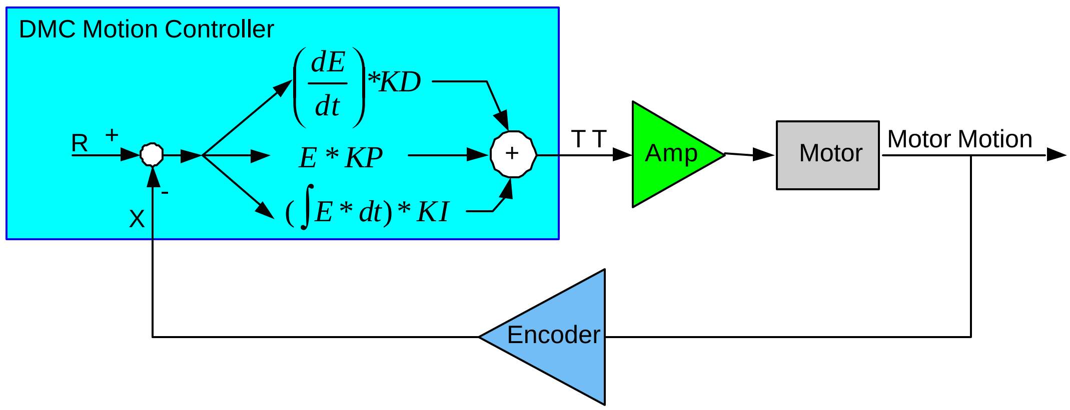

Figure 2. System Diagram

In the diagram above, R is the motor position the DMC controller calculates at each moment. At the same time, the encoder is feeding the real position of the motor, X, into the controller. This position is reported with the DMC Command *TP*. The position error, E, is calculated by taking the difference between R and X. This is reported with the DMC Command *TE*.

This position error E is then processed to obtain the motor command output, the analog voltage or PWM signal, to send to the amplifier. Summing the results from several independent equations forms this command signal; the three most important are listed in the diagram. E is multiplied by a proportional gain *KP* to get the first voltage. Next, multiply the derivative of E, or the velocity, by the derivative gain *KD* to get the second voltage. Finally, multiply the integral of E, or the accumulating error by the integrator gain *KI* to get the third voltage. The sum of these three voltages is sent to the MOCMD output. The DMC Command *TT* reports this output voltage.

To help understand the physical meaning of *KP*, *KD* and *KI*, compare the system in Figure 2 to the simple system in Figure 1. Consider the real position X is to be the true location of the mass, the command position R to be the balancing point, the position error E to represent ΔX, and the force F to be the MOCMD output (*TT*). Then one will easily see that *KP* is actually equivalent to the spring constant K in Figure 1, and *KD* is equivalent to the damping ratio D. Even though there is no equivalent physical model for *KI* in our simple system, the following graph attempts to explain intuitively how it will affect the *TT* output.

Galil Motion Control, Inc. • 3750 Atherton Road • Rocklin, CA 95765 USA • 800-377-6329 • Ph: 916-626-0101 • Fax: 916-626-0102 • www.galilmc.com

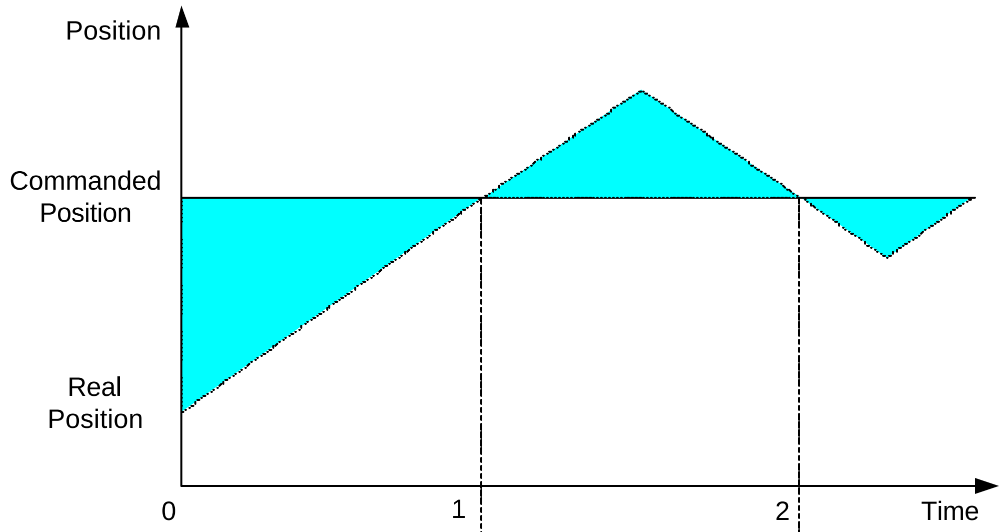

Figure 3a. Position vs. Time

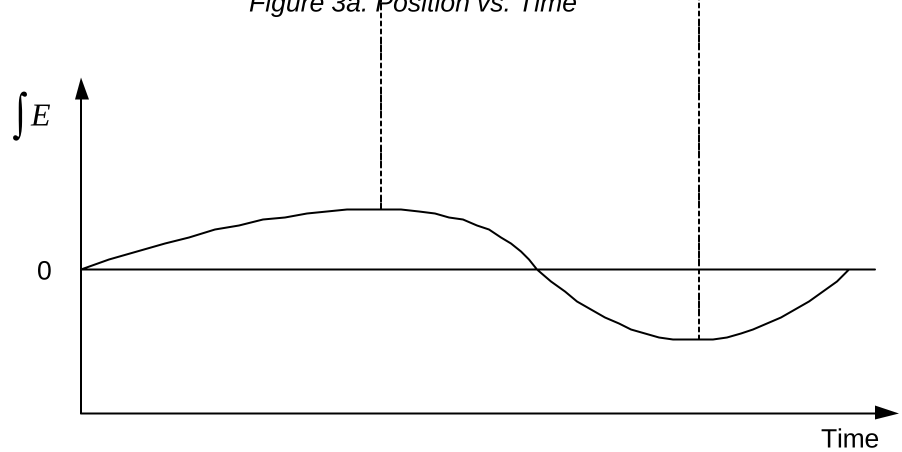

Figure 3b. Control Output from KI

The solid line represents the command position R, and the dotted line represents the real position of motor, X. The voltage output contributed by *KI* is the area between the solid line and the dotted line. At time 0, even if there is a big position error, the contribution from *KI* is only 0 Volts. However, as time continues, this contribution accumulates. At time 1, although the system does not have any position error, the integrator is generating a maximum voltage. After time 1, because the position error reverses direction, the integrator is accumulating negative voltages and the overall output voltage from the integrator drops. Figure 3b shows the control voltage contributed by *KI* terms versus time.

It is intuitive that the integrator introduces oscillation, and even instability, to the system because it has the intention to over compensate the position error and push the motor to the other side of the balancing point. However, it can be very useful if the system has a huge steady frictional force to prevent the motor from getting to the balancing point. Imagine that the dotted line in Figure 3a is always beneath the solid line, in this case, the voltage will keep increasing until it breaks the friction. This is why the *KI* term will significantly reduce the position error. It is necessary to keep in mind that a system

Galil Motion Control, Inc. • 3750 Atherton Road • Rocklin, CA 95765 USA • 800-377-6329 • Ph: 916-626-0101 • Fax: 916-626-0102 • www.galilmc.com

always requires a good solid *KD*, or damper, to stabilize this voltage so that the motor will not bounce around the balancing point forever.

The effects of *KP*, *KD* and *KI*:

How do *KP*, *KD* and *KI* affect the response of the motor? Take a look at the step response of a motor in Figure 4.

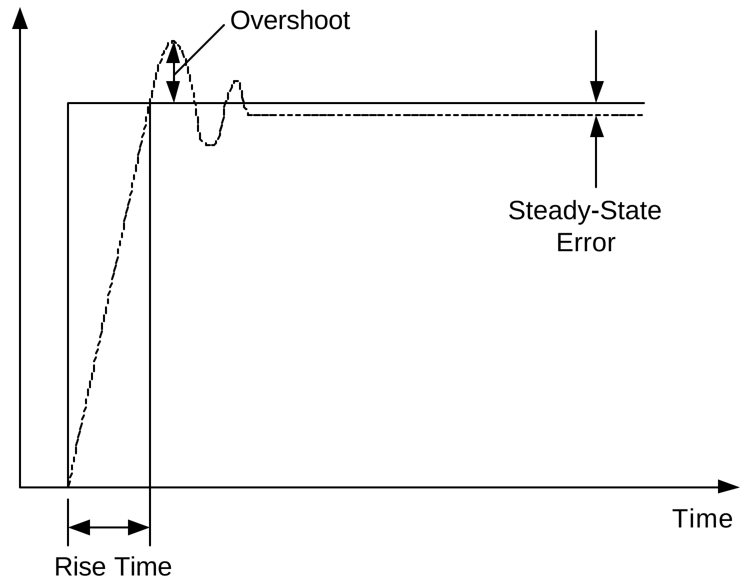

Figure 4. Step Response

Again, the solid line figure is the command position, and the dotted line is the actual motion of the motor. To evaluate the response of the motor, the following three characteristics are used: overshoot, rise time and steady-state error. The overshoot is the maximum amplitude of the vibration, the rise time is the time the motor takes to get to the vicinity of the goal position, and the steady-state error is the position error after the motor stopped. The overshoot shows the stability of the system, the rise time shows the responsiveness, and the steady-state error shows the accuracy.

A good system keeps the overshoot to be small, rise time to be short, and steady state error to be minimal. However, none of the *KP*, *KD* or *KI* gains will improve all the three aspects at the same time. Chart 1 shows how each of the three tuning parameters will affect the three aspects. These trends can be very useful tools in the trial-and-error process of finding the set of gains that optimize the response.

Chart 1. Tuning Parameter Effects on Motor Response Characteristics

	KP	*KD*	*KI*
Overshoot	↗	↘	↗
Rise Time	↘	↗	↗
Steady-State Error	↘	—	↓

It is intuitive that increasing *KP* increases the overshoot. Since the *KD* is the damping ratio of the system, more *KD* will reduce the overshoot. As discussed earlier in the article, *KI* is accumulating the control effort; hence, more *KI* will generate a larger overshoot.

A stronger spring always means quicker response; therefore, increasing *KP* will reduce the rise time. The situation is similar but a less significant effect is contributed by *KI* due to its delaying nature. *KD* is more of a factor against motion, so increasing *KD* will increase the rise time.

A greater KP reduces steady-state error because a stronger spring can fight greater frictional force. Since the *KD* is only effective when motor is moving, it does not have significant effect over the steady-state error. As we discussed earlier, if error persists, the voltage from *KI* will keep increase until either the error is corrected or the output voltage saturate. In an idealistic system where the output voltage will never saturate, the integrator will eliminate the position error.

How to tune the system from scratch:

To manually tune the system means to find a set of *KP*, *KD*, *KI* and other tuning parameters to make your system respond satisfactorily. Before tuning, the first question that should be asked is: how well does the system need to perform? Sometime it is difficult and even impossible to find the absolute optimal parameters for the system. However, if a tolerance for the overshoot, rise time and steady-state error has been defined, it may be easy to quickly find the set of satisfactory parameters following a few simple steps:

Step 1: Set all *KP*, *KI* and *KD* parameters to 0. If the system has a vertical load, make sure a mechanical break is used on the load so that it will not drop. At this point, the motor should turn freely by hand, and the motor should not drift by itself. If it does drift, use the *OF* command to set an offset voltage so that the motor is steady.

Step 2: Gradually increase *KD* until the system shows the signs of instability such as humming noise or vibration. At this point, reduce the *KD* value by 25-30%.

Theoretically *KD* is the damping ratio of the system, a very passive term that should not cause the system to be unstable. However, remember this is a virtual damper created by the controller even when the motor is not moving, and noise can still erroneously be read as speed. With an extremely high *KD* value, a minimal noise can be amplified to a high command voltage and hence cause the system to be unstable.

Step 3: Gradually increase *KP* until the system shows the same signs of instability, and then reduce it by 25-30%.

Step 4: Increase *KI* gradually until the position error (*TE*) is within the specified tolerance. Since the integrator gain will introduce instability to the system, do not push it up to the limit.

Step 5: Fine-tune the system. Now, with the trend table (Chart 1) in mind, we can play with the *KP*, *KD* and *KI* values to further reduce overshoot or reduce the rise time to satisfy the criteria.

Other advanced tuning parameters:

- *IL*, negative integral limit

Sometimes it is necessary for the system to correct the position error aggressively, but do not want the contribution from *KI* to exceed a certain value to cause system instability. In such case, the *IL* command is helpful by adding a limit on the voltage contribution from *KI*. A more important function of the *IL* command is that it can disable the contribution from *KI* when controller is commanding the motor to move, and re-enable it after the commanded motion stops. This function is achieved by specifying a negative value, such as *IL-2*. Figure 5 explains why this can be helpful.

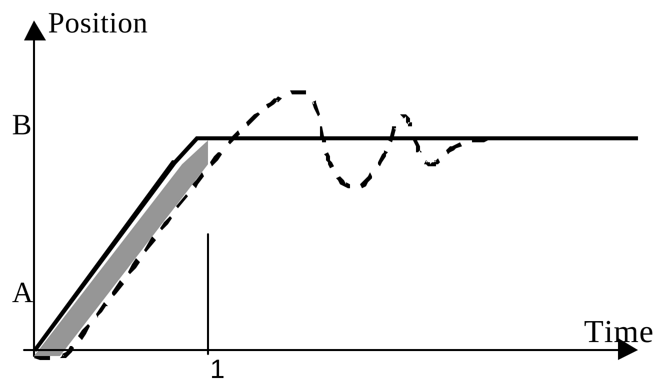

Figure 5. Effect of Negative IL

As before, the solid line is the command position, and the dotted line is the real position. In this example, the motor is commanded to move from point A to point B by time 1. It is intuitive that when the motion first begins, the motor is very likely going to be lagging behind the goal position; therefore, the integral gain *KI* will accumulate a huge control force and hence cause a big overshoot. If a negative integration limit is used, then *KI* will only come into play after command position reaches B. The figure shows that this removes the contribution of *KI* during the shaded area; therefore significantly reducing overshoot.

FV and *FA*, feed forward terms

FV creates a voltage that is proportional to the speed of the motor in the direction of motion. In other words, it pushes the motor forward, and when the motor is commanded to run faster, it pushes harder. This feed forward term blindly adds the voltage to the control output regardless of whether the motor is ahead or behind of its goal position. This command can be very helpful when the motor is driving a big load while maintaining a slow speed. Imagine that the person in Figure 6, pushing his heavy cart filled with coal.

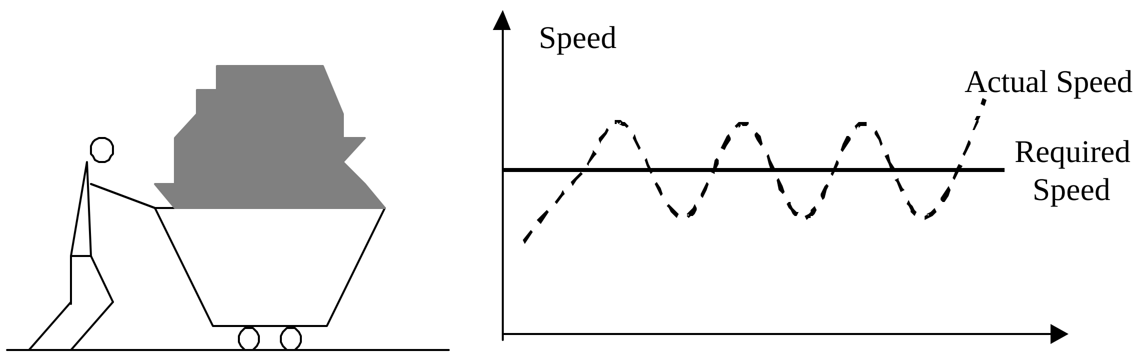

Figure 6. Pushing a Heavy Cart of Coal on a Flat Surface

If it is a requirement to push this heavy cart while maintaining a very slow speed, the real speed will probably be very shaky. This is because the heavy inertia of the cart will make the person push and pull constantly in order to maintain the speed. However, if the cart is not on the flat surface but on a downward slope as shown in Figure 7, the speed will be much steadier because instead of pushing and pulling, it is only necessary to pull the cart. Intuitively, it is now easier to maintain a steady speed.

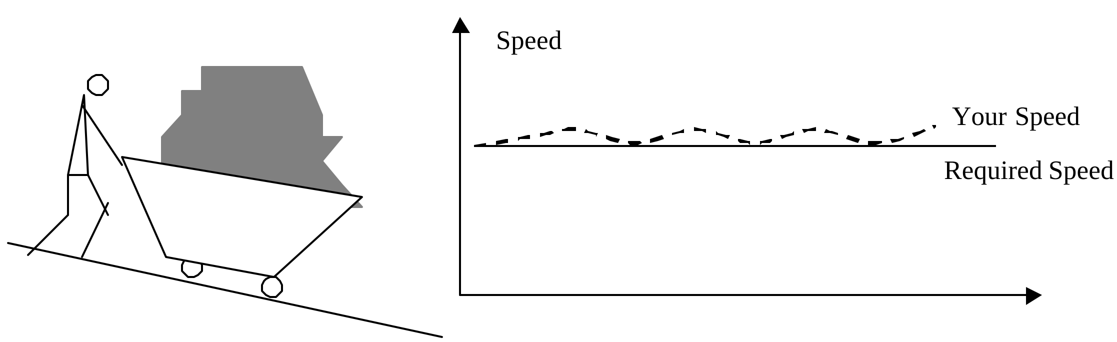

Figure 7. Purshing a Heavy Cart of Coal on a Sloping Surface

The *FV* parameter is similar to stiffness of this slope. The larger the *FV*, the stiffer the slope will be. *FA* is a similar function that adds a voltage when motor is commanded to accelerate or decelerate. The voltage is proportional to the actual *AC* and *DC* value specified. Since *FA* will "push" the motor at its acceleration profile and "hold" the motor

Galil Motion Control, Inc. • 3750 Atherton Road • Rocklin, CA 95765 USA • 800-377-6329 • Ph: 916-626-0101 • Fax: 916-626-0102 • www.galilmc.com

at its deceleration, an appropriate *FA* factor can effectively shorten the time needed for motor to complete the profile.

The Galil controllers offer other useful tools such as a low-pass filter or notch filter to further optimize the performance of your system. Please see Application Note 2431 on how to use them to eliminate high-frequency resonance.