Cleveland State University
Department of Electrical and Computer Engineering
Control Systems Laboratory

Experiment #5

Cascaded Control Loops, Set Point Profiles, and Feed Forward Control

INTRODUCTION

The two primary things a control system must do are to move the controlled output to the set point with little or no final error, and to do it as quickly as possible without excessive overshoot or oscillation, as was stated in Experiment #3. The ability of the control system to do the first of these is expressed by the system's steady state error performance, and the ability of the control system to do the second is expressed by its transient performance. Another very desirable characteristic of controlled systems is their immunity to an external disturbance, sometimes referred to as "stiffness".

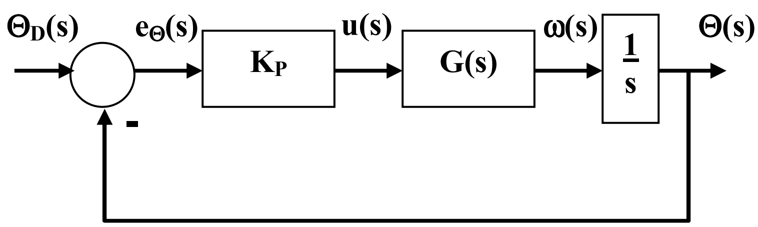

Figure 1: Single Loop Proportional Controller

Generally speaking, when one is controlling a system with a single feedback loop (Figure 1), as controller gain is increased the steady state performance improves, the disturbance immunity improves, and the transient performance also improves. However, a value of gain is usually reached where further increases cause the transient performance to deteriorate in the sense that the controlled output—in responding so fast—overshoots the set point and may even exhibit a decaying oscillation about the set point, particularly when disturbed. Once that gain value is reached, a tradeoff exists—as gain is increased further—between a reduced steady state error and disturbance immunity on the one hand, and deteriorating transient performance on the other. If gain adjustments for a given single loop controller cannot produce both acceptable steady state error, immunity to external disturbance, and transient response, a different controller (generally more complicated, Figure 2) must be used.

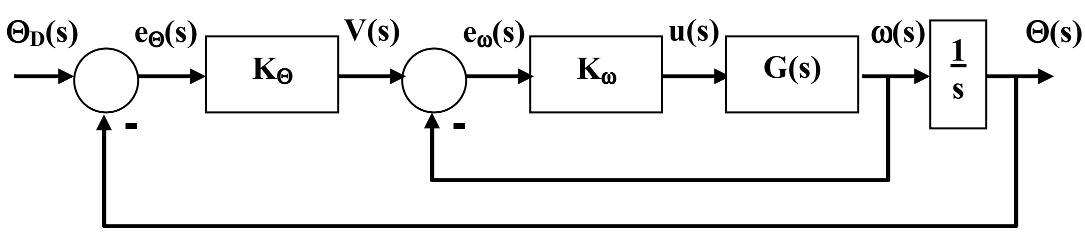

Figure 2: Two Loop Cascade Position Controller

It is also true that a step change in set point is physically impossible to follow, for physically realizable systems. The response of the physical system is limited by the ability of the components to convert power, and the amount of power available to apply, neither of which are instantaneous. No controller can compensate for these limits. The control goal then becomes one of determining the physical limits of the controlled system, and then designing a controller to achieve the performance goals, without exceeding these physical limits.

This experiment explores these general control system techniques using the torsion mechanism. Specifically, the experimental objectives are to:

(i) demonstrate the improvement in transient response, reduction in steady state error, and immunity to external disturbance of a cascaded loop control versus single loop control, using only position error;
(ii) construct a velocity set point profile in such a way as to achieve the performance goals of the system without exceeding maximum physical limits.
(iii) demonstrate further improvement in transient response, reduction in steady state error, and immunity to external disturbance with a cascaded loop control, constructing both velocity and position set point profiles, and using both velocity and position errors as control inputs (velocity feed forward control);

One will control plate position first with the best tuned proportional (P) controller one can configure, then a control with two cascaded proportional (P) loops will be compared to the single loop design. Afterward a triangle velocity set point profile will be used as an input to achieve a desired position, and finally both a velocity set point profile and a position set point profile will be input to a two cascaded loop system to achieve a desired position.

PRELAB

You should come into the lab with a clear understanding of how to determine the closed loop transfer function for the single loop and cascade loop systems of Figure 1 and Figure 2. You should also be familiar how to construct set point profiles in Simulink.

1) Using the results of Experiment #2 and #4 in Figure 1, what is the transfer function $G(s) = \omega(s)/u(s)$ for the controlled system from the control u(s) to velocity $\omega(s)$? What is the transfer function $\Theta(s)/u(s)$ from the control u(s) to position $\Theta(s)$?

2) The standard form for a unity feedback closed loop second order transfer function is:

$$\frac{\theta(s)}{\theta_D(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

where $\boldsymbol{\omega_n}$ is the "natural frequency" of the system and $\boldsymbol{\zeta}$ is the "damping ratio". Assuming one wished a critically damped, single loop control system (**$\boldsymbol{\zeta}$=1**), what is the value of $\boldsymbol{\omega_n}$ and the calculated proportional gain $\mathbf{K_P}$ in terms of the gain **K**, and the time constant $\boldsymbol{\tau}$, of the controlled system transfer function G(s)?

3) Referring to Figure 2: The velocity closed loop transfer function is $\omega(s)/V(s)$. If one

were to simplify this to a simple unity feedback first order transfer function form:

$$\frac{\omega(s)}{V(s)} = \frac{\hat{K}}{\tau_\omega s + 1}$$

what then are the values of "**K-hat**" and $\boldsymbol{\tau_\omega}$ in terms of $\mathbf{K_\omega}$, and the gain **K**, and the time constant $\boldsymbol{\tau}$, of the controlled system transfer function G(s)?

4) Determine a triangle profile for a velocity set point command to the motor, $\omega_D(t)$, which would yield a smooth "S-curve" transition from a position $\theta_D(t) = 0$ at t = 0 to $\theta_D(t) = 1080°$ at t = T = 2sec. What would the max velocity of the triangle profile be, $\omega_{D,max}$ = ?

PROCEDURE

MAKE SURE ALL POWER IS TURNED OFF!

Part I – Response to a Step Change in a Constant Set Point with a Proportional Controller: Set up a real-time control loop for controlling plate position with a proportional controller. Make the set point step change equal 180 degrees, make the step occur two seconds after t = 0 so that you can observe it on the actual mechanism, and use a two-input **MUX** block feeding a scope block so you can observe both the set point change and the response on the same scope. Once you think you have the proper set-up, **ASK THE INSTRUCTOR TO CHECK IT OUT BEFORE APPLYING POWER TO THE MECHANISM.**

a) Set the controller gain to your "best" value from Experiment #3 Part I, observe the step response and note both the steady state and transient performance. Print this graph showing the response.

b) Set the simulation time to 10 minutes and run the simulation. While the simulation is still running and the motor is holding the plate at 180° rotate the inertia plate by hand until the control reaction is very "stiff". Count the number of full turns to this "stiff" point. (A spring would properly be used to calibrate this "stiffness", but for our purpose a qualitative measure will suffice.) **MAKE NOTES OF YOUR OBSERVATIONS.**

c) Repeat part a) and b) for proportional gain value calculated using the system model from Experiment #4. In each case make the same observations and record the same data as in a) and b). **MAKE NOTES OF YOUR OBSERVATIONS.**

d) Repeat part a) and b) for proportional gain value tuned such that there is *no overshoot* in the transient response. (critical damping) In each case make the same observations and record the same data as in a) and b). **MAKE NOTES OF YOUR OBSERVATIONS.**

DISCUSSION QUESTIONS

1) Discuss what theory says the proportional gain should be for this control loop when a step in the set point is applied and the overshoot is zero. Include in this discussion your knowledge of the plant's (controlled system's) transfer function from Experiment #2 and #4. Show the simulation diagram for the system.

2) Now discuss what you ***observed*** the actual tuned proportional gain to be in order to achieve zero overshoot, ***and explain any differences.*** In this discussion use the actual data you took in the lab, and use the general observations you made. Be specific. If things observed do not match theory, you must discuss this and attempt to say why there are differences—and please, don't say a difference between theory and practice is because of *experimental error.*

3) Is it possible to get both good transient performance and good disturbance rejection out of this control loop when using a proportional controller? Discuss this and cite your observations and data—don't just say yes or no.

Part II – Response to a Step Change in a Constant Set Point with a Two Loop Cascade Controller: Set up a real-time control loop for controlling plate position with a two loop cascade controller as shown in Figure 2. Then first, disconnect the output of the position loop gain block, K_Θ, to the summation block, this will allow you to tune the velocity loop separately. Use a velocity step input $V(t) = \omega_D(t) = 180$ rpm as the desired velocity. Use a two-input **MUX** block feeding a scope block so you can observe both the set point change and the response on the same scope. Once you think you have the proper set-up, **ASK THE INSTRUCTOR TO CHECK IT OUT BEFORE APPLYING POWER TO THE MECHANISM.** Tune the velocity loop to achieve maximum performance with critical damping. (no overshoot of the actual velocity, $\omega(t)$)

a) Observe the velocity step response and note both the steady state and transient performance of the velocity $\omega(t)$. Print this graph showing the response. Print the Simulink setup diagram.

b) Reconnect the position loop gain block. Make the position set point step change equal 1080° = 3 revolutions, make the step occur two seconds after $t = 0$ so that you can observe it on the actual mechanism, and use a two-input **MUX** block feeding a scope block so you can observe both the set point change and the response on the same scope. Once you think you have the proper set-up, **ASK THE INSTRUCTOR TO CHECK IT OUT BEFORE APPLYING POWER TO THE MECHANISM.**

c) Set the controller gain to your "best" value from Experiment #3 Part I, observe the position step response and note both the steady state and transient performance. Print this graph showing the response. Print the Simulink setup diagram.

d) Set the simulation time to 10 minutes and run the simulation. While the simulation is still running and the motor is holding the plate at 1080° rotate the inertia plate by hand until the control reaction is very "stiff". Count the number of full turns to this "stiff" point. (A spring would properly be used to calibrate this "stiffness", but for our purpose a qualitative measure will suffice.) **MAKE NOTES OF YOUR OBSERVATIONS.**

e) Repeat part c) and d) for proportional gain value calculated using the system model from Experiment #4. In each case make the same observations and record the same data as in c) and d). **MAKE NOTES OF YOUR OBSERVATIONS.**

f) Repeat part c) and d) for proportional gain value tuned such that there is *a small overshoot* in the transient response. (critical damping) In each case make the same observations and record the same data as in c) and d). **MAKE NOTES OF YOUR OBSERVATIONS.**

DISCUSSION QUESTIONS

1) Discuss what theory says the proportional gain should be for this control loop when a step in the set point is applied and the overshoot is zero. Include in this discussion your knowledge of the plant's (controlled system's) transfer function from Experiment #2 and #4. Show the simulation diagram for the system.

2) Now discuss what you ***observed*** the actual tuned proportional gain to be in order to achieve zero overshoot, ***and explain any differences.*** In this discussion use the actual data you took in the lab, and use the general observations you made. Be specific. If things observed do not match theory, you must discuss this and attempt to say why there are differences—and please, don't say a difference between theory and practice is because of *experimental error.*

3) Is it possible to get both good transient performance and good disturbance rejection out of this two loop cascaded position controller? Discuss this and cite your observations and data—don't just say yes or no.

Part III – Response of the Two Loop Cascade Position Controller to a Smooth "S-Curve" Position Set Point Profile: This is the same situation as in Part II except that a smooth "S-curve" profile will be generated for the Position Set Point, rather than a step input.

a) Set up the Triangle Velocity Set Point Profile you calculated in the Pre-Lab in a Simulink model. Use this Triangle as input to an integrator block as shown in Figure 3. Use a two-input scope block so you can observe both the velocity set point change and the position response on the same scope. Once you think you have the proper set-up, **ASK THE INSTRUCTOR TO CHECK IT OUT BEFORE APPLYING POWER TO THE MECHANISM.** Print this graph showing the response. Print the Simulink setup diagram.

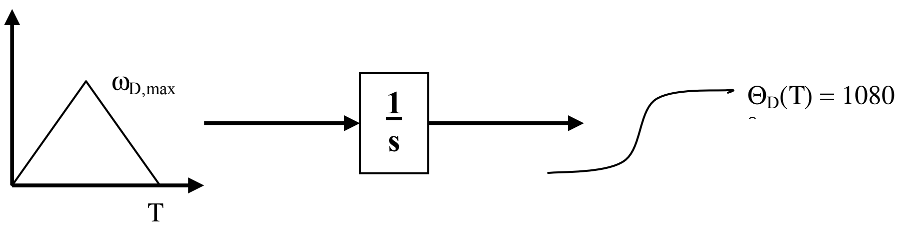

Figure 3: Velocity and Position Set point Profiles

b) Tune the velocity loop separately as in Part II to achieve zero overshoot, but now using the Triangle Velocity Set Point Profile rather than a velocity step input. Observe the velocity triangle response and note both the steady state and transient performance of the velocity $\omega(t)$. Print this graph showing the response. Print the Simulink setup diagram.

c) Connect this smooth "S-curve" Position Set Point Profile as input to the Two Loop Cascade Position Controller. Make the position set point step change equal 1080° = 3 revolutions, make the profile start two seconds after t = 0 so that you can observe it on the actual mechanism, and use a two-input **MUX** block feeding a scope block so you can observe both the set point change and the response on the same scope. Once you think you have the proper set-up, **ASK THE INSTRUCTOR TO CHECK IT OUT BEFORE APPLYING POWER TO THE MECHANISM.**

d) Set the controller gain to your "best" value from Experiment #3 Part I, observe the position step response and note both the steady state and transient performance. Print this graph showing the response. Print the Simulink setup diagram.

e) Set the simulation time to 10 minutes and run the simulation. While the simulation is still running and the motor is holding the plate at 1080° rotate the inertia plate by hand until the control reaction is very "stiff". Count the number of full turns to this "stiff" point. (A spring would properly be used to calibrate this "stiffness", but for our purpose a qualitative measure will suffice.) **MAKE NOTES OF YOUR OBSERVATIONS.**

f) Repeat part d) and e) for proportional gain value calculated using the system model from Experiment #4. In each case make the same observations and record the same data as in d) and e). **MAKE NOTES OF YOUR OBSERVATIONS.**

g) Repeat part d) and e) for proportional gain value tuned such that there is *no overshoot* in the transient response. (critical damping) In each case make the same observations and record the same data as in d) and e). **MAKE NOTES OF YOUR OBSERVATIONS.**

DISCUSSION QUESTIONS

1) Now discuss what you ***observed*** the actual tuned proportional gain to be in order to achieve zero overshoot, compared to your earlier calculated tuning value, and your best

tuning value from Experiment #3, ***and explain any differences.*** In this discussion use the actual data you took in the lab, and use the general observations you made. Be specific. If things observed do not match theory, you must discuss this and attempt to say why there are differences—and please, don't say a difference between theory and practice is because of *experimental error.*

2) Is it possible to get both good transient performance and good disturbance rejection out of this two loop cascaded position controller with a smooth "S-curve" Position Set Point Profile? Discuss this and cite your observations and data—don't just say yes or no.

Part IV – Response of the Two Loop Cascade Position Controller to a Smooth "S-Curve" Position Set Point Profile and a Triangle Velocity Set point Profile: Repeat the same experiment as in Part III except that a Triangle Velocity Set Point Profile and a smooth "S-curve" Position Set Point Profile will be generated for T = 2 second, T = 1 second, and T = ½ second, etc. until the physical limit of the system is reached. This configuration is commonly called a "Velocity Feed Forward" cascade controller. The "inner" velocity closed loop, with the added velocity set point, now performs most of the gross movement of the system.

a) Connect this smooth "S-curve" Position Set Point Profile as input to the position summation block of the Two Loop Cascade Position Controller. Connect the Triangle Velocity Set Point Profile as an additional positive input to the velocity summation block of the Two Loop Cascade Position Controller. See Figure 4. Make the position set point step change equal 1080° = 3 revolutions, make the profile start two seconds after t = 0 so that you can observe it on the actual mechanism, and use a two-input **MUX** block feeding a scope block so you can observe both the set point change and the response on the same scope. Once you think you have the proper set-up, **ASK THE INSTRUCTOR TO CHECK IT OUT BEFORE APPLYING POWER TO THE MECHANISM.**

b) Set the controller gain to your "best" value from Experiment #3 Part I, observe the position step response and note both the steady state and transient performance. Print this graph showing the response. Print the Simulink setup diagram.

c) Set the simulation time to 10 minutes and run the simulation. While the simulation is still running and the motor is holding the plate at 1080° rotate the inertia plate by hand until the control reaction is very "stiff". Count the number of full turns to this "stiff" point. (A spring would properly be used to calibrate this "stiffness", but for our purpose a qualitative measure will suffice.) **MAKE NOTES OF YOUR OBSERVATIONS.**

d) Repeat part b) and c) for proportional gain value tuned such that there is *no overshoot* in the transient response. (critical damping) In each case make the same observations and record the same data as in b) and c). **MAKE NOTES OF YOUR OBSERVATIONS.**

DISCUSSION QUESTIONS

1) Now discuss what you ***observed*** as you included the Triangle Velocity Set Point Profile, ***and explain any differences compared to Part III.*** In this discussion use the actual data you took in the lab, and use the general observations you made. Be specific. If things observed do not match theory, you must discuss this and attempt to say why there are differences—and please, don't say a difference between theory and practice is because of *experimental error.*

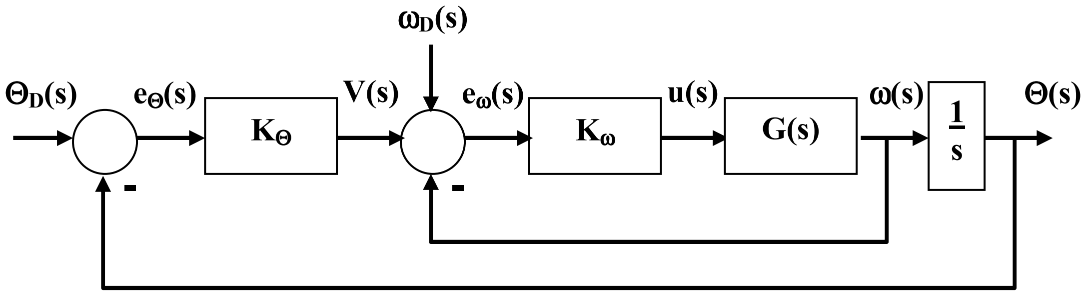

Figure 4: Two Loop Cascade Velocity Feed Forward Controller