MECH 467/541 – Computer Control of Mechatronics Systems

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Project 2: Digital Control of Motion Actuators

This project focuses on the design of control algorithms that deliver the desired performance characteristics of the ball-screw driven table identified in Project I. The performance characteristics are evaluated according to the response speed, accuracy, and robustness of the actuators operating under computer control. In this lab you will practice designing controllers and evaluate their ability to achieve the specified requirements of the ball-screw driven table.

Risks Associated with This Experiment

Category	Task	Hazard / Harm	Controls
Lifting & Handling	-	-	-
Pinch points and rotating equipment	Moving the ball-screw table	Pinch finger	Only move the table using the controller (do not move manually). The safety plexiglass box must be mounted on the table
Dust, chips, airborne	-	-	-
Electrical	-	-	-
Vibration	-	-	-
Noise	-	-	-
Chemicals	-	-	-
Safe disposal	-	-	-
Slips, trips, falls	-	-	-
Working alone	-	-	-
Ergonomics	-	-	-
Other	-	-	-

Residual risk considerations:
N/A

Pre Lab

This pre-lab must be completed and submitted to the TA before the lab. The pre-lab constitutes 50% of your final grade for this lab, and you will not be allowed to perform the lab without completing it. The pre-lab can be **neatly** handwritten or typed but the step response and frequency response plots must be printed out or presented on your computer to the TA.

1. **Discrete Transfer Function Derivation:** The first step in designing a digital controller for the drive is to convert the open loop transfer function identified in Lab1 from continuous domain (s-domain) to discrete domain (z-domain). Based on the model identification carried out in the first project, the block diagram of the open position loop is depicted in Figure 1. Manually obtain the

zero-order hold equivalent of the open loop transfer function ($G_{ol}(z)$) in terms of system parameters. Plug in the parameter values in the final result, and compare your result with the zero order hold transfer function obtained by Matlab's *c2d* command. Ignore the Coulomb friction and saturation blocks.

Note: Use K_a=0.887 [A/V], K_t=0.72 [Nm/A], J_e=7 X10^{-4} [Kgm^2], B_e= 0.00612 [Nm/rad/s], K_e= 20/2π [mm/rad], and sampling time of T= 0.0002 [s] in your calculations. K_d =1 [mm/V] since the DAQ scaling is already done by the special equipment (Beckhoff) we are using in the laboratory. Pitch of the ballscrew is h_p=20 [mm].

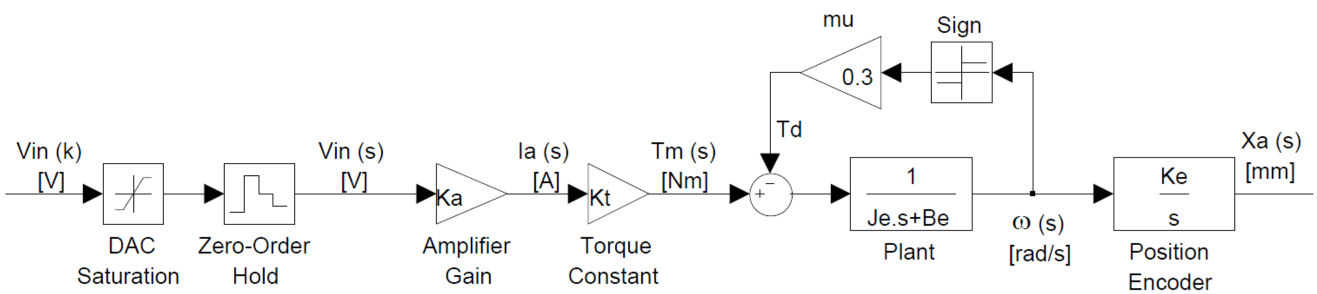

Figure 1 : Open loop Block Diagram of Ball Screw Feed Drive System

2. State Space Model

Obtain the discrete time state space model of the machine shown in Figure 1. Simulate the step response of the system using the discrete state space model of the machine given in Figure 1. Compare the results obtained from discrete transfer function and state space models.

3. Stability Analysis:

By ignoring the Coulomb friction and saturation limits (i.e. nonlinearities),

a. Assume that the position control loop is closed by a proportional controller with a gain K_p [V/mm]. By plotting the root locus of the drive $G_{ol}(s)$ in s-plane and $G_{ol}(z)$ in z-plane (using MATLAB), observe how the closed-loop poles of the system change as the gain K_p increases from zero to infinity. Derive the basic expressions manually (only for continuous system).

b. Find the phase and gain margins of $G_{ol}(s)$ and $G_{ol}(z)$ using Matlab's bode command. Comment on the stability of the closed-loop systems described in s and z domains.

c. Discussion: Is stability in continuous and discrete domains always equivalent? Why? Using MATLAB, find the gain margin of $G_{ol}(z)$ for three different sampling time of 0.02, 0.002, and 0.0002. Which one is more stable? What do you conclude?

4. P-Controller Design:

Using the bode plot of the discrete system $G_{ol}(z)$, find a proportional gain K_p such that the unity gain cross over frequency in z domain is 60 rad/s. Include the basic expressions for the procedure of calculating K_p (you can use MATLAB for extracting the values of magnitude and phase).

Based on the block diagram in Figure 1, create a Simulink model for the closed-loop system with P-Controller by including zero order hold. Include the Coulomb friction and Saturation blocks. Use the Coulomb friction model derived in Lab 1 with μ_k = 0.3 [Nm]. The limits for the Saturation block are ±3 [A]. Obtain the step response of the closed loop digital control system with and without the friction model. Comment on the effect of Coulomb friction on the overshoot, rise time, and settling time of step response. How does the saturation block affect the overshoot, rise time, and settling time? (Try different values of saturation limit between 0.5-3 [A])

5. Lead – Lag Compensator Design:

The controller structure is given as,

$$C(s) = K\frac{1+\alpha Ts}{1+Ts}$$

where gain K and parameters α, T are the parameters of the compensator which needs to be designed.

a. Using the bode plot of the discrete system $G_{ol}(z)$, design the compensator to achieve 60 degrees phase margin at gain cross over frequency of $\omega_c = 60Hz = 377\,\text{rad/s}$. Include the basic expressions for the procedure of lead-lag design (you can use MATLAB for extracting the values of magnitude and phase). Plot the frequency response of the open loop system by including the compensator, and show that the design criteria is met.

b. Cascade an integral action ($\frac{K_i + s}{s}$) to the lead lag compensator with a gain $K_i = \omega_c / 10$ (note: ω_c must be in rad/s). Simulate the step and ramp input response with friction disturbance again, and show the effect of integral action on the steady state error. Compare the results with and without integral controller.

Note: Once you finish designing the controller in s-domain, you must transform it to discrete domain before implementing it in your Simulink. Since the ZOH block is already implemented in MATLAB, for discretizing controller, use c2d(Gcont,Ts,'tustin') so the ZOH effect is not considered twice.

6. Discussion

On the same bode diagram, plot the magnitude and phase of the following transfer functions: $G_{ol}(s)$, LL(s), LLI(s), $G_{ol}(s)$*LL(s), $G_{ol}(s)$*LLI(s). (LL: lead-lag, LLI: lead-lag-integrator). Comment on how the lead-lag compensator and the integrator affect the magnitude and phase. Also comment qualitatively on how DC gain and gain cross over frequency affect steady state error and rise time.

Note:

- In obtaining frequency response functions, make sure to exclude the Coulomb friction and saturation limits. Frequency response functions are linear functions and cannot include such nonlinear elements.
- To plot your Simulink scope results in Matlab you need to first load your scope data into the workspace. You can do this by double clicking on the Scope icon in the simulink file→ click on

 →choose the Data history tab→ check the Save data to workspace box (if it is not checked)→ change the variable name to your desired name, and “structure with time”→Apply→Ok. Make sure to uncheck the box which limits the stored data to the last 5000 data points.

Experimental Tasks:

A. Measurements

The ballscrew parameters are already loaded in the TwinCAT model. Plug in your designed controller paramaters in the model and run the machine to obtain the response to step (1mm) and ramp (10mm/s) inputs for each of the three controllers you designed.

B. Analysis

For each controller (P, LL, LLI) and for each input (step/ramp), compare the 1) experimental results and 2) your Simulink results. When comparing corresponding results, plot them on top of each other in one graph. Also use subplots to avoid having too many individual figures in your report. To aid your analysis address the following questions:

Comparison of Experiments and Simulation

1) Find the rise times and over shoots of the experimental step responses. Tabulate this data along with the rise time and over shoot of your simulated responses. How do the two compare? How are they similar and how are they different? Discuss possible sources of discrepancy that could be leading to differences in the step responses

2) Find the steady state errors of the experimental ramp responses. Tabulate this data along with steady state error of your simulated response. How do the two compare? How are they similar and how are they different? Discuss possible sources of discrepancy that could be leading to differences in the ramp responses.

Comparison of Controllers

3) In comparing the proportional controller to the lead-lag controller, how does an increased bandwidth affect the performance with regards to rise time of the step response and steady state error of the ramp response? What is the reason for this difference?

4) Why is it not possible to design a lead lag compensator with a very large bandwidth? What factors limit the system? Assume the system has no delay from the zero order hold, is it still possible to design a lead lag compensator with infinitely large bandwidth?

5) What benefits does the integrator provide? Prove this idea mathematically using the error transfer function with the integrator and final value theorem.

6) Why does the integrator cause an overshoot? How would you reduce this affect? What is the trade off?

7) Though it seems the lead-lag integrator out performs the lead-lag and proportional controller there may be scenarios where the latter are preferred. Discuss these possible scenarios.

   Please make your discussions very brief (2-3 lines per question).

Report Requirements:

The report must be typed and orderly. It accounts for 50% of your lab grade. Poorly presented reports will not be accepted. Equations may be handwritten into the report, but they must be written very neatly and numbered. Please be as concise as possible. Do not provide unnecessary information. Credit will however be given for concise comments which demonstrate a good understanding of the material covered in the lab.

The following are required of you.

1. **Title Page:** Your name, student ID, email, etc
2. **Abstract:** 3-4 lines describing the objective of the laboratory as you understand it.
3. **Introduction:** Describe the role of control design in industry and the layout of your report (maximum 5 to 6 lines)
4. **Body**: In this part you need to present your analyses and discussions. Make sure to read the handout thoroughly and answer all the discussion questions. Other useful comments are welcome (as long as they are concise).
5. **Conclusion:** Explain what you have understood from the lab (5-8 lines).
6. **Appendix:** MATLAB scripts and Simulink block diagram.