AC 2008-1786: INTEGRATING EXPERIMENT, MODELING AND DESIGN USING A HANDS ON HYDRAULIC POSITIONING LABORATORY FOR MECHANICAL CONTROL SYSTEMS EDUCATION

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Integrating Experiment, Modeling and Design using a Hands on Hydraulic Positioning Laboratory for Mechanical Control Systems Education

Abstract

As part of a laboratory intensive curriculum, Mechanical Engineering students at California Polytechnic State University, San Luis Obispo are required to take a senior level class in Mechanical Control Systems. In addition to three one-hour lectures, students attend a weekly three hour laboratory session where course concepts are reinforced through hands-on modeling and experimentation. This paper describes a newly implemented and innovative laboratory experience which is centered on a hydraulic position control system. Often experiments in Mechanical Controls are heavily influenced by non-linearities such as friction or backlash which cause inexperienced students to lose confidence in linear system modeling as an effective analysis and design tool. A hydraulic system was chosen for this laboratory due to excellent correlation between experimental results and the linear modeling techniques taught in the course. This laboratory experience is designed to integrate linear system modeling techniques, experimentation and data collection, control system design, and design verification through physical testing using a variety of hardware and software tools. The main objectives of the laboratory are to give the students practice and confidence in advanced control system modeling, experience with precision hydraulic positioning systems, practice in designing Proportional-Integral (PI) controllers, exposure to digital control systems and experience and physical understanding of the sometimes dramatic condition of instability. The methodology includes a unique procedure that uses root locus concepts and asks the students to drive the system to instability to determine system parameters. The paper describes the laboratory experience in detail and gives some example results and an assessment of student learning.

Introduction

California Polytechnic State University – San Luis Obispo (Cal Poly) founded in 1903 is one of 23 campuses of the California State University (CSU) System. Cal Poly is primarily an undergraduate institution with approximately 19,500 enrolled undergraduates and 1180 faculty. Roughly 5000 students are enrolled in the College of Engineering which is comprised of nine departments. The largest department, Mechanical Engineering, has approximately 1000 undergraduates, 40 Masters Students and 23 full time tenure and tenure track faculty. The department awards about 190 BSME degrees each year.

Laboratory Intensive Curriculum

Cal Poly's University wide motto is "Learn by Doing," which is supported by the Mechanical

Engineering Department's philosophy of "Hands On" engineering. Consequently, the mechanical engineering curriculum is laboratory intensive. Nearly all upper division required and elective courses are associated with a required three hour weekly laboratory in large, modern, undergraduate laboratory facilities. Required courses in Mechanical Vibrations, Design, Fluids, Thermal Sciences, and Mechanical Control Systems all require a three-hour weekly laboratory. Seven senior Technical Elective courses also have associated laboratories including HVAC, Mechatronics, Experimental Methods in Mechanical Design, Composite Materials, Internal Combustion Engines, Refrigeration, Robotics Mechanical Engineering curriculum.

Course Description- ME422: Mechanical Control Systems

The senior level *Mechanical Control Systems* course is required of all Mechanical Engineering undergraduates. The main topic presented is classical control theory including the modeling and control of physical systems using time response, frequency response and computer simulation. Lecture and textbook content is reinforced in a hardware-oriented laboratory where pairs of students work directly with electrical and mechanical hardware. It is a 10 week course consisting of three 50 minute lectures and one three hour lab meeting each week. Typical enrollment in each lecture is 35 students and 16 students in each lab section. Approximately 70 students take this class each quarter. The course has 11 stated learning outcomes including:

- Students learn to model physical systems with linear differential equations and transfer functions.
- Students can determine system error, response time and stability.
- Students understand the benefits derived by the addition of feedback, together with its disadvantages, such as instability.
- Students can employ classical control techniques in the analysis of controlled systems.
- Students understand the effects of proportional, integral and derivative control actions, together with their combinations on system response.
- Students can use the root locus method for system analysis and design.
- Students can use digital computers in the assessment of system response and in parameter selection in design.

The lab meetings occur in a dedicated state of the art Parker Hannifin Mechanical Controls Laboratory. The laboratory experiences are tied to the lecture content in order of increasing complexity and knowledge. Each lab experience lasts for two weeks. The five experiences are:

1) Modeling and Simulation with Matlab/Simulink®
2) Electric Motor Modeling and Control (Motomatic)
3) Fluid Level Modeling and Control (Two Tank System)
4) Hydraulic Position Modeling and Control
5) PID Design (Hydraulic System)

One aspect of all the laboratory experiences involves creating linear system models and using Simulink®[4] to analyze these models. With the exception of the first experiment, models are created for existing laboratory hardware, and the students make comparisons between predicted responses and actual system responses. Students are expected to operate all equipment with only occasional input from an instructor. Creating control system experiments where measurements closely match system models is difficult due to inherent non-linearities in most mechanical systems. For example, Coulomb friction in the electric motor (Motomatic) modeling experiment must be accounted for in the Simulink® model in order to use the model to accurately predict system response. The existence of the non-linearities has a tendency to undermine the students' confidence in the usefulness of the linear control theory presented in the lecture portion of the class.

In this work, the authors describe the fourth of the laboratory experiences, the Hydraulic Positioner Experiment. The experiment described here was designed to replace a similar pneumatic positioning experiment. Similar to the motor-control experiment, non-linearities in the air-control system and coulomb friction of the air cylinder had to be accounted for in the students Simulink® models in order to achieve agreement between predicted and measured system response. This often took many trial and error iterations as the students found it difficult to quantify the non-linear effects. One primary goal of changing to a hydraulic experiment was to achieve better agreement between the linear control system model and the measured system response in order to focus the students experience on understanding and using linear control system theory.

In the hydraulic experiment, the students learn about the essential components of a hydraulic positioning system, develop a model of the hydraulic system, practice block diagram reduction, characterize various system parameters through guided experimentation and calculation, develop a Simulink® model, compare predicted system response to experimental results and design and test a Proportional Integral (PI) controller. It also includes a unique experience of intentionally driving the system to instability as a method of determining system parameters. This paper describes the experimental hardware, the associated modeling and testing of the hydraulic system and an assessment of student learning.

Experimental Hardware

A photograph of one of the four experimental stations is presented in Figure 1. Figure 2 provides a schematic of the main elements of the electrical/computer control system. The prime mover is a 0.5 inch diameter bore hydraulic cylinder with a 0.25 inch diameter through rod. Hydraulic power (flow and pressure) is provided to four lab stations through a remote pressure-compensated variable displacement pump that maintains 1000 psi system pressure. The cylinder is attached to a 29 lb mass that can translate freely on a low friction rolling slide. Position of the mass is measured using a linear potentiometer. Flow to the cylinder is controlled using a small, two stage, flapper-nozzle style, Dyval® hydraulic servo valve with a rated flow capability of 0.5 gpm at 1000 psi pressure drop. The first stage is a torque motor that controls the flapper position within the valve which in turn positions an internal spool. Spool position in the valve directs flow to either end of the cylinder (see Lugowski[5] for a description of a similar fluid power laboratory). The system is digitally controlled using Matlab/Simulink® and the Real Time Windows Target (RTWT)[6]. This allows the students to use a familiar GUI to do real time control of the system. Birdsong[1] provides a complete description of the use of this interface.

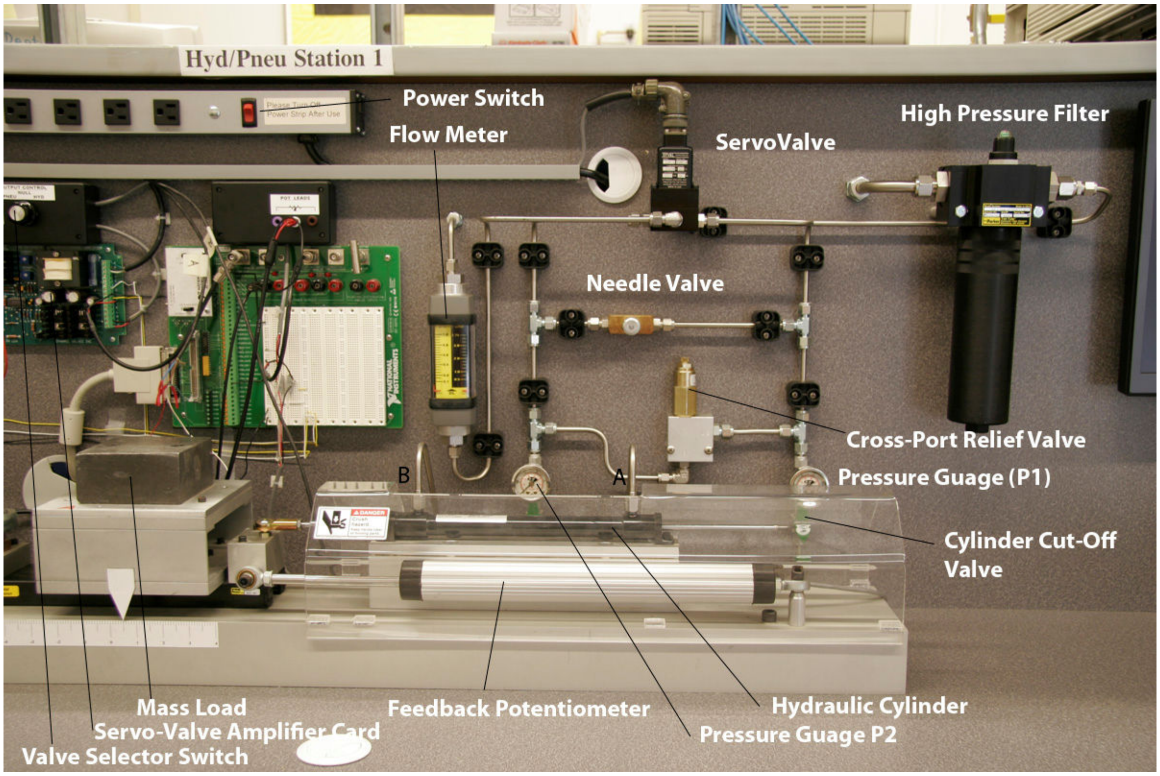


Fig. 1: Hydraulic Position Control System

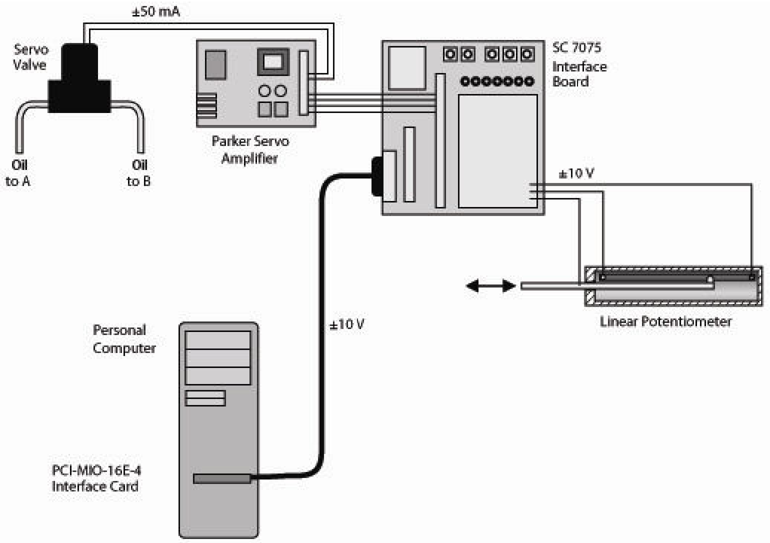


Figure 2: Computer Control and Feedback System

Physical System Modeling (Pre-lab)

Prior to attending the first week of the hydraulic positioner laboratory, the students are required to develop a block diagram of the hydraulic system assuming a proportional controller. They must then reduce this block diagram to a single transfer function. At this point in the quarter, the students are familiar with the techniques required to complete this task. In the lab write up (see http://www.calpoly.edu/~jridgely/), the students are given a description of the system components along with the block diagram of the servo-valve and hydraulic cylinder after Merritt[2] (see Figure 3). It is not expected that the students derive this portion of the model due to its complexity and their limited knowledge of hydraulic systems. Each block is described in the lab manual and the nomenclature is briefly defined here in Table 1. The students are expected to add the controller, mass, damping and feedback to generate the complete position control block diagram as shown in Figure 4 and reduce this diagram to a single transfer function as shown in Figure 5. These solutions are checked by the lab instructor at the beginning of the first lab period.

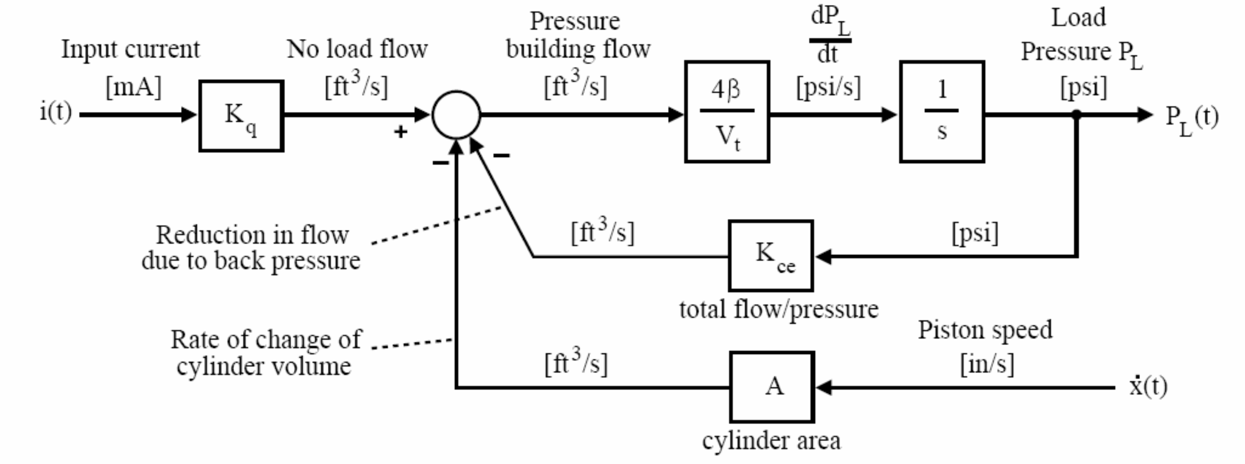


Figure 3: Servo-Valve and Cylinder Block Diagram

Symbol	Definition (units)	Values Obtained
$i(t)$	Amplifier output current (±50 mA max)	Given
Kq	Servo-Valve Flow Gain (ft^3/s/mA)	Measured
β / V_t	Hydraulic Oil Bulk Modulus (lb/in^2)/ Volume of oil trapped between servo-valve control ports (in^3)	Calculated
K_{ce}	Total Flow-Pressure Coefficient (in^3/sec/psi)	Calculated
A	Area of Cylinder Bore – Area of Cylinder Rod (in^2)	Measured
K_{amp}	Servo-Valve Amplifier Gain	Given
K_p	Proportional Gain	Input
M	Moving Mass (lb•s^2/in)	Given
B	Viscous Damping Coefficient	Deduced from Given Data
K_{pot}	Potentiometer Gain (Volts/in)	Measured

Table 1: Nomenclature for System Model

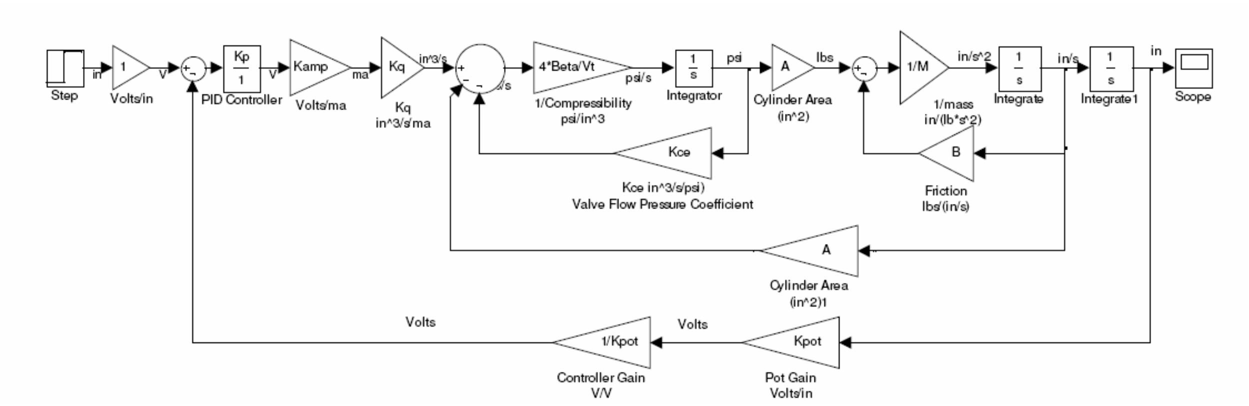


Figure 4: Position-Controlled Hydraulic Cylinder Simulink® Model

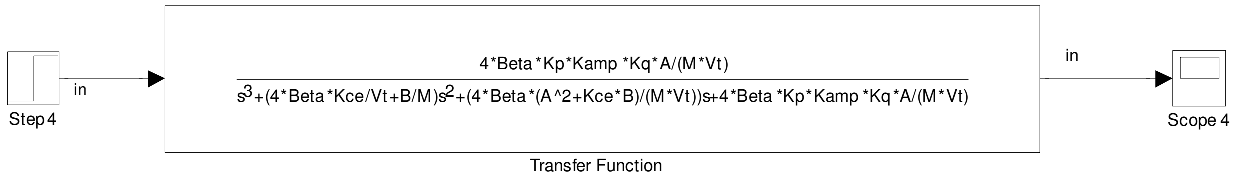


Figure 5: Block Diagram Reduced to a Single Transfer Function

System Characterization

During the first week of lab, the students are expected to characterize the system and provide quantities for the model parameters as listed in Table 1. The students are given the weight of the moving mass, the amplifier gain, the maximum current to the servo valve and the bore of the cylinder (the students measure the diameter of the rod and they calculate the cross-sectional area). By moving the mass a known distance by hand and noting the change in the voltage output from the potentiometer, the students can calculate the potentiometer gain. Next the students open the cylinder bypass needle valve (see Figure 1) and apply hydraulic power to the bench. The students then measure the flow through the valve at amplifier input voltages from -10 to +10. Note that the students must monotonically increase the voltage or the data will be affected by valve hysteresis. This data is then manipulated by the students to eliminate the constant valve internal leakage (included in the data) and account for the flow direction through the valve (not apparent at the flow meter). The adjusted data can then be plotted to find the no-load valve flow gain, K_q. Lastly students are given test data showing friction loads of the cylinder/mass system at different speeds. By plotting this load vs. speed data, the students can conclude that friction forces are dominated by coulomb friction and not viscous damping; therefore the value of B in the model should be zero. The only two remaining quantities left to fully characterize the linear system model are the ratio of the bulk modulus to the pressurized volume (β/V_t) and the total flow-pressure coefficient (K_{ce}).

Determination of these quantities is problematic for hydraulic systems in general. The trapped volume in the denominator of the first unknown is the simplest to approximate by considering the size of the hydraulic cylinder and the size of the lines. Unfortunately the effective value of bulk modulus for hydraulic oils tends to vary greatly (50,000-250,000 psi) in use depending on the amount of air entrained in the fluid. Furthermore the elasticity of various pressure holding elements (tubing, cylinder, etc.) should be included to accurately model the system with an effective bulk modulus, making this impractical for the students to measure. The second unknown, the flow-pressure coefficient (K_{ce}) is also difficult to determine from easily measured quantities. The value depends on internal cylinder leakage, leakage at the ends of the cylinder seals and the flow change due to load pressure. In order to determine these two unknowns, the authors have developed a closed-loop testing procedure to calculate the two unknown quantities which is described below.

The students are asked to use the RTWT to close the control loop with a proportional controller and document the system response to a step input. They are instructed to save response data using various values of proportional gain. The first proportional gain value is given, the second value must be experimentally determined as the highest without causing any system overshoot. The third gain value should cause a 25% system overshoot and lastly the students are asked to slowly increase the gain until the system reaches instability. This is a fairly dramatic event accompanied by noisy workbench vibrations. The noise and vibrations give the students a hands-on, visceral understanding of the meaning of “instability.” The hydraulic system is fairly robust and is not damaged by the short time it is allowed to be unstable. The software is set up to run for only a few seconds of closed loop control so that the system is not unstable for a long period of time. The instructor also gives an explanation that running a system at instability is not a common practice and should not be done unless you can ensure the results will not cause damage. The software also saves and plots the position of the mass for each step response test. From these plots the students can then determine the frequency of the marginally stable system. This concludes the first week of the two week experience.

Now the students are ready to determine the unknown system parameters so they can create a useful simulation of the system. They can do this using the following procedure. The students found the form of the denominator of the closed loop transfer function as shown in Figure 5 is:

$$D_G = s^3 + a_2 s^2 + a_1 s + a_0 , \qquad (1)$$

which can be factored into the form:

$$Dg = (s+a)(s^2 + 2\varsigma\omega_n s + \omega_n^2)^{3} \qquad (2)$$

where a is a constant

ζ is the damping ratio

ω_n is the natural frequency.

At this point the students must determine that at the limit of stability, $\zeta = 0$, and the form of the closed loop transfer function must be:

$$Dg = (s+a)(s^2 + \omega_n^2) \qquad (3)$$

The students can then expand equation (3) and equate it to the denominator of the closed loop transfer function they determined in the pre-lab (see Figure 5) to arrive at equation (4) below.

$$s^3 + as^2 + \omega_n^2 s + \omega_n^2 = \mathrm{s}^3 + (4\frac{\beta}{\mathrm{V_t}}\mathrm{K_{ce}} + \frac{\mathrm{B}}{\mathrm{M}})\mathrm{s}^2 + 4\frac{\beta}{\mathrm{V_t}}\frac{(\mathrm{A}^2 + \mathrm{K_{ce}B})}{\mathrm{M}}\mathrm{s} + 4\frac{\beta}{\mathrm{V_t}}\frac{\mathrm{K_p K_{amp} K_q A}}{\mathrm{M}} \quad (4)$$

By equating coefficients of the complex Laplace variable, s, the unknown quantities β/V_t and K_{ce} can be determined to complete the system model. Care must be taken to use correct units for this calculation and students commonly make errors by using incompatible units such as inches and slugs, etc.

The students next input their system model into Simulink®. They can run simulations and match predicted step response with the measurements taken during the first week of lab. During the second week of this laboratory, the students are asked to explore the implementation of a Proportional Derivative (PD) controller and Proportional-Integral (PI) by alternatively adding derivative control and integral control. The students slowly increase the derivative gain to reduce overshoot and save the results. To explore the PI controller the students change the source to a ramp function, quantify the steady state error and reduce it using the integral control. Lastly the students are asked to make a root-locus plot (using software) using the open-loop transfer function and see the movement of the closed loop poles for the values used in their experiments. The students must turn in a lab report with deliverables as listed in the lab handout.

Typical Experimental Results

Figure 5a gives an example of the typical data students collect to determine the valve flow gain during the process of system characterization. The students then must reason that the lowest value of flow will be when the spool in the servo-valve is centered. Values of flow on either side represent different flow directions and the flow when the spool is centered is the internal leakage flow of the servo valve. The students must then subtract the leakage flow and account for the flow direction to obtain Figure 5b. The slope of this graph is the linearized flow gain of the servo valve, K_q. Once the students have completely characterized the system and made a Simulink® model, they are asked to compare actual system response to what is predicted with Simulink®. Figure 6 shows an overlay of the simulation and actual results for a relatively low proportional gain. Note that the system displays what looks to be a typical first order response. Figure 7 shows results of the experimental system and the simulation at a higher gain where the system has a third-order response and final Figure 8 shows a yet higher gain when a pair of second order poles dominates the response. Figure 9 shows the response of the system and simulation to a ramp input, clearly indication steady state error. Note in all cases the excellent correlation between the simulation and the actual system response without having to include non-linear elements in the simulation.

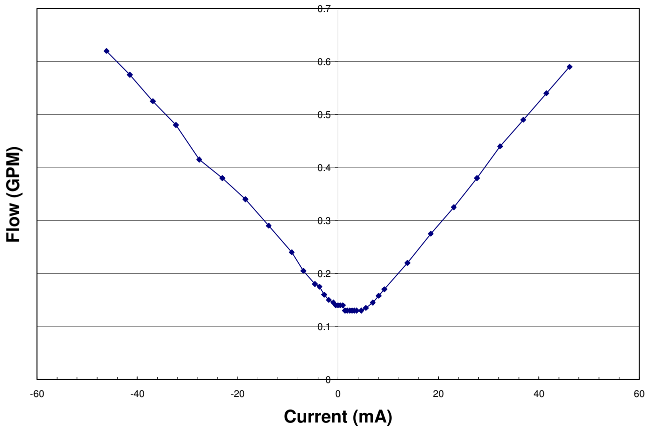


Figure 5a: Raw Flow Data

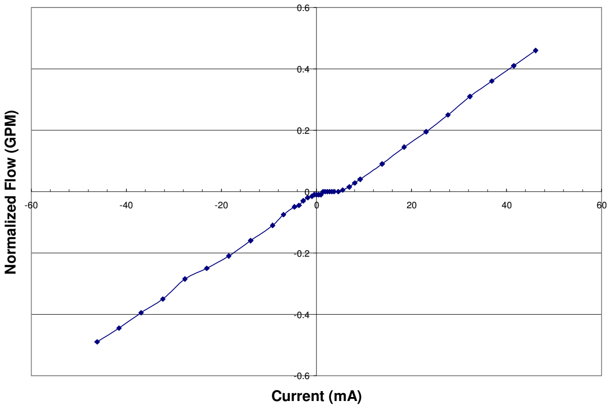


Figure 5b: Normalized Flow Data

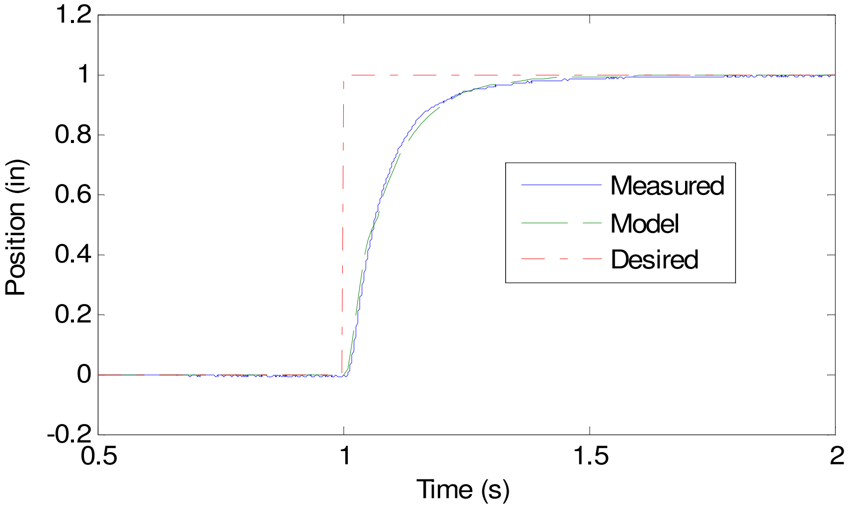


Figure 6: System Step Response and Simulation with $K_p = 10$

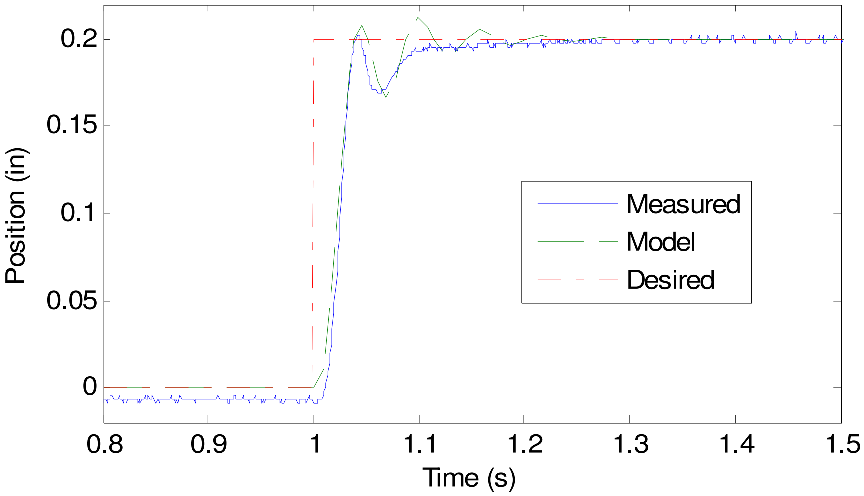


Figure 7: System Step Response and Simulation with $K_p = 25$

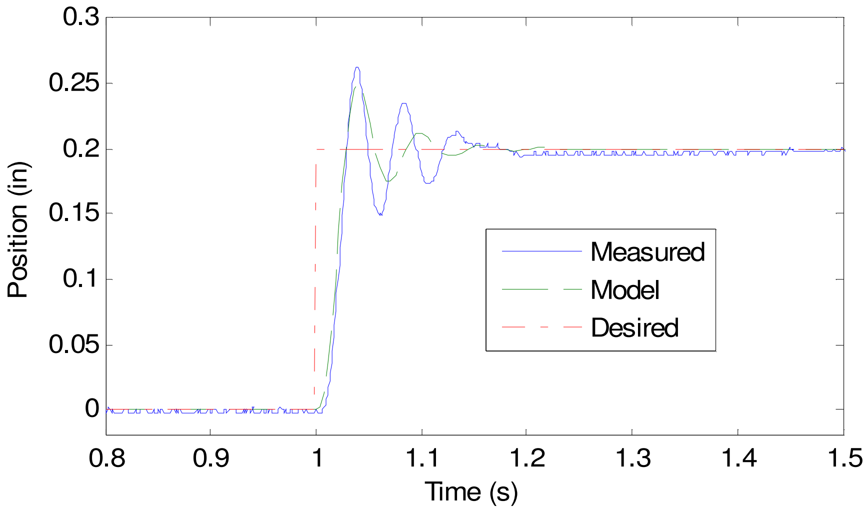


Figure 8: System Step Response and Simulation with $K_p = 46$

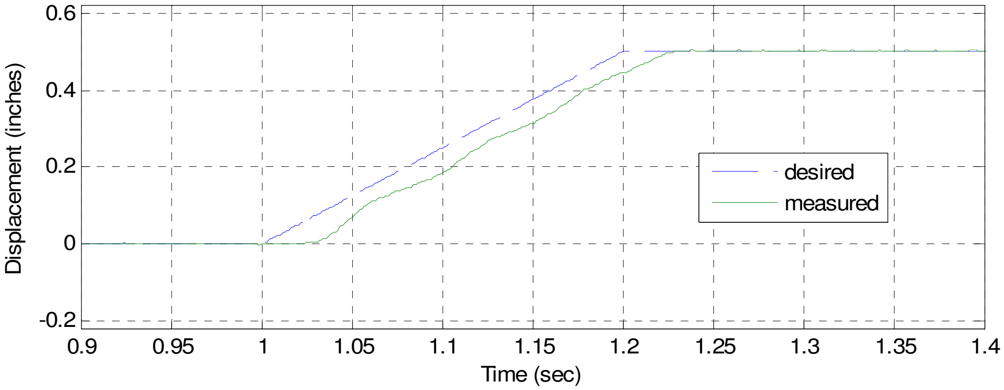
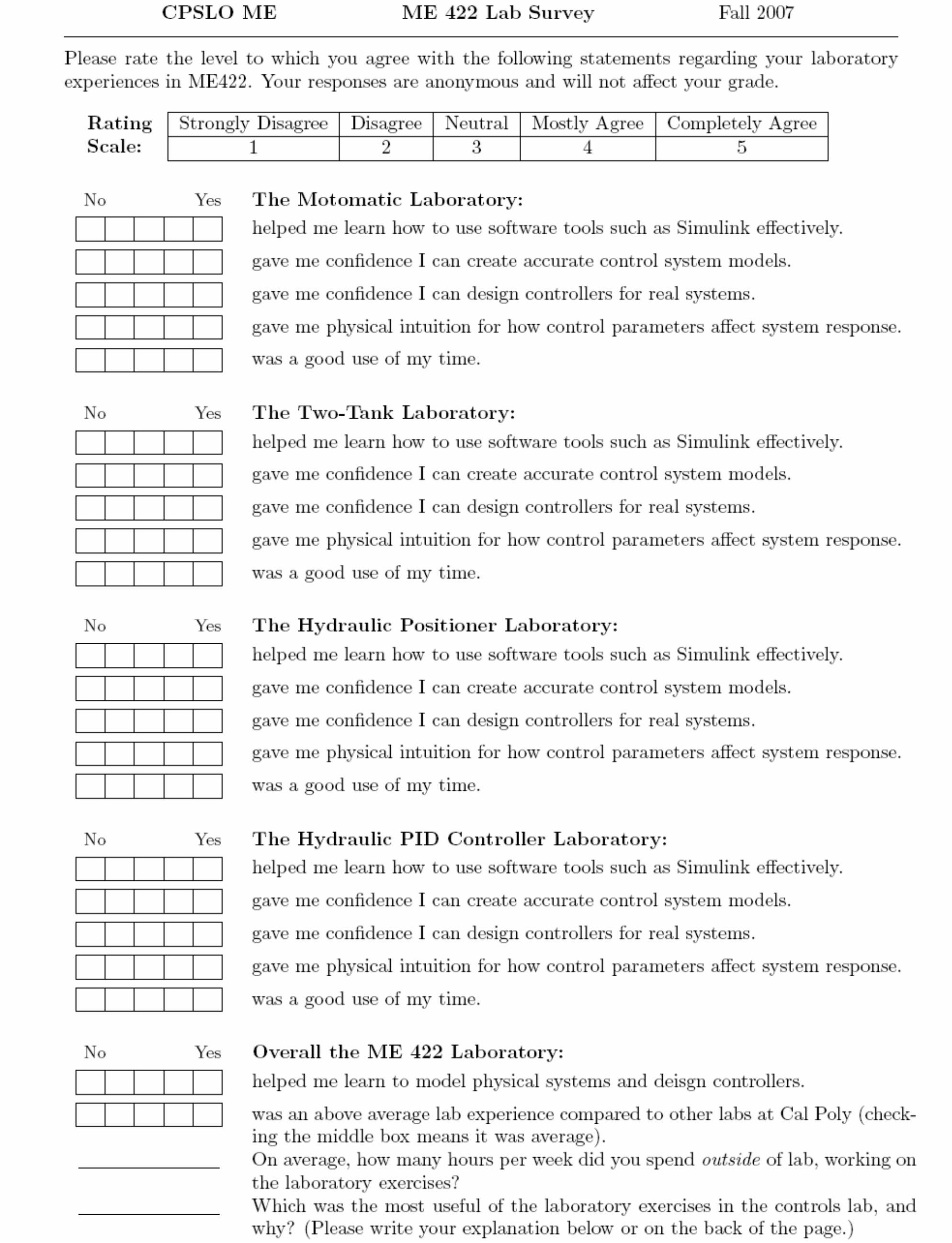


Figure 9: System Ramp Response and Simulation Showing Steady State Error

Assessment

The new hydraulic positioner experiment replaced an older pneumatic positioner experiment. For the older system, it was difficult for the students to make linear system models that accurately predicted system behaviors due to the dominant non-linearities of the pneumatics and the amount of coulomb friction. Anecdotal observations indicated that the students lost confidence in the power of linear system modeling as a design tool as they needed to "tune" Simulink® models using non-linear elements. Although the students no longer use the pneumatic system, the authors have sought to assess the new experiment and associated student outcomes. This was done indirectly through the use of a survey and directly through a question imbedded on the final exam. The survey is given in Figure 10. Average survey results for 65 students enrolled in the class during the fall quarter of 2007 are given in Figure 11. Note that as compared to the other labs during the quarter, the students consistently rated the hydraulic positioner lab as the one that helped them learn to use Simulink® most effectively and gave them the greatest confidence and intuition into control system modeling and controller design. Unfortunately the authors do not have any data to compare for the older pneumatic positioner laboratory. A direct assessment method of imbedding a final exam question proved to be less informative. Random groups of students were given identical problems (either identifying a transfer function from a Bode plot or designing a proportional controller) except for a reference to the hydraulic positioner lab. Interestingly, those students who were given problems that referenced the lab did worse than those who attempted to solve the identical problem with no reference to the lab. The groups scored roughly equivalent on the overall test.



CPSLO ME **ME 422 Lab Survey** Fall 2007

Please rate the level to which you agree with the following statements regarding your laboratory experiences in ME422. Your responses are anonymous and will not affect your grade.

Rating Scale:	Strongly Disagree	Disagree	Neutral	Mostly Agree	Completely Agree
	1	2	3	4	5

No Yes **The Motomatic Laboratory:**

☐☐☐☐☐ helped me learn how to use software tools such as Simulink effectively.
☐☐☐☐☐ gave me confidence I can create accurate control system models.
☐☐☐☐☐ gave me confidence I can design controllers for real systems.
☐☐☐☐☐ gave me physical intuition for how control parameters affect system response.
☐☐☐☐☐ was a good use of my time.

No Yes **The Two-Tank Laboratory:**

☐☐☐☐☐ helped me learn how to use software tools such as Simulink effectively.
☐☐☐☐☐ gave me confidence I can create accurate control system models.
☐☐☐☐☐ gave me confidence I can design controllers for real systems.
☐☐☐☐☐ gave me physical intuition for how control parameters affect system response.
☐☐☐☐☐ was a good use of my time.

No Yes **The Hydraulic Positioner Laboratory:**

☐☐☐☐☐ helped me learn how to use software tools such as Simulink effectively.
☐☐☐☐☐ gave me confidence I can create accurate control system models.
☐☐☐☐☐ gave me confidence I can design controllers for real systems.
☐☐☐☐☐ gave me physical intuition for how control parameters affect system response.
☐☐☐☐☐ was a good use of my time.

No Yes **The Hydraulic PID Controller Laboratory:**

☐☐☐☐☐ helped me learn how to use software tools such as Simulink effectively.
☐☐☐☐☐ gave me confidence I can create accurate control system models.
☐☐☐☐☐ gave me confidence I can design controllers for real systems.
☐☐☐☐☐ gave me physical intuition for how control parameters affect system response.
☐☐☐☐☐ was a good use of my time.

No Yes **Overall the ME 422 Laboratory:**

☐☐☐☐☐ helped me learn to model physical systems and deisgn controllers.
☐☐☐☐☐ was an above average lab experience compared to other labs at Cal Poly (checking the middle box means it was average).
__________ On average, how many hours per week did you spend *outside* of lab, working on the laboratory exercises?
__________ Which was the most useful of the laboratory exercises in the controls lab, and why? (Please write your explanation below or on the back of the page.)

Figure 10: Student Laboratory Survey

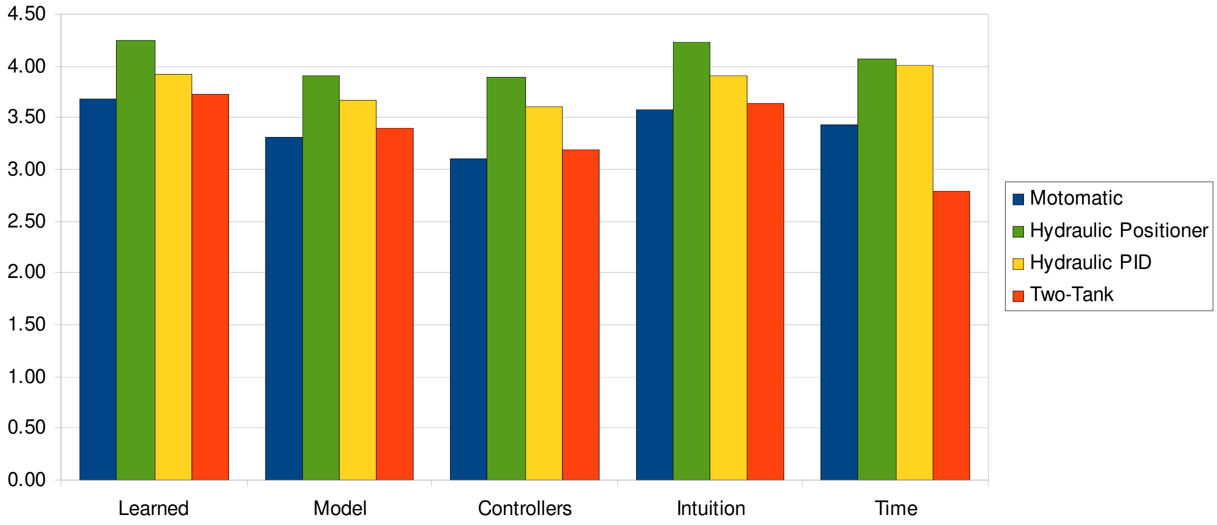


Figure 11: Student Survey Results

Conclusion and Recommendations

A hydraulic servo-position control experiment was developed and is used in the Parker Hannifin Mechanical Control Systems Laboratory at Cal Poly State University, San Luis Obispo for a required undergraduate course. This two week laboratory exercise requires the students to work with servo controlled hydraulic hardware, develop an accurate linear model of the system, practice block diagram reduction, characterize system parameters through “hands-on” experimentation and compare the resulting model to the actual system step and ramp responses. In characterizing the system, the students experience closed loop instability and use the resonant frequency to determine unknown system parameters. The developed linear model very accurately predicts actual system response that is difficult to achieve in many laboratory experiments with mechanical systems due to nonlinearities such as Coulomb friction. The students explore the model’s prediction of steady state error and response using PD and PI control. They also relate root locus plots to the actual system response. Student surveys indicate that the students find this an effective lab in terms of learning control simulation software, gaining confidence in linear system modeling, controller design and overall a good use of their time. Direct assessment of learning outcomes did not yield useful data and the tool will need to be redesigned. Overall the students and faculty are satisfied with the lab experience and would recommend its use by other institutions to support an introductory Mechanical Control Systems class.

Acknowledgements

The authors would like to thank the Parker Hannifin Corporation for its generous support of our Mechanical Control Systems Laboratory. The Cal Poly Mechanical Engineering Student Fee Allocation Committee also provided funding to support the development of this particular laboratory exercise, and Jens Jorgensen who provided technical assistance with the hydraulic modeling.

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