Exercise 2

Motomatic Servo Control

This exercise will take two weeks. You will work in teams of two.

2.0 Prelab

Read through this exercise in the lab manual.

Using Appendix B as a reference, create a block diagram of a simple motor system. The system should have the following components:

- The input is a voltage V_A from an electronic amplifier.
- The motor is a first-order dynamic system whose input is V_A and whose output is motor speed ω (in radians per second). The motor's transfer function should include a gain K_m (in radians per second per volt) and a time constant T_m (in seconds).
- The output of the system is motor shaft position angle θ. You know how to get θ from ω.

Turn in a page with the equations of motion and block diagram for the motor system at the beginning of the first lab session.

2.1 Introduction

This lab utilizes the Motomatic motor control system. This system has been a favorite in the controls lab for a (very) long time. The Motomatic can be configured to work with either a position control or velocity control feedback loop. We will study position control. Electromechanical position control systems are the basis of most motion control systems used in industry. The movement of a robot's joints or a machine tool's positioning axes are examples of electromechanically controlled motions. Modern aircraft, spacecraft, and many ships operate on the "fly-by-wire" principle, in which computers control the motion of the vehicle in response to requests from the pilot of where to go.

When the Motomatic is wired as a *servo*, or position control system, a twist of the input knob on the lower left corner of the control panel produces a rotation of the motor which is connected to the control box. The larger the input twist, the larger the angular displacement of the motor. It's a little like power steering. However, power steering is a system which "boosts" your steering energy, but you still have a direct mechanical connection to the wheels. With the Motomatic servo control, there is no direct mechanical connection between the input knob and the output motor. Instead, the connection is made electronically through the control system.

In order to understand and control this system, you will begin by modeling the Motomatic piece by piece. This modeling is done with the control loop *open*, which means that the feedback path in the closed control loop is broken, disabling the feedback control. The model will be used to create a simulation in Simulink™. You will then wire all the components into a closed-loop servo system and run a step response test. If your model has been constructed properly, the Simulink™ output will closely resemble the Motomatic's actual behavior. You may need to refine your model somewhat in order to ensure that the model predicts the performance of the Motomatic system as accurately as possible. This type of modeling and simulation is commonly used in industry to design controllers for automated systems. The process is also used to troubleshoot problems with the dynamic response of existing systems.

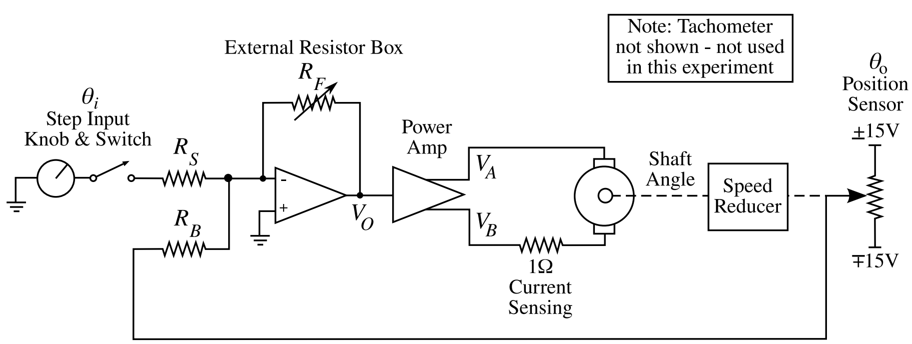

Figure 2.1: *Motomatic System Diagram*

2.1.1 Equipment

The position control system configuration for this experiment is shown in Figure 2.1. In order to simulate the closed-loop system, you must first measure the characteristics of the following individual components:

- The operational amplifier (op-amp) is connected as an inverting, summing amplifier. You could vary the gain of this amplifier by changing the value of the op-amp resistor R_F, but leave it at 5kΩ. A diagram of the summing

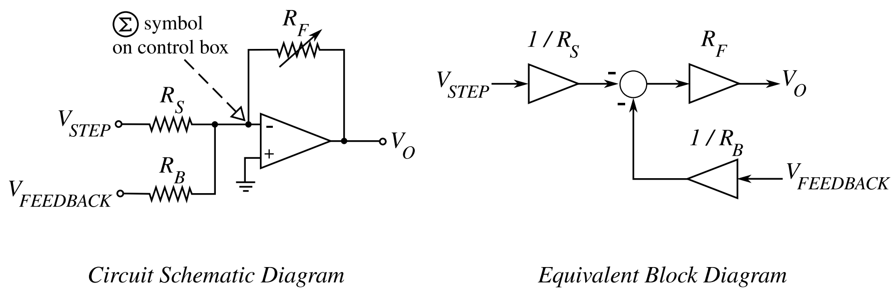

Figure 2.2: *Summing Amplifier*

circuit is shown in Figure 2.2. For this circuit, the relationship between the inputs and output is as follows:

$$V_O = -\frac{R_F}{R_S} V_{STEP} - \frac{R_F}{R_B} V_{FEEDBACK}$$

Note that the diagram on the Motomatic controller box does not show the grounded (non-inverting) input but it's still there, connected internally.

- The power amplifier has a fixed gain. It also has a light which flashes red to indicate that the amplifier is *saturated*, which means that the amplifier cannot produce as much voltage as it is being asked to. This occurs when the size of a step change in voltage is too great, and it is seen as a brief red flash from the normally green amplifier light. You should try to prevent saturation during measurements, as in that condition the amplifier will act as a *non*linear element.

- The motor is a permanent magnet, brushed DC motor. It produces torque as a function of input current. We will model motors later in class, but for now treat the motor as a black-box element.

- The position sensor potentiometer produces a voltage which varies linearly with angle over 340^o of rotation. The other 20^o are a "dead zone" within which the reading is not useful.

- The speed reduction unit's belts can be configured to provide speed changes in the following approximate ratios: $1:1$, $\sqrt{3}:1$, $3\sqrt{3}:1$, and $9:1$.

The goal of this lab is to find the transfer function of the angular positioning system. The input is the knob angle, θ_i; and the output is the angle of the motor shaft as measured by the potentiometer, θ_o.

2.1.2 Component Testing

Your first goal is to measure the properties of the components of the system. You will set up the system in *open loop* mode, which means that the feedback path from the position sensing potentiometer to the op-amp will not be connected.

(1) **Input Signal** Turn the step input knob all the way counterclockwise. Set the test meter selection switch to position 3, `step input`; this allows you to measure the step input voltage. *Hint: You can connect a voltmeter or oscilloscope to the banana jacks just below the meter for a more precise measurement.* Set the toggle switch above the step input knob to the (+) setting. Now when you turn the knob through a given angle, you control the voltage from the step input source. Turning the switch on and off is what produces the "step", or nearly instant change in voltage. Record the voltage at several angles (for example 0, 90, 180, and 270 degrees) from the zero voltage point, then plot the results and find the relationship between step voltage and angle. The value should be in volts per radian.

(2) **Op-Amp Summing Circuit** Rather than measuring the op-amp gain, we can use the values of its resistors to compute the gain; for this type of circuit, such a computation is generally accurate to within 1–5%. Use the diagram and formula in Section 2.1.1 to compute the op-amp's gain. Note that the gain may be a negative number (meaning if the input voltage is positive, the output is negative); it may also be less than one.

(3) **Power Amplifier** The power amplifier's output voltage is some constant number times its input voltage. Look at Figure2.1 to see that the power amplifier's input is the op-amp's output. Connect the power amplifier to the op-amp, and make sure that the feedback loop is disconnected. Also disconnect the motor leads for this measurement. (This does *not* mean to disconnect the op-amp resistor R_F; it must always be connected.) Also disconnect the motor leads for this measurement. Measure the input and output voltages and plot a graph of output *vs.* input. Determine the power amplifier's voltage gain K_A, in volts per volt. Is this a positive or negative gain?

(4) **Motor** The motor will be modeled as a first-order transfer function,

$$G_m(s) = \frac{K_m}{T_m s + 1}$$

where K_m is the steady-state gain and T_m is the time constant. This linear model is somewhat imprecise, and it will be improved by modeling the nonlinear sticking friction in Simulink™.

First determine the steady-state gain K_m of the motor for speeds less than 1000 rpm. This will require a plot of the motor's steady-state speed against the amplifier output voltage, or ω_m *vs.* V_A. The slope is $K_m = \omega_m / V_A$. Be sure to take 5-10 readings at different voltages and speeds. Remember that a handheld voltmeter must be used to measure V_A.

When you look at the motor speed *vs.* voltage graph, you should notice that a first-order fit to the data does not go through the origin. As shown in Figure 2.3, the motor has zero speed at a substantial voltage. This is due to static friction which must be overcome before the motor will move at all. From your graph, determine V_{DB}.

Now find the motor time constant, T_m. This is done by plotting the response of the motor velocity to a step input voltage. Estimate the step input voltage which is required to cause the motor to run at a steady-state speed of 1000 rpm, and set the knob to that voltage. Connect an oscilloscope to measure the motor speed as measured by the tachometer. Set the 'scope to `normal` triggering mode (see Appendix D), and adjust the trigger level so that when you flip the step input switch from the off position to on, the first-order step response curve is clearly visible on the screen. Download the waveform data to the computer; create and print a graph of the step response. Measure the motor's time constant from the graph. Your graph should be included in your report. Clearly show the $\omega/\omega_{ss} = 63\%$ position and measured time constant on your graph.

(5) **Speed Reducer** Make sure the speed reduction unit is set to reduce the motor speed as much as possible. Measure the speed reduction ratio by counting how many turns of the input shaft are required to make the output shaft rotate by exactly one turn. For greater accuracy, you might try two or more turns of the output shaft.

(6) **Position Sensing Potentiometer** Here you will determine the gain K_{pot} of the feedback sensing potentiometer in volts per radian. The potentiometer should still be mechanically disconnected from the drive shaft. The `feedback` switch should be on and in the negative direction; this is needed to supply power to the potentiometer. The wire in the `Position Compensation` line should be disconnected. Beginning at an arbitrary location, turn the shaft through 180^o (or π rad), and measure the voltage change which results from this movement. It helps to hold some sort of straightedge against the drive coupling as you turn the shaft, so that you can turn it by exactly 180^o. Note that the pot has a "dead zone" in which the output changes quickly from +15V to -15V. It is best to avoid this zone when making your measurement. It may be a good idea to average several measurements in this step.

2.1.3 System Modeling

(7) **Open-Loop Modeling** Using the data you have recorded in the previous steps, you can now create a model of the motor using Simulink™. First you want to model the system as it was set up in the step response test of Step (4). The feedback compensation line was disconnected, so the system was running open-loop. Your model therefore includes the input knob, op-amp input gain (but not feedback gain), power amplifier, speed reducer, and motor.

You should create two models at this time, a linear model and a nonlinear one. The difference between these two models is how they represent the motor. You measured a deadband due to stiction in the motor; this is a nonlinear phenomenon, and it can't be represented in a linear model. Instead, the linear model represents the motor's performance as if it were linear, $\omega_{ss} = K_{m,lin} V_A$. You determine the constant $K_{m,lin}$ by making an estimate of the "average" slope of the ω_m *vs.* V_A data, as shown in Figure 2.3. The linear model will use the value $K_{m,lin}$ for the motor

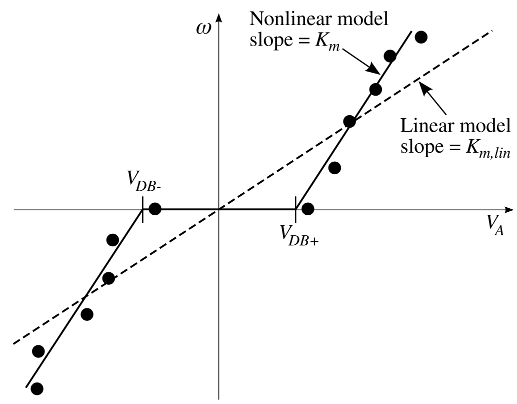

Figure 2.3: *Linear and Nonlinear Motor Curves*

constant. The nonlinear model, which should be a bit more accurate but cannot be used to find a transfer function, uses the value K_m for the motor constant and also includes a `Dead Zone` block from the Simulink™ `Discontinuities` library.

Your goal in this step is to create Simulink™ models which reproduce the step response behavior of the real system. This means that the time constant and steady-state speed in your simulations' responses should be about the same as those for the real motor. It is expected that your simulations won't be perfectly accurate no matter how accurately you have measured the components of the system. (Why is this?) However, if your simulated time constant or steady state speed are way off – more than 25% or so – you should go back and check your measurements and model again. The model needs to be done properly before you can get anywhere in the next section.

(8) **Closed-Loop Modeling** When your open-loop model is working properly, it should be fairly easy to modify your model so that it represents the closed-loop system. This is done by adding the output potentiometer in a feedback path which connects the output position θ to the correct input of the op-amp summing amplifier. Arrange the model so that it looks like the general form for a feedback control system, with most components in a left-to-right "forward" path and the potentiometer in a right-to-left feedback path below the forward path.

The output of your Simulink™ model runs for the closed-loop system

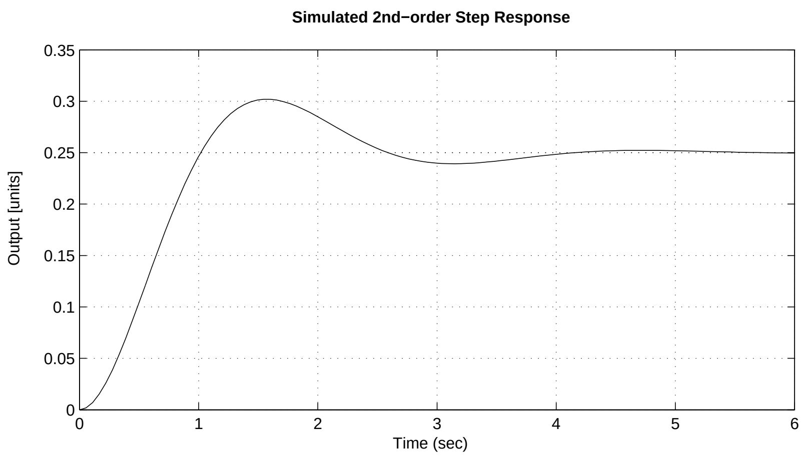

Figure 2.4: *Response of a Generic Second-Order System*

should look similar to (but not exactly the same as) the underdamped second-order response shown in Figure 2.4.

2.1.4 Week 1 Deliverables

At the *beginning* of the lab session for the second week, you should turn in a package of three items:

- A printout of your Simulink™ model for the non-linear system (including the `Dead Zone` block). On each signal line connecting two blocks, write the **units** of that signal.

- A photocopy of the parameter sheet's front side, filled in with values for all system parameters such as gains and time constants needed to model the system. Transient performance and feedback gains do not need to be filled in yet.

- Graphs showing the expected closed-loop response of the Motomatic, with the linear model's and nonlinear model's graphs on the same axes. These graphs should be created using Matlab™, not a spreadsheet program; see Appendix B, Section B.3 for instructions. There must be graph titles and axis labels, but these may be handwritten if convenient.

2.2 Week 2: Closed-Loop Testing and Tuning

You have completed your simulations of the closed-loop Motomatic system. Now it's time to test those simulations against reality by performing step response tests of the closed-loop system. You will be able to see what was different between the model and the physical system and then "tune" the model so that it reflects the behavior of the real system as closely as possible.

(9) **Closed-Loop Transient Response Tests** Connect the Motomatic as a closed-loop position controller. The connections are shown schematically in Figure 2.1. First connect the feedback path so that it sends a position feedback signal to the summing amplifier. Note the toggle switch marked "Feedback." This switch turns the feedback signal on and off and controls the signal's polarity. When the switch is set to (+), the ±15V voltages will be connected to the position sensing pot in such a way that the feedback voltage increases as the shaft angle increases. We will use the system with the switch set to (-), which connects the ±15V voltages the other way – providing negative feedback which produces the correct error signal for controlling the shaft's position. Do *not* connect the velocity feedback signal in this lab.

Make sure the potentiometer, speed reducer, and motor are all connected properly. Also make sure the op-amp resistor R_F is set to 5 kΩ. Apply a step input voltage to the system. In order to get the clearest signal and minimize the effects of stiction and other nonlinearities in the system, you must use the largest step input you can without causing the power amplifier to saturate. Saturation causes a red flash from the power amp indicator light just after you apply the input step. Adjust the step voltage until you have found the largest voltage which won't saturate the amplifier.

Connect the oscilloscope so that it measures the output of the position sensing potentiometer as a function of time. Adjust the triggering, voltage scale, and time scale so that you get a clear graph of position *vs.* time. The graph should look something like the underdamped response shown in Figure 2.4. It won't look exactly the same; one reason is that the Motomatic system is nonlinear due to stiction and other effects. Stiction will cause the response graph to look somewhat different, and it will also cause the steady-state output $\theta_{o,ss}$ to be slightly different each time you do a step response test. This is because the friction can cause the output shaft to become stuck at different locations for each test. You can minimize this problem by doing several tests, say around ten, and measuring the change in output angle $\theta_{ss} - \theta_0$ for each. The average value should be a good representation of the properties of the system. You need an accurate value for $\theta_{o,ss}$ because it is used to calculate the percent overshoot, an important parameter for experimentally determining second-order system equations.

Measure and record the percent overshoot $\%OS$, rise time T_r, and settling time T_s for the system with a 5 kΩ op-amp resistor R_F.

2.2.1 Gain Response Tests

Now it's time to look at one of the most important differences between open-loop and closed-loop systems. If you change the gain of an amplifier in an open-loop system, the result is just what you'd expect: the output gets larger or smaller. But what happens if you change the op-amp gain in the Motomatic operated as a *closed-loop* system? It might not be quite what you had expected.

Perform a second closed-loop step response test; but this time, set the op-amp resistor R_F to 10 kΩ. This will double the summing amplifier's gain for both the step input signal *and* the feedback signal. We are interested in the effect of the change of feedback signal gain, so set the step input amplitude to half what it was in the previous test. Then save your data from this latest test, print a graph, and use it to find the percent overshoot $\%OS$, rise time T_r, and settling time T_s for the system with a 10 kΩ op-amp resistor R_F.

Finally, repeat the process with a 20 kΩ op-amp resistor R_F which gives an even higher op-amp gain. Report your results for percent overshoot, rise time, and settling time on the parameter sheet. Your laboratory memo should answer the question, how does increasing the feedback gain affect the response of the system? Comment on what happens to T_r, $\%OS$, and T_s – is there a pattern or trend?

(10) **Analysis of First Models** You need to compare the Simulink™ models which you made last week to the real system. The responses should be similar, but you're not expected to have achieved perfection!

- Make a block diagram of the linear closed-loop system in symbolic form, using the variable names given here. Determine the closed-loop transfer function in symbolic form and in numerical form. Show this in your report and show the numerical transfer function on the parameter sheet. During the computation of the closed-loop transfer function, the open-loop transfer function should have been computed as well; record this on the parameter sheet also.
- Substitute numbers for the variables in the transfer functions, watching your units carefully. Report the numerical transfer functions on the parameter sheet.

(11) **Tuning the Model** You have probably found that the simulations aren't quite a perfect representation of the time response of the Motomatic system. You can improve this representation a bit by "tuning" your model. In this step, you alter the model's physical properties (gains, time constants, and so on) to make the response of the simulation more closely resemble the response of the physical system.

This may seem like you're just fudging the numbers, but it is reasonable to do so in many cases. This is because you're trying to use a linear model (or a linear model modified with a deadband) to represent a *non*linear system; also, measurements of system parameters are always a bit uncertain. Your best chance at accounting for these effects is to tune the model somewhat. You can tune your model by adding extra gain blocks in between the existing model blocks (label each "`tuning`"), beginning with a gain of 1 and changing that gain to improve the model's accuracy. Another parameter which can be tuned is the width of the deadband.

Tune your model as best you can to reflect the behavior of the real system. Show, on one graph, plots of the closed-loop step response of: the real system, your first nonlinear model with a deadband, and your best final tuned nonlinear model.

2.3 Deliverables

For this exercise, you are to hand in the following items:

- A short memo about this exercise, following the format shown in Appendix A on Page A-1. Your memo should contain answers to the following questions:

  1. How does the nonlinearity of the system affect the time response?
  2. Compare the trends in T_r, $\%OS$, and T_s from your data to the trends you would expect from theory. Explain any differences you can see.
  3. Compare the open-loop response to the closed-loop response of the system.

- Printouts your three Simulink™ models – linear and nonlinear before tuning, and nonlinear after tuning. These should all be on one page; it may be convenient to just put all three block diagrams in one Simulink™ model file.

- A combined graph which shows the closed-loop step response of the real system, first untuned simulation, and final tuned simulation – all on the same axes, to the same scale.

- The step response graph from which you determined the motor's time constant.

- Your derivation of the open-loop and closed-loop transfer functions in symbolic and numerical form. These can be turned in as hand calculations.

- A plot showing the change in T_r, $\%OS$, and T_s (on the vertical axis) *vs.* op-amp resistance R_F (on the horizontal axis).

- Any other supporting information and calculations which are relevant to the exercise.

Motomatic System Characterization (Spring 2011)

Team Members: ________________________________

Param.	**Value**	**Units**
K_{knob}		
R_S		
R_B		
R_F		
K_a		

Param.	**Value**	**Units**
$K_{m,lin}$		
K_m		
V_{DB}		
T_m		
K_{pulley}		
K_{pot}		

	Experimental results	**Tuned nonlinear model results**	**Units**
$\%OS$			
T_P			
K_{ss}			

	Open-loop transfer function	**Closed-loop transfer function**
Symbolic		
Numerical		

	$\mathbf{R_F = 5k\Omega}$	$\mathbf{R_F = 10k\Omega}$	$\mathbf{R_F = 20k\Omega}$
%OS			
$\mathbf{T_r}$			
$\mathbf{T_s}$			