MAE 106 Laboratory Exercise #3
Feedback I: P-type Velocity Control of a Motor

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REQUIRED PARTS:

Qty	Parts	Equipment
3	1KΩ resistor	Breadboard
1	10KΩ resistor	Oscilloscope
1	LM324 Quad op-amp	DC Power Supply
2	100KΩ resistor	Function generator
4	Banana –to-alligator-clip cable	Motor-tachometer-amplifier combo
2	Banana-to-banana cable	IC puller
var.	Wires	wrist grounding strap
		scope probe

1 Introduction

Engineers sometimes want to control the speed of a motor (for example, auto cruise control). In this lab, we will construct a circuit that will control the speed of a DC (direct current) motor using P-type (or proportional) velocity control. The resulting control system will be described by first order dynamics (i.e a first order differential equation). In the frequency domain, the system will behave like a first-order, low-pass filter (where desired velocity is the input and actual velocity the output). Thus, this lab not only shows you how to control the speed of the motor with feedback, it also shows you in general how a first-order control system respond.

The velocity “control law” for the motor is:

$$u = - K (\omega_{actual} - \omega_d) \qquad (1)$$

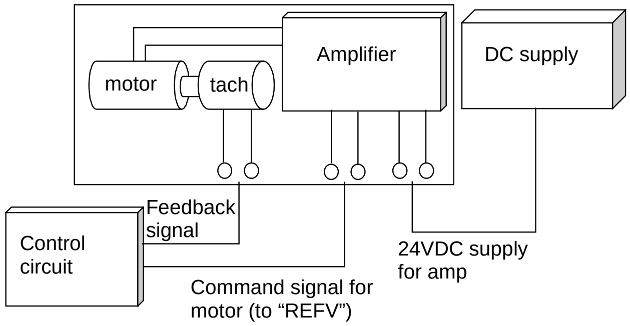
where

u = the control (our input to the system)
K = feedback gain
ω_{actual} = actual motor speed
ω_d = desired motor speed

A control law is an equation that computes an input (u, something we control that influences the system, sometimes called a “control”) to the system. In our circuit implementation of this controller (Figure 2), the motor speed variables are represented as voltages. ω_d is represented by a voltage produced by the function generator. ω_{actual} is represented by a voltage produced by a tachometer. Since this controller determines the input to the controlled system using sensed information about some state in our system, measured by a sensor (the tach), it is said to use “feedback.” Many types of sensors produce a voltage that is proportional to the variable that they sense.

Notice how equation 1 looks much like $F=k\Delta x$, the equation for a spring. Think of this controller as a spring, only in the motor velocity world instead of position world. Just as a spring constantly tries to return to its unstretched length, this controller drives the motor towards some desired speed. A bigger K is like having a stiffer spring. Given the appropriate system dynamics, this controller can drive ω_{actual} to ω_d, which is what we want!

2 Proportional Velocity Control System



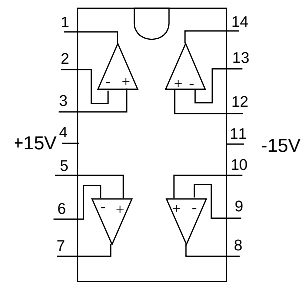


Figure 1 Motor-Amplifier set up **Figure 2 – Top view of LM324 Quad-Op Amp**

The motor in this experiment is attached to a built-in tachometer, which is really just another motor that is turned by the powered motor. The tachometer measures motor speed by producing a voltage proportional to rotational velocity (remember the back EMF term in the motor equation). The motor is connected to a relatively expensive amplifier (the motor was about $20 and the amplifier about $300) that is set up in "torque mode" which means that the amplifier takes an input voltage and passes a proportional current through the motor windings. The amplifier has an internal feedback loop that makes the current proportional to the input voltage. The resulting motor torque is proportional to the input voltage to the amplifier, independent of the motor's speed $\tau = \alpha v_i$, where α = BC , with B = the torque constant of the motor and C = calibration constant of the amplifier. Assuming that the motor drives an inertial load (i.e. the inertia of its own shaft), its dynamics are: $\tau = J\dot{\omega}$ where J is the shaft inertia. The amplifier and motor thus together implement the equation: $J\dot{\omega} = \alpha v_i$. By taking the Laplace Transform of this equation, we can find the transfer function of the amplifier/motor system: $\frac{\omega(s)}{v_i(s)} = G(s) = \frac{\alpha}{Js} = \frac{K_m}{s}$ Where K_m is a constant. Remember, the transfer function relates the input (voltage) to the output (motor speed) in the complex frequency domain. We can now use this transfer function to draw a block diagram of the feedback system:

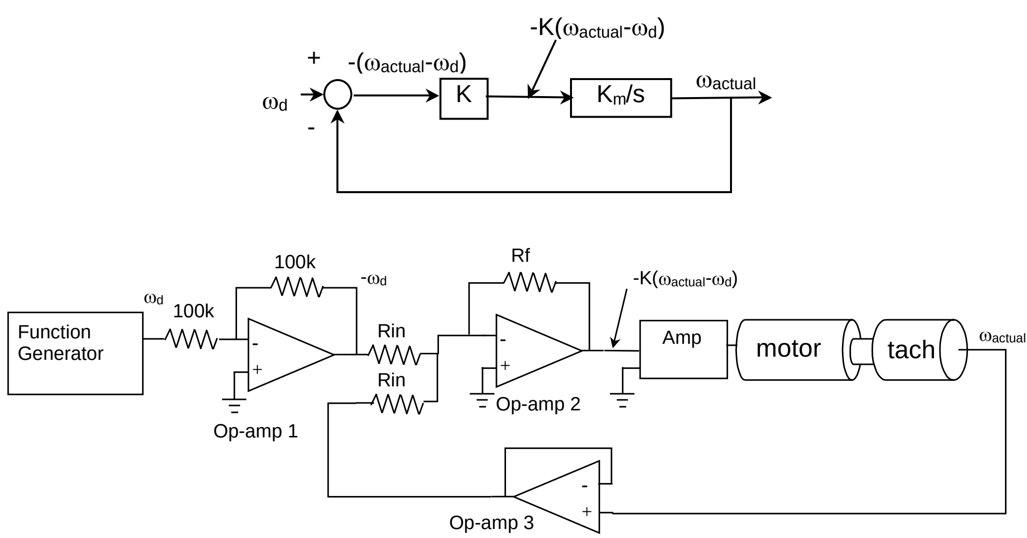


Figure 3 – Block diagram and circuit implementation of P-type velocity control

The transfer function of the *closed loop system* shown in Figure 2 is

$$\omega_{actual}(s)/\ \omega_d(s) = KK_m/(s + KK_m)$$

where ω_{actual} is the measured angular velocity of the shaft, and ω_d is the desired (or "reference") angular velocity that we input to the controller. The transfer function has the form of a first-order low-pass filter with a time constant of $\tau = 1/KK_m$

Q1 Figure 3 shows a control circuit that can implement the block diagram for the controller. The key thing to remember is that variables such as velocity and desired velocity are represented as voltages in the circuit. Describe the specific purpose of each op-amp. Find the equivalent K from the circuit diagram in terms of the resistor values. What physical features of the motor/amplifier does the K_m/s term represent? (Hint: what does a 1/s term represent in the time domain and what is K_m equal to?)

Construct the circuit in Figure 3. Copy the pin numbers for the LM324 op amp chip onto the Figure 3 diagram. *Note:* The motor/amplifier boards have room for a position sensing potentiometer to be coupled to the motor shaft: <u>you do not need this pot for this lab</u> – make sure it is not connected as you an easily break it. *Important: wire your circuit neatly! A neat circuit requires little extra time to wire, and it's easier to debug. In general, circuits take much more time to debug than they do to initially wire!*

With $R_{in} = 1K\Omega$ and $R_f = 10K\Omega$, set the function generator to pass a 2Vpp (1V amplitude) 10 Hz sine wave to the system and to the oscilloscope. Also capture the tachometer output on the scope. If all is well, the motor's velocity should follow the sine wave. If the motor doesn't turn at all, the power supply to the amplifier may not be set up to provide enough current to the motor. Make sure the current switch on the power supply is set on "high," and adjust the current knob to provide "enough" current to the motor. If the motor is running at full speed, something may be wrong with your circuit (for example, you may have implemented positive feedback instead of negative feedback). Turn off the power to the motor. Debug your circuit systematically, considering what each voltage should be. Verify that op-amp 1 is inverting and op-amp 3 is following. Verify that the output of op-amp 2 changes as you adjust ω_d with ω_{actual} constant.

Practical Exam 1: Demonstrate to the TA that your motor follows the sine wave.

Q2 Changing R_f changes the feedback gain of the system. Try to get intuition about how the gain affects system performance by experimentally determining the following information. Report the results in a table such as this:

		R_f = 10 KΩ	R_f = 1 KΩ
1	f_c		
2	$\tau = 1/\omega_c$		
3	τ		
4	e_{ss}		
5	K_m		
6	Open loop gain		

1) The "cut-off" frequency. At this frequency, the output amplitude is .707 of the input amplitude and the output waveform lags the input by 45 degrees. frequency at the -3db point (ω_{-3db}). The cutoff frequency is used by engineers to

describe when the frequency at which the control system performance starts to degrade. Sometimes this frequency is called the 3dB point. dB stands for "decibels" and is a unit commonly used by engineers to describe frequency responses. Amplitude in dB = $20\log_{10}$(amplitude). The amplitude is decreased by 3dB at the cut-off frequency, since $20\log_{10}(0.707)=-3.0$dB.

2) Compute time constant ($\tau = 1/\omega_c$) where ω_c (in rad/sec) is obtained from part 1. In other words, infer τ from the measured cut-off frequency. Memorize the fact that ω_c [in radians] = $2\pi f_c$ [in Hertz]
3) The time constant (τ) measured from the time response of the system. Display both the input square wave and output exponential response on the scope. Measure τ on the scope using the cursors.
4) The steady state error. Input 10V DC from the function generator and record the difference between the input and output voltages.
5) The predicted value of K_m (Knowing K and knowing τ you can compute what K_m ought to be).
6) The magnitude of the open loop gain of the system = $K*K_m/s$

P1 Using the Labjack, record the input voltage for the function generator (which represents the "desired motor velocity") and the output voltage from the tachometer (which is the "actual motor velocity") at three input sinusoid frequencies: $.1*\omega_c$, ω_c, and $10*\omega_c$.

Q3 Get the function generator to pass a small constant (DC) voltage to the system and try to move the motor shaft by hand. Why is it difficult to change its rotation? Power down the system and make $R_f = 1K\Omega$. Turn the system back on. Can you stop the motor from turning now? Explain the difference.

Q4 How does the system behavior change as you changed R_f in question Q3?

Q5 What do you think caused the steady state error measured above? Integral control is one way to get rid of steady state error.

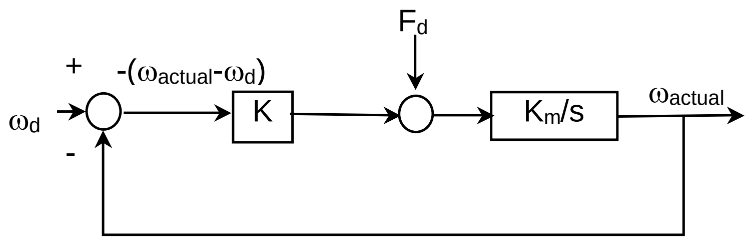
Q6 In a previous lab, you implemented a voltage controller for a motor. In this lab, you implemented a velocity controller. Explain why the two control circuits achieve the same thing (controlling velocity) if the motor load is constant. If you want to design a rotating sign that you can adjust the speed (e.g. UNOCAL 76 rotating ball), which circuit would you use? Consider the relative costs of the two circuits, and which circuit would be better for an indoor sign versus an outdoor sign where there are gusts of wind.

WRITE-UP

- due at your next laboratory session
- each student must complete his or her own write-up
- make sure to use your own words!!
- include your name and laboratory time on the write-up
- the write-up must be type-written
- Graphs for the lab write-up must be generated using Excel or Matlab, and must include labels on the axes, voltage and time scales used on the scope, and a legend for multiple-line plots.

- Page limit = 2 pages, including graphs

1. What type of filter does the motor velocity control system act like?
2. Turn in a graph for P1, overlaying the desired velocity and the actual velocity at the three input frequencies for several cycles of the input.
3. One of the major benefits of feedback is its ability to cancel the effects of unmodeled “disturbances”. Disturbances are outside influences that affect the output of the system you are trying to control, keeping it from achieving the desired behavior. In the case of the system you built, the desired behavior was for the motor to track a desired reference velocity. Sometimes you tried to prevent the shaft from rotating at the desired velocity by using your hand. The forces applied by your hand can be viewed as a disturbance F_d, and can be incorporated into the block diagram in the following way:



Derive an expression that relates ω_{actual} to ω_d and F_d. Explain why high-gain feedback (i.e. big K) was able to cancel the effects of the “hand disturbance” on the motor shaft.