ECSE 371 Lab #11
Closed-Loop PWM Motor Speed Control

Review the Bob Pease article on PID Control, as well as the other items on Canvas. Also, HH, 13.2.8 and 13.2.9. Please read the entire lab before you begin!! See Step 6 for the Saturday Schematic

STEP 1, PWM Generator:

Design, build, and test a circuit that outputs a ~15KHz PWM waveform (driving just an oscilloscope) with a duty-cycle that can be smoothly and (approximately) linearly varied from near zero to near 100% as a 0 to 10VDC control voltage is applied; your circuit will be similar to the one you used for the switching power supply in Lab 10. Operate the PWM circuit on 15V to 18V, single supply. The triangle or sawtooth waveform that you are using should have a magnitude of about 10Vpk to provide adequate noise immunity. Use a reference Zener diode, a potentiometer, and a voltage divider to provide the 0 to 10 V control voltage that is independent of the power supply voltage. You might consider the use of a local regulator (3-terminal or a zener + BJT emitter-follower)

Caution: *for the remainder of this lab, you* ***must*** *configure the bench supply for parallel operation because the motor will draw up to 10A under full load. Note that external test leads must be used to externally wire the output terminals in parallel. In this configuration, the total power supply output current will equal the* ***sum*** *of the two currents displayed on the bench supply meters; however, the output voltage will be equal to the value displayed on* ***either*** *of the voltmeters. Please must consult the power supply instructions at:*
http://engineering.case.edu/lab/circuitslab/sites/engineering.case.edu.lab.circuitslab/files/docs/HeTest_3005F-3_Power_Supply_Operation_090407.pdf

STEP 2, MOSFET stage and initial open-loop motor tests:

Add a MOSFET output power stage to the rectangular-wave output of your PWM circuit; you may use an N-channel or a P-channel. The PWM generator and the MOSFET power stage will be powered by the 15 to 18V bench supply, configured as discussed above to provide 10 A; the output of your circuit is to be used to provide a unipolar PWM voltage to the large permanent-magnet DC motor. Remember to include a 1N5819 (or equivalent) Shottky diode* across the motor to suppress the motor's inductive kick.

You will need to attach some sort of simple heat sink to your MOSFET, especially when you take measurements that last more than several seconds.

The power stage will handle very high currents and must be assembled on a soldered perforated board. See comments below.

You can load the motor (requiring it to produce more torque) by resistively loading the output of the coupled generator with a power rheostat or power resistors; the generator and load resistance comprise a *dynamometer*. Full load "FL" for this lab is when the generator load is set so that the average *<u>motor</u>* current (**not** the generator current) is about 6 ADC.

STEP 2, continued

Verify that you can **smoothly** control the speed of the motor by manually adjusting the duty-cycle of your circuit with the 0-10V control voltage. This is ***<u>open-loop</u>*** control.

STEP 2(a):

Use a current probe to view the motor and diode currents. (Carefully review the instructions when using the current probes; **only use it on insulated wires**. <u>Always verify calibration of the current probe and scope - check this with a bench supply and a simple DC measurement).</u>

If your circuit does not work <u>perfectly</u> in open loop, it will <u>never</u> work when you close the loop later in the lab. There should be no oscillation, discontinuities, or switching glitches; check carefully for smooth, linear control of motor speed, and check the current and voltage waveforms on the oscilloscope.

► Adjust the generator load resistance to produce a motor current of about 4A and a supply voltage of 15V, record the voltage and current waveforms of the motor and diode. ***Include these images in your lab report and be prepared to discuss these waveforms.***

STEP 2(b):

Obtain R_{DSon} from the data sheet for the MOSFET you are using. Estimate the worse-case MOSFET power dissipation including <u>resistive</u> and <u>switching</u> losses. (*At what operating point will worse-case MOSFET dissipation occur?*) Unless you have a large heat sink, you should avoid long-duration tests at heavy load.

► **$P_{d(max)}$ of MOSFET_____ W**

STEP 2(c):

Is the current rating of the 1N5819 adequate? You may use the "math" measurement feature of the scope to determine power dissipation, or you may simply estimate. *At what operating point will worse-case diode dissipation occur?* Be prepared to explain your answer. Must you always use a fast recovery part?

► **P_d of 1N5819_______ W**

STEP 3, Add incremental encoder:

Equip your motor with an incremental encoder to monitor RPM: Arrange an IR emitter/detector pair to sense the pattern on the edge of the 60-tooth reflective encoder disk; discrete IR emitters and detectors are available in the parts drawers. Use a small piece of perforated copper-clad board and necessary hardware to mount the emitter and detector such that they provide a usable speed signal. Remember: (A) *the angle of incidence equals the angle of reflectance"*. (B) The focal length of the emitter and detector is about 0.1". (C) with proper adjustment, you should get a relatively clean, stable sinewave of with a minimum amplitude of one or 2 Vpp. If you do not get a good signal, do not proceed until you do!!

STEP 3, continued.

Design and test a circuit that will process the detector output and provide a clean logic signal with a frequency and that is proportional to RPM. <u>Do not proceed unless you have optimized the arrangement of the optical components.</u> You should get a relatively clean signal of at least 1-2 volts peak-to-peak at the detector output, but some signal conditioning will probably still be necessary in addition to a comparator. Vary the motor speed and confirm that the sensor circuitry is working properly (please!). At 15 VDC, the no-load motor speed will be around 4000-7000 rpm. By measuring the frequency of the detector output, you can determine the motor speed; you may use the "frequency counter" function of the oscilloscope.

STEP 4, Open-loop speed regulation tests:

STEP 4(a):

Record the approximate <u>minimum RPM</u> at which he motor runs smoothly without "cogging" (@ NL):

► **Minimum speed:________RPM**

STEP 4(b):

Measure the <u>open-loop</u> **load** regulation of the motor when running on your PWM circuit (as in Step 2 above): first, operate on a 15V supply and adjust the PWM duty cycle for a NL speed of about 75% of maximum; record this NL speed. Then, keeping the duty cycle the same, run the motor at FL by loading the output of the *generator* with a rheostat or fixed resistors: Set the generator load- resistance so that the *motor* current (not the generator current) is about 6A; record this FL speed. Calculate and record load regulation. (NL to FL,

► **NL speed: __________RPM** ► **FL speed: __________RPM**

► **Open- Loop load regulation: _______%______________**

STEP 4(c):

Measure the <u>open-loop</u> **line** regulation of the motor at no load. As before, operate at 15V and adjust the PWM duty cycle for a NL speed of 75% of maximum. Record the NL speed. Next, increase the power supply voltage to 18V and again record the NL speed.

► **Low- Line speed: ___________RPM** ► **High- Line speed: __________RPM_**

► **Open- Loop line regulation: ________%______________ __________**

Note that the definition and measurement of *speed* regulation is very similar to that of *power supply* regulation.

STEP 5, F to V converter:

Design, build, and test a frequency-to-voltage converter that will provide a DC voltage proportional to RPM when driven by the output signal of your encoder. Your F-to-V converter must be active over the full expected speed range of the motor. Assume that the minimum motor speed will be about 100 RPM.

STEP 6, Close the loop and perform initial tests:

Modify your circuit to incorporate *proportional* (P) *closed-**loop*** **feedback** to regulate the speed of your motor from around 100 rpm to near-maximum (MOSFET duty cycle equals 100%). The speed of the motor (the "setpoint") will now be set by a reference voltage

provided by a potentiometer -the one that was previously used to set the control voltage. An error amplifier will compare the reference voltage (setpoint) to the RPM signal provided by your F-V converter; the error amplifier will adjust the PWM duty- cycle until the speed error is zero. Be sure to utilize the potentiometer over its full rotation so that good setpoint resolution results. You may try adding *integral* (I) control to improve performance. Don't attempt derivative control (ever).

Adjust the error- amplifier gain and other variables to optimize speed regulation as well as response time to a step change in setpoint or output torque. You can produce such a step change in torque simply by connecting and disconnecting the generator load resistor. Another figure of merit: The lower the minimum RPM, the better your circuit is working.

Be careful with the response time of your F-V converter. Your goal should be a motor control that responds quickly to changes in load or setpoint, without oscillation or excessive overshoot. Keep the response time of your F-V converter as short as seems reasonable.

If there is too much ripple in the output of the F-V converter, the motor- speed may exhibit noticeable ripple; on the other hand, if the cutoff frequency of the filter is too low, the controller may be unstable, or response time to torque and setpoint changes may be too slow.

<u>Note the following:</u>

1. The 0-10V control voltage was used in step 2 to change the duty cycle, and therefore change the speed of the motor. This was done to demonstrate open-loop control. After the circuit was converted to closed-loop operation, speed was be adjusted by changing the setpoint potentiometer, and the error amplifier varied the PWM duty-cycle until the speed error was close to zero.

2. Later in this lab, the power supply will be varied from 15 to 18V. Your F-V converter and/or other parts of your circuit must function properly over this range. However, since you are now operating **closed loop**, it should not matter if the PWM duty cycle changes as the supply voltage is varied -the error amplifier should do its job and override these changes

►Saturday: Email a preliminary schematic of your complete closed-loop circuit.◄

STEP 7: closed-loop speed regulation testing.

STEP 7(a):

Record the approximate minimum RPM at which he motor runs smoothly without "cogging" (@ NL):

► **Minimum speed:____________ RPM**

STEP 7(b):

Verify that your circuit has enough error-amplifier gain: Confirm this by running at minimum speed and stalling the motor (or trying to); the motor voltage must increase substantially. You can attempt to stall the motor by shortening the generator output or by very carefully pinching the motor shaft with your fingers. **Do not touch the encoder disc.**

► **NL Motor voltage at minimum speed: _______V**

► **Motor voltage at minimum speed setting under stall condition: _______V**

STEP 7(c):

Line regulation: Measure the change in RPM (at nominal FL and 75% of max speed) as the supply voltage is varied from 15V to 18V. Calculate and record line regulation.

► **Low Line speed: ____________RPM** ► **High Line speed: ____________RPM_**

► **Closed- Loop line regulation: ________%**

STEP 7(d):

Load regulation: Measure the change in RPM (at ~75% of max speed and Vsupply = 15V) as the load is varied from NL to FL. Calculate and record line regulation.

► **NL speed: _______________RPM** ► **FL speed: _______________ RPM**

► **Closed- Loop load regulation: ________%**

STEP 7(e):

Load Step Response: Run the motor at FL, then generate a step to NL by quickly disconnecting the rheostat from the generator. Measure the approximate time it takes for the motor to reach steady-state after the step change in load.

► **Approximate step response________________ Sec**

STEP 8:
For optimum performance, you need a speed signal that has low ripple at very low speeds (100 rpm or less, for example); therefore, your F-V converter needs an averaging filter with a long time constant. Unfortunately, with a long delay in the F-V converter, it might be difficult to stabilize the system and response time will be poor.

STEP 8, continued:
The solution is to use an F-V converter that will quickly respond to a speed change, yet still provide low ripple. You could accomplish this with an encoder disc that provides more pulses; this would permit the use of a LP filter that has a higher cut-off frequency, and faster response would result. Or you could keep the number of pulses/rev the same and you could find a way to provide a LP filter with a shorter delay. Think about using a S&H here.

Redesign your F-V converter for faster response. Then adjust your error-amplifier gain and see if the performance of your system improves.
►**Record your observations.**

For recitation, keep the circuit in Step 8 set-up and operating.

Comments:

1. GRADING: The lab will be graded according to the performance of the circuit. Performance will be determined by speed regulation, and by the ability of your circuit to quickly respond to step changes in the setpoint or in the load. The motor should rapidly and cleanly move to the new operating point, without overshoot ("underdamped") or undershoot ("overdamped"). Also, your control should work down to very low speeds (<100 RPM if possible).

2. ASSEMBLY:
This is a **high-power, fast switching-speed** circuit. Do not try to build the MOSFET section on the plug-in breadboard. Instead, Mount the MOSFET, Schottky, and gate driver on a small piece of perforated board using a compact layout with short, heavy wires. Leave a short loop of insulated wire to sense diode current using the current probe. Be careful how and where you connect the power section to the rest of the circuit, motor, and power supply. Bypass the power supply at your circuit, and at other critical places such as the error amplifier circuit and any reference voltages.

High rates of dV/dT and dI/dT can cause problems due to inductive voltage drops and induced voltages and currents. These problems can be minimized by using heavy wire and keeping wire lengths short and current loops small. Also, it is important to optimize rise and fall times: keeping them slow enough to minimize problems toto EMI, yet fast enough to reduce dissipation. Control of switching times is easy with MOFETS. Because of gate capacitance, simply raising the value of the series resistance at the gate of the MOSFET will reduce switching times.

3. Again, BEFORE USING THE SUPPLY IN PARALLEL MODE, USE BANANA LEADS TO PLACE THE POWER SUPPLY OUTPUTS IN PARALLEL!!! Failure to do this may damage the supply. Please read the instructions.

4. To load the generator (dynamometer), use power resistors in series or parallel, one of the large rheostats that are in the lab. Long-term, DO NOT EXCEED THE CURRENT RATING NOTED ON THE RHEOSTAT. The maximum generator output current will be around 8 amps.

5. In your lab report, include a complete schematic as well as the values of the parameters measured in the various steps. Also, your observations and waveforms where asked.

6. It may be helpful if, when first closing the loop, you temporarily operate your PWM and control circuit from a separate (HP?) bench supply, and the MOSFET/motor section from the dual bench supply. Isolating the power supplies may make things easier because the high motor currents will not affect the PWM generator. Naturally you will have to provide a "common" ground connection for the two supplies.

In this way you can, for example, change the motor supply only and see if the motor speed changes – without worrying about what your control circuit is doing. This can be a quick and valuable test.
Remember to not exceed the power supply current limit – even under pulse conditions!!. If the bench supply goes into current limit, it will drive you and your circuit crazy as the power supply- output voltage changes.

7. You will have a problem when operating at very low RPM. At low RPM, the F-V output will have very high ripple. This ripple will be amplified by the error amp, and speed variations will be seen at the motor. We have also found that these bench supplies (and many supplies) may have trouble with the varying peak currents; the current limit may cut in early and screw up your circuit. Therefore, I suggest you be sure to get the project completed before you spend too much time trying to get good, steady performance below 100 RPM or so.

If you stay at higher RPM, you should have no problem stabilizing the circuit – as long as you do not have noise problems, comparator glitches, etc. and your error amp gain is not too high. Also remember to keep your MOSFET rise and fall times relatively slow so as to not fill the air (and your circuit) with unnecessary EMI.

8. When the motor is running NL, you are still drawing 1-2 A. This is 10 – 20W or more, so you will feel the motors get warm. At high torque you are talking 100W or more, and this is a lot of energy. Be careful with your MOSFET temperature.

9. Regarding the "fast" F-V converter to be used in Step 8: Start thinking about it this way:

Draw a nice diagram of the output waveform of the LP filter and the encoder pulse train. Do this for a few different RC time-constants and frequencies.

Note that if the time constant is small and the frequency low, you will have a lot of ripple. However, see if you can find a way to use a sample-and hold so that you end up with a fast-responding, constant voltage that is closely proportional to the average value of the pulse train.

(You may simulate this, of course).

*We have fast-recovery and Schottky diodes in the lab. However, if you are ever in an emergency and find that you need a high-current, fast diode, you can get sneaky and use the S-D diode of a separate MOSFET; these diodes will have a current rating near that of the MOSFET drain, and will have pretty low Tr-r. This diode is often characterized on the data sheet. The diode won't have a forward voltage as low as a Schottky, but it will be pretty good. Short the gate and source together.

$$10V\sqrt{0.5} = 7.07V$$

All motors have resistance. How will the temperature of a motor respond to a PWM input? How do RPM and torque respond to a PWM input??

Additional Comments on this lab:

1. You can, of course drive the motor with a P-channel MOSFET. However, doing so requires a driver that is a little complicated. Please simplify your life and consider using an N-channel MOSFET.

2. In any case, as I have urged in the past, keep your switching speeds low. Why make life difficult? Dissipation should not be too much of a problem at 15 or 20 kHz operating frequency. Nevertheless, I suggest you change the frequency up and down by 10 kHz or more observed waveforms.

3. All DC motors have armature inductance, so don't forget the Schottky or fast recovery diode to "catch" the inductive kick. Assuming you have an N channel MOSFET with the motor (correctly) connected to the drain. This diode should prevent the drain from rising above the supply voltage when they MOSFET turns OFF. You may notice, however, that there may be a voltage spike at the drain which may exceed the rail voltage. This spike may precede ringing. How could this be possible? What you think is going on?

4. Some of you have huge capacitors in places where larger resistor values would result in smaller capacitors. Large capacitors are expensive, sometimes cannot be inserted by machine, and take up expensive real estate! Also, if you have large capacitors, the associated resistors tend to be low in value and will needlessly waste power.

5. Following the comment above, many of you use resistor values that are generally smaller than necessary. Remember that a 1K resistor in a 15 V circuit will draw 15 mA and be warm to the touch. (An op amp at the same supply voltage will only draw about 1 mA). If you have a resistor lower than a few K anywhere in a circuit, please check it over.

6. Do not forget the phototransistor has to be followed by an official frequency- to- voltage converter. You do not want a period- to-voltage converter.

7. You miss the fact that if you limit the voltage- swing at the output of a comparator you will, naturally, also limit the hysteresis provided by the positive-feedback resistor. For example, what is the output voltage swing of a comparator that is directly driving the base of a BJTs transistor?

8. I strongly suggest that you initially get your circuit working with proportional (P) control only. Optimize performance in this configuration first, and then add integer (I) control. In general, you can keep the proportional gain low to enhance stability; then you could add integral feedback to improve regulation because the integral loop will slowly drive the motor to the set point speed. Including differential (D) feedback will usually drive you and your circuit crazy.

9. Use heavy wires and be aware of wire lengths, but provide loops to measure diode and drain current!