Lab 8. Speed Control of a D.C. motor

The Motor Drive
Motor Speed Control Project

1. Generate PWM waveform
2. **Amplify the waveform to drive the motor**
3. Measure motor speed
4. Measure motor parameters
5. Control speed with a computer algorithm

![Diagram of motor speed control system](image_url)
Buehler 12 volt permanent-magnet dc motor with tachometer output

Electrical Connections

- yellow/green -- tachometer output
- blue/red -- motor winding

Note: Tachometer wires may not have two colors on some units.
Exploded view
Motor electro-mechanical models

- $R_a$ – armature winding resistance
- $L_a$ – armature winding inductance
- $i_a$ – armature current
- $V_t$ – terminal voltage
- $e_a$ – back emf
- $T_m$ – developed torque
- $T_L$ – torque needed for load
- $\omega$ – rotational speed
- $B$ – friction coefficient
- $J$ – moment of inertia
Motor Electrical Dynamics

\[ v_t = R_a \cdot i_a + L \frac{di_a}{dt} + e_a \]

\[ e_a = K \omega_m \]

\( e_a \) = “back emf” (electromotive force) generated within armature windings

Note: back emf = 0 at standstill and increases linearly with motor speed
Mechanical Dynamics Analogous to Electrical Circuits!

Equations for these systems have similar form.
Motor Mechanical Dynamics

\[ T_m = K \cdot i_a \]

\[ T_m = J \cdot \frac{d\omega}{dt} + B \cdot \omega + T_L \]

- \( T_m \) = developed torque increases with current
- \( J \) = motor moment of inertia
- \( B \) = motor friction coefficient
- \( \omega \) = angular velocity of the motor
- \( T_L \) = torque required to drive the load
Laplace Transformed Equations

- **Electrical**

\[ V_t(s) = R_a \cdot I_a(s) + L_a \cdot sI_a(s) + K \cdot \Omega(s) \]

- **Mechanical**

\[ K \cdot I_a(s) = J \cdot s\Omega(s) + B \cdot \Omega(s) + T_L(s) \]
Steady state analysis (s=0)

- **Electrical steady state**
  \[ V_t = R_a \cdot I_a + K \cdot \Omega \]

- **Mechanical steady state**
  \[ K \cdot I_a = B \cdot \Omega + T_L \]

- **Solve for speed**
  \[ \Omega = -\frac{R_a}{R_a B_m + K^2} \cdot T_L + \frac{K}{R_a B_m + K^2} \cdot V_t \]
Motor speed vs. load torque

- Speed is related to load torque and terminal voltage

\[ \Omega = \frac{R_a}{R_a B_m + K^2} \cdot T_L + \frac{K}{R_a B_m + K^2} \cdot V_t \]

Graph showing the relationship between speed (\(\Omega\)) and torque (\(T_L\)) with different loads and increasing terminal voltage (\(V_t\)). Operating points are indicated for speeds 1 and 2, and loads 1 and 2.
Transient response experiment

- Measure $V_{\text{motor}}$, $V_R$, and $V_{\text{tach}}$
- $I_{\text{motor}} = V_R$ (because $R = 1$)
Experimental results

Current reaches 1 amp during startup!
What we now know:

- For a given load, motor speed is proportional to voltage applied to its terminals.
- Use of a PWM signal allows the *average* voltage of the signal to be varied by varying duty cycle.

\[
V_{avg} = V_{digital} \left( \frac{T1}{T1+T2} \right)
\]

where:
- \( T1 \) = “ON” time
- \( T2 \) = “OFF” time

- We have a 12v dc motor (max. terminal voltage is 12v)
  - A 3 volt signal will be insufficient to produce full speed, PLUS …
  - Motor may draw *amps* of current, whereas digital chip outputs can typically supply only *milliamperes*

Idea: Use a single transistor switch to amplify the digital PWM signal to drive the motor.
Basic Transistor Switch

(ideal models)
Switching an Inductive Load
(motor winding)

- Inductor voltage-current law:
  \[ V_L(t) = L \frac{di_C}{dt} \]

- When current \( i_C \) is switched off,
  - \( \frac{di_C}{dt} \) is large and negative
  - Inductor voltage is large and negative
  - Collector voltage > \( V_{cc} \)

- \( Q \) may be destroyed!
Switching an Inductive Load
(need to protect switch Q)

- **Use anti-parallel diode** *D!!!*
  - reverse biased when Q is ON
  - gives alternate current path when Q switches OFF (when inductor voltage becomes negative)
  - protects Q
    - Collector voltage is clamped to $V_{cc} + V_{diode}$
  - a.k.a. *freewheeling* diode

![Diagram of switching an inductive load with an anti-parallel diode](image-url)
Drive design model

\[ V_{\text{high}} \]

\[ I_B \]

\[ I_{\text{load}} \]

\[ V_{BE(sat)} \]

\[ V_{CE(sat)} \]
Drive Design parameters

- Maximum load current, $I_{LOAD}$
- Transistor current gain, $h_{FE}$
- Transistor voltage $V_{BE(sat)}$ in saturation mode
- Microcontroller output voltage, $V_{high}$
Design Equations

- Requirement for base current in the ON state

\[ I_B \gg \frac{I_{LOAD}}{h_{FE}} \]

- Calculate base series resistance, \( R \)

\[ R = \frac{V_{high} - V_{BE(sat)}}{I_B} \]
EE Board variable power supply

Positive Supply
VP+ output voltage & current limit

VP+ ON

Actual VP+ Current

Waveforms Power Supply Window
Connect grounds of multiple power supplies

- **Discovery board GND**
- **External circuits**
- **external power supply option**

---

**Diagram Description**

- **External power supply**
  - +5 Vdc
  - Ground

- **USB cable**
  - +5 Vdc
  - Ground

- **EEBoard**
  - VP+
  - Ground

- **Discovery board**
  - 5V
  - 3V
  - Voltage regulator
  - $v_{DD}$
  - GND
  - $v_{SS}$

- **External circuits**
  - $v_{CC}$
  - Keypad, motor drive, ...

---

*Make these connections.*
Lab Procedure

- Verify proper PWM signal generation
- Measure ac tachometer output (yellow/green leads) at multiple non-zero speeds
- Plot motor speed vs. PWM signal duty cycle
- Repeat for several PWM signal frequencies, over a range of values
  - Find the “best” frequency (produces most linear plot)
Choice of devices

- Transistor ($Q$)
  - 2N3904 is cheap but under-rated for current
  - 2N2222 has higher current rating
  - Both may be destroyed if motor is stalled

- Diode ($D$)
  - 1N4001 is a rectifier diode: a bit slow, has large diameter leads
  - 1N4148 (or 1N914) is a switching diode: faster, but has low current rating (but is not expensive)
## 2N2222 NPN transistor data

Source: Fairchild Semiconductor

### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{CEO}$</td>
<td>Collector-emitter voltage (base open)</td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>$V_{CBO}$</td>
<td>Collector-base voltage (emitter open)</td>
<td>75</td>
<td>V</td>
</tr>
<tr>
<td>$V_{EBO}$</td>
<td>Emitter-base voltage (collector open)</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>$I_C$</td>
<td>Collector current</td>
<td>1</td>
<td>A</td>
</tr>
</tbody>
</table>

### Electrical Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>min</th>
<th>max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{FE}$</td>
<td>Dc current gain</td>
<td>$I_C = 150 \text{ mA}$, $V_{CE} = 1 \text{ V}$</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{CE(sat)}$</td>
<td>Collector-emitter saturation voltage</td>
<td>$I_C = 150 \text{ mA}$, $I_B = 15 \text{ mA}$</td>
<td></td>
<td>0.3</td>
<td>V</td>
</tr>
<tr>
<td>$V_{BE(sat)}$</td>
<td>Base-emitter saturation voltage</td>
<td>$I_C = 150 \text{ mA}$, $I_B = 15 \text{ mA}$</td>
<td>0.6</td>
<td>1.2</td>
<td>V</td>
</tr>
</tbody>
</table>
# 2N3904 NPN transistor data

Source: Fairchild Semiconductor

## Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{CEO}$</td>
<td>Collector-emitter voltage (base open)</td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>$V_{CBO}$</td>
<td>Collector-base voltage (emitter open)</td>
<td>60</td>
<td>V</td>
</tr>
<tr>
<td>$V_{EBO}$</td>
<td>Emitter-base voltage (collector open)</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>$I_C$</td>
<td>Collector current</td>
<td>200</td>
<td>mA</td>
</tr>
</tbody>
</table>

## Electrical Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>min</th>
<th>max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{FE}$</td>
<td>Dc current gain</td>
<td>$I_C = 100\ mA,\ V_{CE} = 1\ V$</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{CE(sat)}$</td>
<td>Collector-emitter saturation voltage</td>
<td>$I_C = 50\ mA,\ I_B = 5\ mA$</td>
<td></td>
<td>0.3</td>
<td>V</td>
</tr>
<tr>
<td>$V_{BE(sat)}$</td>
<td>Base-emitter saturation voltage</td>
<td>$I_C = 150\ mA,\ I_B = 5\ mA$</td>
<td></td>
<td>0.95</td>
<td>V</td>
</tr>
</tbody>
</table>
## 1N4148 switching diode data

Source: Fairchild Semiconductor

### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{RRM}$</td>
<td>Maximum repetitive reverse voltage</td>
<td>100</td>
<td>V</td>
</tr>
<tr>
<td>$I_O$</td>
<td>Average rectified forward current</td>
<td>200</td>
<td>mA</td>
</tr>
<tr>
<td>$I_F$</td>
<td>Dc forward current</td>
<td>300</td>
<td>mA</td>
</tr>
<tr>
<td>$I_C$</td>
<td>Collector current</td>
<td>200</td>
<td>mA</td>
</tr>
</tbody>
</table>

### Electrical Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>min</th>
<th>max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_F$</td>
<td>Forward voltage</td>
<td>$I_F = 100$ mA</td>
<td>1</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>$I_R$</td>
<td>Reverse leakage</td>
<td>$V_R = 20$ V</td>
<td>0.025</td>
<td></td>
<td>$\mu$A</td>
</tr>
<tr>
<td>$t_{rr}$</td>
<td>Reverse recovery time</td>
<td>$I_F = 10$ mA, $V_R = 6$ V, $I_{rr}$ = 1 mA, $R_L = 100$ ohm</td>
<td>4</td>
<td></td>
<td>ns</td>
</tr>
</tbody>
</table>