Actuation:
DC Motors; Torque and Gearing;
Encoders; Motor Control

RSS Lecture 3
Wednesday, 11 Feb 2009
Prof. Seth Teller

Today

• Three types of DC motors
  – Permanent magnet; servo; stepper (if time)
• Torque, efficiency and gearing
  – Motor “sizing” and safety
• Electronic motor control
  – Power, driver and microprocessor control
• Motor shaft “position” (angle) sensing
  – Potentiometers, optical encoders

Early DC Motors

• Orsted (1819): DC current produces a B field
• Faraday motor (1821)
  – Magnet; bowl of mercury; stiff wire attached at top
  – Run DC current through wire; it rotates about magnet
• Effect came to be known as “Lorentz force”
  – Induced force perpendicular to current direction, B field

Administrative Notes

• Friday 1pm: Communications lecture
  – Discuss: writing up your ideas for an architecture to solve final course challenge
• Monday 16 February (Presidents Day)
  – MIT Holiday; No Lecture, No Lab
• Tuesday 17 February (Virtual Monday)
  – MIT on Monday schedule; Lecture, Lab as usual
After some engineering refinement …

- Wind wire coil around armature to strengthen B field
- Mount armature on rotor; attach rotor to drive shaft
- Enclose rotor and drive shaft within stator
  - Permanent magnet or electromagnet
- Supply DC voltage and current as shown below

How does the motor keep spinning?

- Commutator (copper) and brushes (not shown)
- Blue coil is the one in contact with + terminal

Motor Power, Torque, and Efficiency

\[ P_e = V \cdot I \]

\[ P_m = T \cdot \omega \]

\[ T = F \cdot r \] is the torque; it is the tangential force \( F \) delivered at a distance \( r \) from shaft center [N m]

\( \omega \) : Angular velocity of shaft [radians / sec]

Efficiency \( e = \frac{P_m}{P_e} \)

RPM vs. Torque

- When a conductor moves within a magnetic field:
  - Current produced in conductor
  - Current is called “back-EMF”
  - Back-EMF is proportional to shaft angular velocity, and opposes current supplied by PS
  - Thus as shaft (armature) RPM increases, permanent magnet-induced current increases
  - Thus supplied current from PS decreases
  - Thus as RPM increases, torque decreases!
**Pittman GM9236S025 DC Motor (12VDC)**

**“Speed-Torque Characteristic”**

*What does this plot mean?*

*How can we interpret it?*

![Graph showing Speed vs. Torque and Current vs. Torque for a Pittman GM9236S025 DC Motor.](graph1.png)

**Load vs. RPM, Power, and Torque**

- **Increase load on the shaft**
  - RPM drops (direction on plot?)
  - Rotation-induced voltage across armature (opposing PS) decreases
  - Thus (since $V=IR$) more current will flow from the power supply
  - Thus more torque will be produced

- **Decrease load on the shaft**
  - RPM goes up (direction on plot?)
  - Rotation-induced voltage across armature (opposing PS) increases
  - Thus (since $V=IR$) less current will flow from the power supply
  - Thus less torque will be produced

- **What if you apply fixed voltage $V$?** Equilibrium “no-load” state.

![Graph showing Speed vs. Current for various loads.](graph2.png)

**Pittman GM9236S025 DC Motor**

**“Power-Torque Characteristic”**

*What info is in this plot?*

![Graph showing Power vs. Torque and Efficiency vs. Torque for a Pittman GM9236S025 DC Motor.](graph3.png)

**Motor operating regimes**

- **Continuous torque (480 oz. in. for Pittman motor)**
  - Torque that won’t overheat the motor

- **Peak torque (2585 oz. in. for Pittman motor)**
  - Momentary, intermittent or acceleration torque
  - Torque maximized at **stall** (immobilized shaft)

- **Peak output power ($T \cdot \omega$)**
  - Calls for much more than continuous torque level

- **Peak efficiency**
  - Maximum battery duration
  - But only ~10% of peak torque!
Gearing Down

- Gearbox:
  - Transmits power mechanically
  - Transforms shaft angular velocity \( \omega \) and torque \( T \) (how?)

- Gear ratio
  \[ R = \frac{\# \text{ teeth}_\text{out}}{\# \text{ teeth}_\text{in}} \]
  - So \( \omega_{\text{out}} = \omega_{\text{in}} / R \)
  - \( T_{\text{out}} = e (T_{\text{in}} \cdot R) \)

- What is \( e \)?
  - Gearbox efficiency, \( 0 < e < 1 \)

Interfacing Motor and Microprocessor

- So far, we’ve looked only at constant 12VDC
- In reality, must control motor direction and speed
- Two issues:
  - 1. PSOC alone can’t provide sufficient current
  - 2. How do we control the motor speed?
Interfacing Motor and Microprocessor

- Combine **separate power source** with control signals from microprocessor using some interface circuitry:

  ![H-bridge diagram](image)

  - This circuit is called an *H-bridge*.
    - In ORCboard, it's in an **L6205 DUAL FULL BRIDGE DRIVER**
    - Direction of motor is determined by corner-paired switch that determines direction of potential and thus current flow

H-Bridge Circuit States

- **Open**
  - No voltage applied across motor M

- **Forward**
  - $V_{in}$ applied

- **Reverse**
  - $V_{in}$ applied

PWM: Pulse Width Modulation

- Apply motor voltage as *square wave* at *fixed frequency* (from 60Hz to 50KHz; Orc uses ~16KHz)
- Control motor speed/power by changing the *duty cycle* (or *pulse width*) of voltage signal
  - At 0% duty cycle, motor is off
  - At 100%, full power
  - At 50%, half power etc.
- Effectively produces a *time-averaged* voltage signal
- Inductive load of motor smoothes input signal in coils
- ... But how do we know at what value to set the pulse width?

Shaft Encoders

- Report motor shaft speed (easy) or position (harder)
- Codewheel: Circular disk mounted on motor shaft with many alternating black and white regions
- Optical sensor reads / emits codewheel region transitions
- Counting the pulses produced in any time interval yields *change* in shaft angle (how to compute distance traveled?)
- This is basic *odometry* used for control & “dead reckoning,” or estimation of position relative to some starting point

Clark and Owings

Wikipedia

Agilent
Servomechanisms (servo motors, servos)

- DC motor in an integrated package with 3 extra elements:
  - Gearbox between motor shaft and output shaft
    - Provides low-speed, high-torque output
  - Feedback-based position control circuit (pulse-width control)
    - Drives servo to commanded "position" (shaft angle)
    - Shaft angle sensing (potentiometer)
    - Current sense for torque sensing
  - Limit stops on output shaft
    - These mechanically delimit servo’s minimum & maximum “position”

Stepper Motor (Example: 90-degree bipolar)

- Stator: even N coils arrayed around rotor symmetry axis (out of plane of page)
  - Controller does commutation: Energizes coils in rotational sequence; rotor swings into alignment to successive states
  - When the coil is kept energized, motor produces “holding torque”

- Rotor: permanent magnet(s) mounted on output drive shaft
  - Adv: holding torque, speed and position control without using encoders or feedback
  - Angular resolutions of < 1deg are available!
  - Brushless!

Comparison of Motor Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Pluses:</th>
<th>Minuses:</th>
<th>Best For:</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Motor</td>
<td>Common Wide variety of sizes Most powerful Easy to interface Must for large robots</td>
<td>Too fast (needs gearbox) High current (usually) Expensive PWM is complex</td>
<td>Large robots</td>
</tr>
<tr>
<td>Hobby Servo</td>
<td>All in one package Variety; cheap; easy to mount and interface Medium power required</td>
<td>Low weight capability Little speed control</td>
<td>Small, legged robots</td>
</tr>
<tr>
<td>Stepper Motor</td>
<td>Precise speed control Great variety Good indoor robot speed Cheap, easy to interface</td>
<td>Heavy for output power High current Bulky / harder to mount Low weight capability, low power Complex to control</td>
<td>Line followers, maze solvers</td>
</tr>
</tbody>
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Supplementary Reading

- Theoretical
  - Foundations of Electric Power, J.R. Cogdell
  - Electric Motors and their Controls: An Introduction, Tak Kenjo

- Practical
  - Building Robot Drive Trains, D. Clark and M. Owings
  - Mobile Robots: Inspiration to Implementation, J.L. Jones, B. Seiger, A.M. Flynn