Electric Motors

6.141 / RSS Lecture 3
Wednesday, 12 Feb 2014
Prof. Seth Teller

Today

• DC (permanent magnet) motors
  – Basic principles
  – Characterization
  – Sensing rotation with encoders
  – Choosing one that’s adequate (“sizing”)
  – Gears
  – Electronic support for control
• Servo Motors
• Stepper Motors - time permitting
Basic Principles

- **Orsted (1819):** DC current produces a magnetic 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.

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**DC motor (based upon Lorentz force):**

- **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.
Completing a rotation

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

Motor Power, Torque, and Efficiency

\[ P_e : \text{Supplied Electrical Power, in watts [J/s]} \]
\[ P_e = \] 

\[ P_m : \text{Output Mechanical Power} \]
\[ P_m = \] 

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

\[ \omega : \] 

Efficiency \( e = ? \)
Back-EMF

• When a conductor moves within a static magnetic field:
  – Current is 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) angular velocity increases, rotation-induced current increases
  – Thus supplied current from PS decreases
  – Thus as ω increases, torque decreases!

Pittman GM9236S025 DC Motor (12VDC)

“Speed-Torque Characteristic at 12VDC”

What does this plot mean?

How can we interpret it?
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 increases (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 happens under **no load**?

Pittman GM9236S025 DC Motor

“Power-Torque Characteristic”

What info is in this plot?
**Motor operating regimes**

- **Continuous torque (480 oz. in. for Pittman motor)**
  -...
- **Peak torque (2585 oz. in. for Pittman motor)**
  - Momentary, intermittent or acceleration torque
  - Torque maximized at

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**Example motor datasheet (detail)**

**GM9236S025**

Lo-Cog® DC Servo Gearmotor

<table>
<thead>
<tr>
<th>Assembly Data</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-Load Speed</td>
<td>$\omega_{n}$</td>
<td>rpm</td>
<td>71 (7.1)</td>
</tr>
<tr>
<td>Continuous Torque</td>
<td>$T_{c}$</td>
<td>oz.in. (Nm)</td>
<td>480</td>
</tr>
<tr>
<td>Peak Torque (Stall)</td>
<td>$T_{pm}$</td>
<td>oz.in. (Nm)</td>
<td>2500</td>
</tr>
<tr>
<td>Weight</td>
<td>$W_{m}$</td>
<td>oz. (g)</td>
<td>25.7</td>
</tr>
</tbody>
</table>

**Motor Data**

| Torque Constant | $K_{e}$ | Nm/rad (N.m/°) | 2.75 | (2.05E-02) |
| Back EMF Constant | $K_{f}$ | V/rpm (V/min) | 2.40 | (2.05E-02) |
| Resistance | $R_{e}$ | Ω | 0.71 |
| Inductance | $L$ | H | 0.05 |
| No Load Current | $I_{o}$ | A | 0.23 |
| Peak Current (Stall) | $I_{pm}$ | A | 16.9 |
| Motor Constant | $K_{m}$ | oz.in./A (Nm/A) | 1.11 | (2.00E-02) |
| Friction Torque | $T_{f}$ | oz.in. (Nm) | 0.09 | (5.5E-03) |
| Motor Inertia | $J_{m}$ | oz.in/s² (kg.m²) | 1.0E-03 | (7.1E-06) |
| Electrical Time Constant | $\tau_{e}$ | ms | 1.05 |
| Mechanical Time Constant | $\tau_{m}$ | ms | 8.5 |
| Viscous Damping | $b$ | oz.in/degree (Nm.s) | 0.053 | (5.6E-06) |
| Damping Constant | $K_{d}$ | oz.in/degree (Nm.s) | 12.6 | (8.6E-04) |
| Maximum Operating Temperature | $T_{max}$ | °F (°C) | 211 | (110) |
| Thermal Impedance | $R_{t}$ | °F/°C | 64.3 | (18.9) |
| Thermal Time Constant | $\tau_{t}$ | min | 51.5 |

**Creation Data**

| Production Ratio | | |
| Efficiency | 65.5 |
| Efficiency | 0.80 |
| Maximum Allowable Torque | oz.in. (Nm) | 540 | (3.7E-01) |

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Gearing Down

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

- Gear ratio
  $R = \frac{\text{# teeth}_{\text{out}}}{\text{# teeth}_{\text{in}}}$

  $\omega_{\text{out}} = \frac{\omega_{\text{in}}}{R}$

  $T_{\text{out}} = e \cdot (T_{\text{in}} \cdot R)$

  $e$ is the gearbox efficiency, $0 < e < 1$

  What is $1-e$ portion?
  - Heat (friction, deformation), sound

Motor Sizing Example

- Robot's task: climb ramp of inclination $\theta = \pi/6$ at constant velocity $v = 1 \text{ in/sec}$

- How much torque must each wheel motor deliver? (Current, power needed?)

- What else do you need to know?

  $F_t = w \sin \theta$ (tangential component)

  Equate power terms:
  $F_t v = 2T \omega \theta v$

  Since $v = \omega r$

  Then $F_t \omega r = 2T \omega$

  So that
  $T = \frac{F_t r}{2}$

  $\omega = \frac{w \sin \theta}{0.5(2.5 \text{ in})} = \frac{25 \text{ lb.} \times 0.5 \times 2.5 \text{ in}}{2} = 15.625 \text{ lb.-in.} = 250 \text{ oz.-in.}$

  Current (from datasheet) = ~2 A

  Power = $I \times V = 2 \text{A} \times 12 \text{V} = \approx 25 \text{ W}$
Microprocessor Control of DC Motor

- So far, we’ve seen only constant +12V DC
- In practice, we control motor direction and speed by modulating sign and time average of voltage
- Motor direction
- Motor speed

Controlling Motor Direction

- This circuit is called an H-Bridge.
  - In uORC, it’s an L6205 DUAL FULL BRIDGE DRIVER
  - Motor direction 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 left to right across M

• Reverse
  – $V_{in}$ applied right to left across M

PWM: Pulse Width Modulation

• Apply motor voltage as a 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 smothes input signal in coils

• Duty cycle: Laptop sends 8-bit value (0..255) to $\mu$ORC PSOC

Wikipedia

Clark and Owings
Sensing: Motor Shaft Encoders

- Report motor shaft speed (easy) or position (harder)
- Codewheel: Circular disk with alternating black and white regions, mounted on motor shaft
  - Optical sensor detects 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 pose relative to some starting point

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

Clark and Owings, p. 29
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

Recap and What’s Next

Today:
• Some practical aspects of DC motors
  – Operation, sizing, applications
In Lab:
• Continued work on Lab 2
Forum (this Friday):
• Expectations for briefings, collaboration
Next Lecture (Tuesday at 1pm – virtual Monday):
• Cameras and low-level vision