Design with Electric Motors: Analysis and Selection

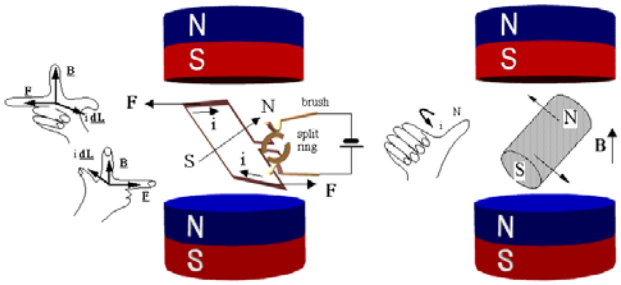
24-370 - Spring 2011
Professor Steve Collins

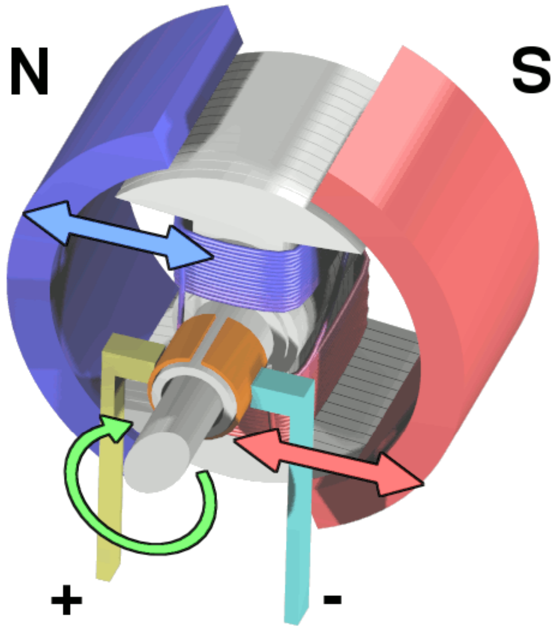
Reminders and Announcements

- Project 2 testing Monday
  - Silly hat competition… continues :D
  - Robotic arm and wrist available in ME Shop
  - Saturday ME shop hours: 9:00 - 3:00
  - Reimbursement forms now online (Item 6)
  - Quick Project 2 questions?

What are Electric Motors?

- Electromechanical devices that transform between electrical and mechanical domains
  - For instance, from current to torque
  - Based on electromagnetism, i.e. magnetic fields





Types of Electric Motors

- DC motors
  - Commonly used in robotics applications
  - Variable speed and torque
  - Permanent magnets (usually)
  - Variants: brushless (electronic commutation), coreless (lighter rotor),
- AC motors
  - Commonly used for high power applications
  - Constant (high) speed, poor low-speed pos control
  - Magnetic field typically induced in rotor (induction)

Other mech power sources vs. motors

- Gasoline engines
  - Higher fuel energy density ($5 \cdot 10^7$ vs. $5 \cdot 10^5$ $J \cdot kg^{-1}$)
  - Lower efficiency (~25% vs. ~75%)
  - More noise, local pollution, minimum (stall) speed
- Gas turbines and jet engines
  - Similar to gasoline engines, but efficiency ~40%
- Nuclear reactors
  - Very high fuel energy density ($3 \cdot 10^{12}$ $J \cdot kg^{-1}$)
  - Lower efficiency: ~40%
  - Generally steam-based, radiation issues

Other mech power sources vs. motors

- Mammalian muscle tissue
  - Higher fuel energy density ($4 \cdot 10^7$ vs. $5 \cdot 10^5$ $J \cdot kg^{-1}$)
  - Lower efficiency (~25% vs. ~75%)
  - Equally quiet, low pollution, low speeds
  - Self-healing vs. gradually deteriorating

Design with Electric Motors

- Selection, rather than continuum design
  - Discrete set of options available by catalog
- Highly dependent on mechanical usage
  - Torque, speed, power
  - Efficiency
- Simultaneously choose gear box
- Many types available
  - We will primarily consider DC motors (brushed)

Mechanical uses of electric motors

- Provide mechanical input to system
- Open-loop drives:
  - Self-regulated by electrical or mechanical reactions
  - e.g. Project 2 drive shaft
- Closed-loop control of current:
  - Regulation of voltage to achieve desired current
  - e.g. electric car
- Closed-loop control of mechanical output:
  - Automatic control of current
  - Feedback control of output torque, velocity, or position
  - e.g. robotics applications

Simple models of motor function

- Isolated torque production
  - Neglect speed and inertial effects
- Maximum drive speed
  - Neglect external loads
- Maximum power production
  - Best combination of speed and torque
- Maximum control bandwidth
  - Account for speed, torque, and inertial effects

Key properties of electric gear motors

- Peak torque
  - Peak current, i_{max}, motor torque constant, K_τ
- Maximum speed
  - Rated voltage, V, motor voltage constant, K_V
- Maximum power
  - Optimal combination of torque and speed (rated)
- Dynamic response (time constant, bandwidth)
  - Torque, speed, inertia, and load
- Efficiency
  - Gearbox, backdrivability
- Mass

General mathematical motor model

- Derive from basic familiar equations:
  - Newton's second law: $\Sigma\tau = J\cdot\alpha$
  - Ohm & Faraday: $V = i\cdot R + L\cdot di/dt$
- And two new ones:
  - Motor torque equation: $\tau_m = K_\tau\cdot i$
  - Back EMF equation: $V_{BEMF} = K_V\cdot\omega$
- Coupled equations for motor dynamics:
  - $V = i\cdot R + L\cdot di/dt + K_V\cdot\omega$
  - $K_\tau\cdot i - \tau_a - b\cdot\omega = J\cdot\alpha$

Simplified torque analysis

- Simplifying assumptions:
  - Velocity is zero → no back EMF, no damping
  - No inductance, or steady state current
- Implications:
  - $i = V/R$ = maximum (stall) current
  - $\tau_m = K_\tau \cdot V/R = \tau_{stall}$ maximum (stall) torque
- How might we apply to the design process?
  - Max applied torque, τ_a, implies min τ_{stall}
- Gearbox torque losses
  - Gearbox inefficiency presents as friction torque loss

Simplified velocity analysis

- Simplifying assumptions
  - Applied torque is zero → no external resistance
  - Steady-state current → no inductance effects
  - Neglect damping
- Implications
  - ω increases until reaching V/K_v, driving i to 0
  - No current, no torque ($K_\tau \cdot i$), so acceleration is 0
  - $\omega \approx V/K_v \approx$ maximum (no-load) motor speed
- Application to design process?
  - Max output speed must be less than no-load speed

Simplified power analysis

- Relate max power, torque, and speed?
  - Not the product of max torque and max speed
- Simplifying assumptions
  - Constant current or no inductance
  - Constant optimal (nominal) speed and torque
  - Power = torque times velocity, or $P_{max} \approx \tau_{m\_nom} \cdot \omega_{nom}$
- Implications for design
  - Constraint on minimum motor power
  - Optimal gear ratio for motor and application
  - Include losses in gearbox

Efficiency analysis

- Efficiency, η = energy out / energy in, $0 \leq \eta \leq 1$
- Typically applied to a single conversion
  - Electromechanical: work / electrical energy
  - Mechanical: work out / work in
- For typical DC motors, $\eta \approx 0.9$
  - Additional gearbox term of 0.4-0.8 (from torque)
  - Where does energy go?
- Gross efficiency might also include:
  - Battery efficiency: operational energy / charge
  - Power plant efficiency: electrical / chemical

Dynamic analysis

- Dynamic response → full equations of motion
- Implications:
  - Basic properties (R, L, K_τ, K_v) all contribute
  - Partially captured by mechanical time constant
  - External loads, i.e. V_a, τ_a, contribute
- Implications for mechanical design
  - Dynamic motor evaluation needed
- Matlab example
  - See next lecture notes (ran out of time)