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

RSS Lecture 3

Wednesday, 11 Feb 2009

Prof. Seth Teller

RSS I (6.141J / 16.405J) S09

Administrative Notes

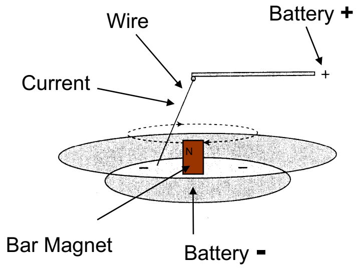
- Friday 1pm: Communications lecture
  - Discuss: writing up your ideas for an architecture to solve final course challenge
- Monday 16 February (Presidents Day)
  - MIT Holiday; **No Lecture, No Lab**
- Tuesday 17 February (Virtual Monday)
  - MIT on Monday schedule; Lecture, Lab as usual

Today

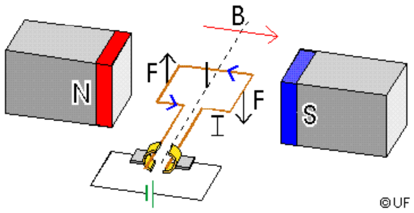
- Three types of DC motors
  - Permanent magnet; servo; stepper (if time)
- Torque, efficiency and gearing
  - Motor “sizing” and safety
- Electronic motor control
  - Power, driver and microprocessor control
- Motor shaft “position” (angle) sensing
  - Potentiometers, optical encoders

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



Faraday Motor

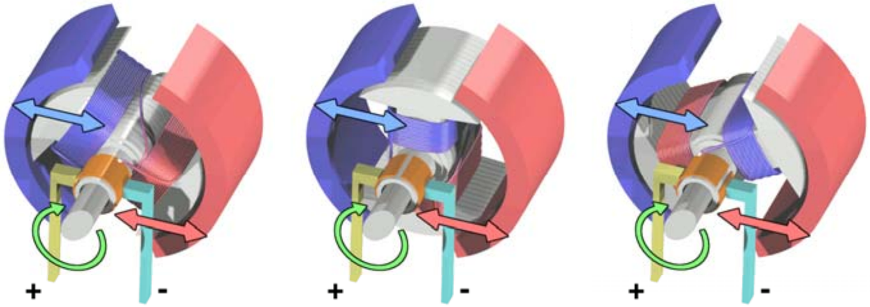


UF Phys. 3054

Lorentz Force

After some engineering refinement …

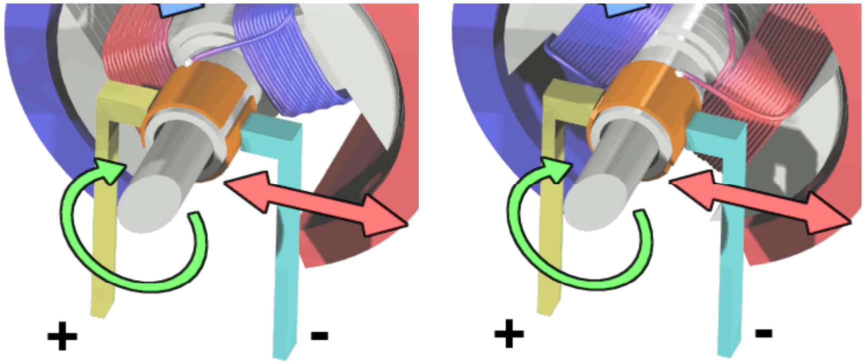
- Wind wire *coil* around *armature* to strengthen B field
- Mount armature on *rotor;* attach rotor to *drive shaft*
- Enclose rotor and drive shaft within *stator*
  - Permanent magnet or electromagnet
- Supply DC *voltage* and *current* as shown below



Wikipedia

How does the motor keep spinning?

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

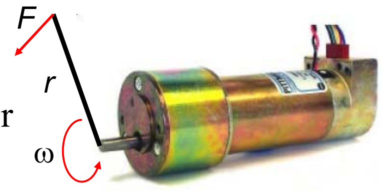


Wikipedia

Motor Power, Torque, and Efficiency

P_e : Supplied Electrical Power, in watts [J / s]

$P_e = V \bullet I$



P_m : Output Mechanical Power

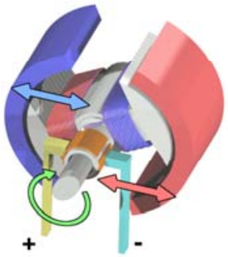
$P_m = T \bullet \omega$

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

ω : Angular velocity of shaft [radians / sec]

Efficiency e = ? P_m / P_e

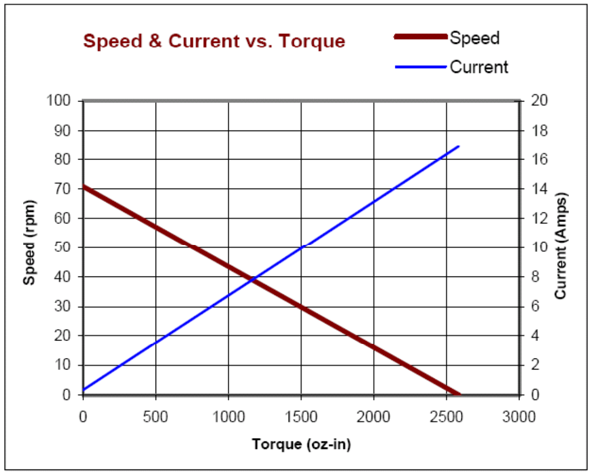
RPM vs. Torque



- 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"



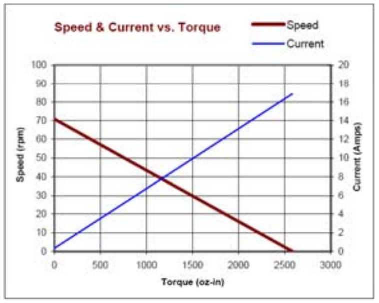
Pittman

What does this plot mean?

How can we interpret it?

Load vs. RPM, Power, and Torque

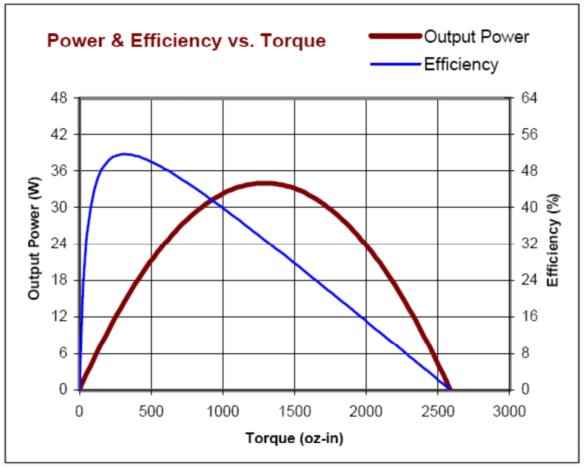
- **Increase load** on the shaft
  - RPM drops (direction on plot?)
  - Rotation-induced voltage across armature (opposing PS) decreases
  - Thus (since V=IR) **more** current will flow from the power supply
  - Thus **more torque** will be produced
- **Decrease load** on the shaft
  - RPM goes up (direction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



(Details depend on the motor geometry, materials, # of windings, supply voltage)

Pittman GM9236S025 DC Motor

"Power-Torque Characteristic"

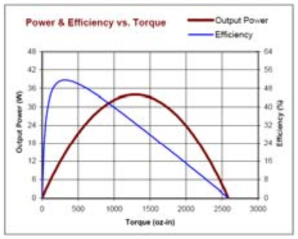


Pittman

What info is in this plot?

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!



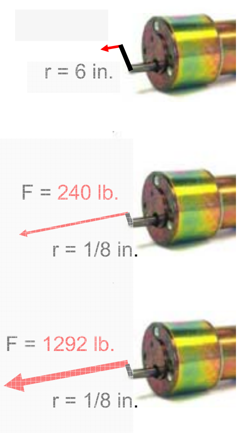
Example motor datasheet (detail)

GM9236S025

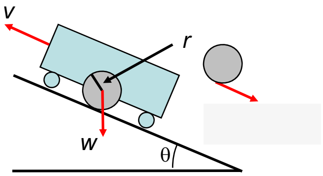
Lo-Cog® DC Servo Gearmotor

Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	12	
No-Load Speed	S_{NL}	rpm (rad/s)	71	(7.4)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	480	(3.4E+00)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	2585	(1.8E+01)
Weight	W_M	oz (g)	23.7	(671)
Motor Data				
Torque Constant	K_T	oz-in/A (N-m/A)	3.25	(2.29E-02)
Back-EMF Constant	K_E	V/krpm (V/rad/s)	2.40	(2.29E-02)
Resistance	R_T	Ω	0.71	
Inductance	L	mH	0.66	
No-Load Current	I_{NL}	A	0.33	
Peak Current (Stall)[2]	I_P	A	16.9	
Motor Constant	K_M	oz-in/√W (N-m/√W)	4.11	(2.90E-02)
Friction Torque	T_F	oz-in (N-m)	0.80	(5.6E-03)
Rotor Inertia	J_M	oz-in-s^2 (kg-m^2)	1.0E-03	(7.1E-06)
Electrical Time Constant	τ_E	ms	1.06	
Mechanical Time Constant	τ_M	ms	8.5	
Viscous Damping	D	oz-in/krpm (N-m-s)	0.053	(3.5E-06)
Damping Constant	K_D	oz-in/krpm (N-m-s)	12.5	(8.5E-04)
Maximum Winding Temperature	θ_{MAX}	°F (°C)	311	(155)
Thermal Impedance	R_{TH}	°F/watt (°C/watt)	56.3	(13.5)
Thermal Time Constant	τ_{TH}	min	13.5	
Gearbox Data				
Reduction Ratio			65.5	
Efficiency[3]			0.80	
Maximum Allowable Torque		oz-in (N-m)	500	(3.53)

Pittman



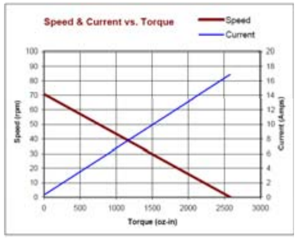
Motor Sizing Example



- Robot's task: climb ramp of inclination $\theta = \pi/6$ at constant velocity v = 1 in/sec
- How much *torque* must each wheel motor deliver? (*Current, power needed?)*
- What else do you need to know?
  - Weight w = *~25 lbs;*
  - Wheel radius r = ~2.5 in.
- $\mathbf{F_t} = w \sin \theta$ (tangential component)
- Equate power terms: $\mathbf{F_t}\, v = 2\, T\, \omega$
- Since $v = \omega\, r$
- Then $\mathbf{F_t}\, \omega\, r = 2\, T\, \omega$
- So that $T = \mathbf{F_t}\, r / 2$

  $= w \sin \theta\, r / 2$

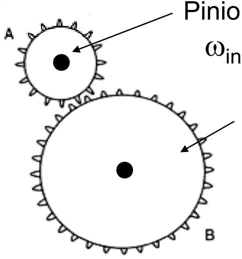
  $= (25 \text{ lb.})(0.5)(2.5 \text{ in}) / 2$
- Convert units: = 15.625 lb.-in. = **250 oz**
- Current (from datasheet) = ~**2 A**; Power =



Gearing Down

- Gearbox:
  - Transmits power mechanically
  - Transforms shaft angular velocity ω and torque T (how?)
- Gear ratio

  R = # teeth_{out} / # teeth_{in}
- So $\omega_{out} = \omega_{in} / R$
- $T_{out} = e\,(T_{in} \cdot R)$
- What is e ?
  - Gearbox efficiency, 0 < e < 1



Pinion **A** (driver):
ω_{in}, T_{in}

Wheel **B** (follower):
ω_{out}, T_{out}

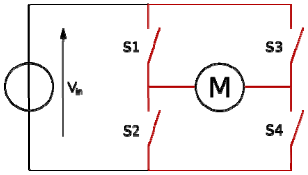
- Where does (1-e) part go?
  - Heat (friction, deformation), sound

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:



- 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

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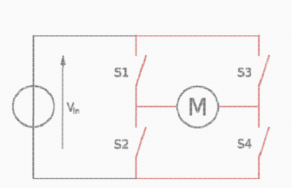
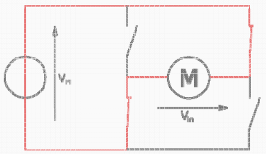
H-Bridge Circuit States

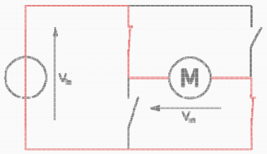
- Open
  - No voltage applied across motor M



- Forward
  - V_{in} applied



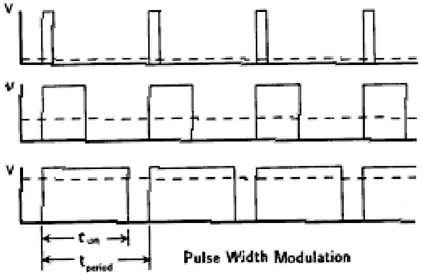
- Reverse
  - V_{in} applied



Wikipedia

PWM: Pulse Width Modulation

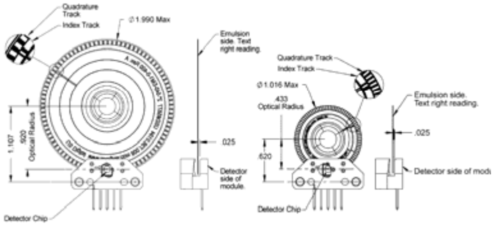
- Apply motor voltage as *square wave* at *fixed* frequency (from 60Hz to 50KHz; Orc uses ~16KHz)
- Control motor speed/power by changing the *duty cycle* (or *pulse width*) of voltage signal
  - At 0% duty cycle, motor is off
  - At 100%, full power
  - At 50%, half power etc.
- Effectively produces 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?

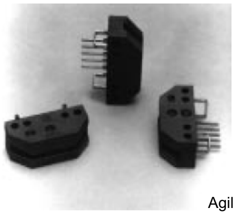


Clark and Owings

Shaft Encoders

- Report motor shaft speed (easy) or position (harder)
- Codewheel: Circular disk mounted on motor shaft with many alternating black and white regions





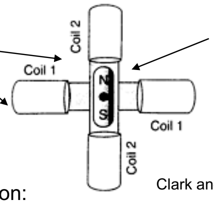
Agilent

- 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

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)



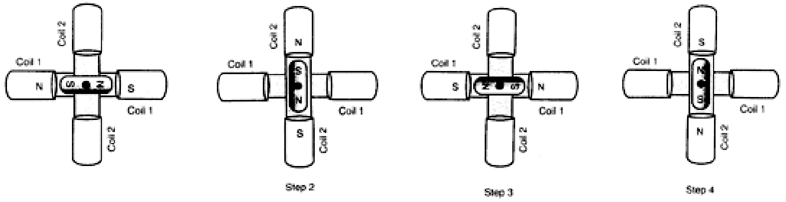
Stator: even N coils arrayed around rotor symmetry axis (out of plane of page)

Rotor: permanent magnet(s) mounted on output drive shaft

Clark and Owings

- 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"

- Adv: holding torque, speed and position control without using encoders or feedback
- Angular resolutions of < 1deg are available!
- Brushless!



Comparison of Motor Types

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

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