Electric Motors

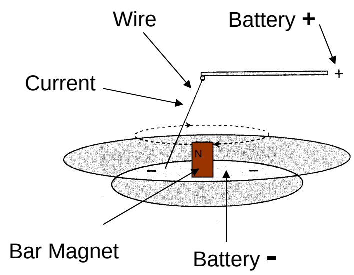
6.141 / RSS Lecture 3
Wednesday, 12 Feb 2014
Prof. Seth Teller

Today

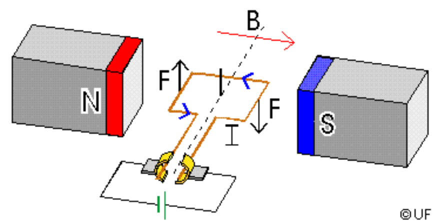
- DC (permanent magnet) motors
  - Basic principles
  - Characterization
  - Sensing rotation with encoders
  - Choosing one that's adequate ("sizing")
  - Gears
  - Electronic support for control
- Servo Motors
- Stepper Motors - time permitting

Basic Principles

- Orsted : DC current produces a
- Faraday motor (.)
  - 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



Faraday Motor

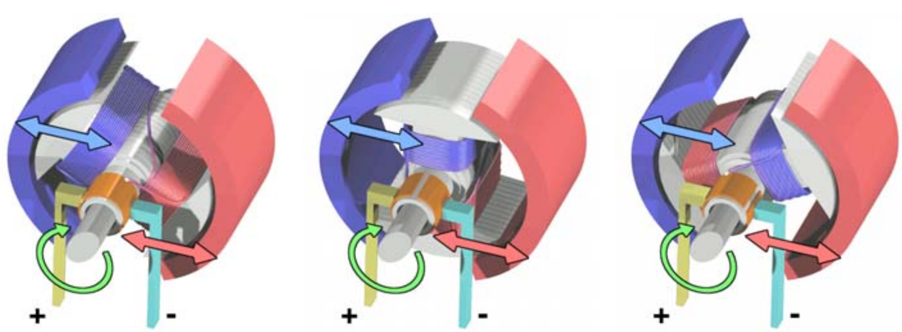


UF Phys. 3054

Lorentz Force

DC motor (based upon Lorentz force)

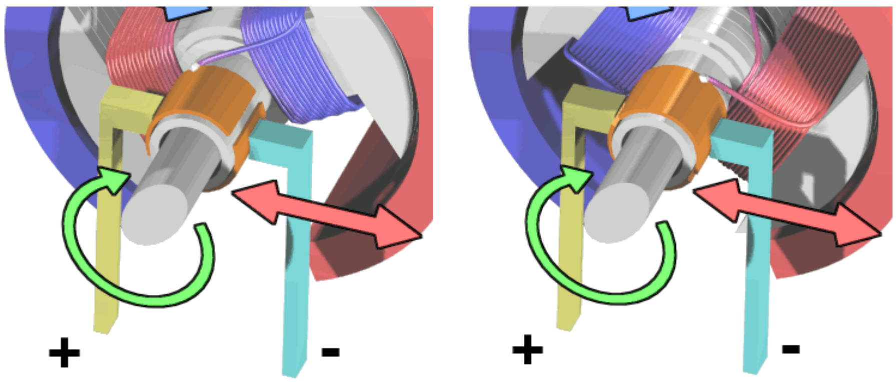
- Wind wire *coil* around *armature* to strengthen B field
- Mount armature on *rotor;* attach rotor to *drive shaft*
- Enclose rotor and drive shaft within *stator*
  - Permanent magnet or electromagnet
- Supply DC *voltage* and *current* as shown below



Wikipedia

Completing a rotation

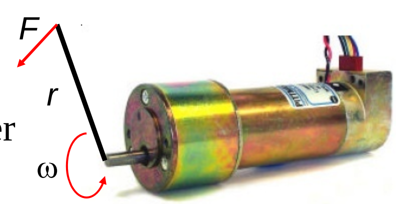
- Reverse current direction
- Commutator (copper) and brushes (not shown)
- Blue coil is the one in contact with **+** terminal



Motor Power, Torque, and Efficiency

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

$P_e =$



P_m : Output Mechanical Power

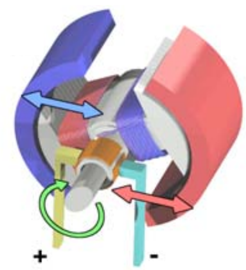
$P_m =$

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

ω :

Efficiency e = ?

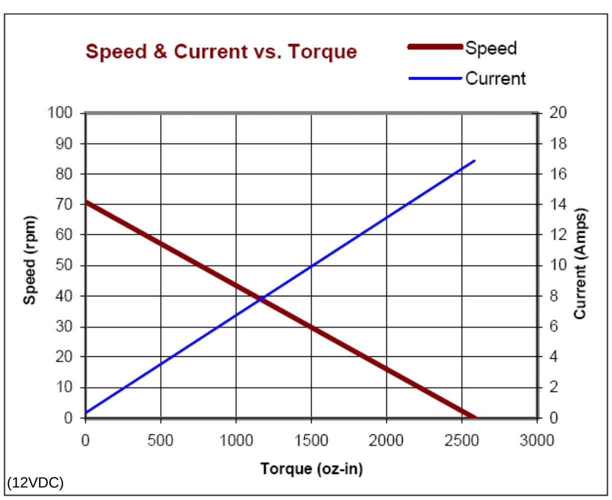
Back-EMF



- When a conductor moves within a static magnetic field:
  - Current is produced in conductor
  - Current is called "back-EMF"
  - Back-EMF is to shaft angular velocity, and current supplied by PS
  - Thus as shaft (armature) angular velocity increases, rotation-induced current
  - Thus supplied current from PS
  - Thus as ω increases, torque

Pittman GM9236S025 DC Motor (12VDC)

"Speed-Torque Characteristic at 12VDC"



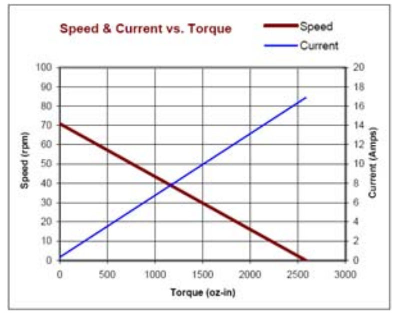
Pittman

What does this plot mean?

How can we interpret it?

Load vs. RPM, Power, and Torque

- **Increase load** on the shaft
  -
  -
  -
  -

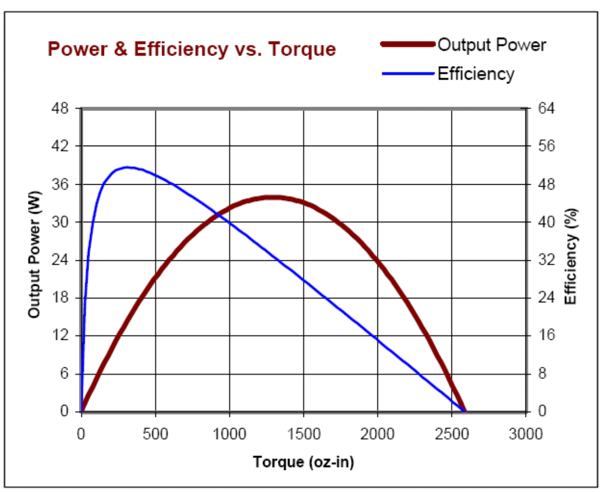


(Details depend on the motor geometry, materials, # of windings, supply voltage)

- **Decrease load** on the shaft
  -
  -
  -
  -
- What happens under **no load**?

Pittman GM9236S025 DC Motor

"Power-Torque Characteristic"

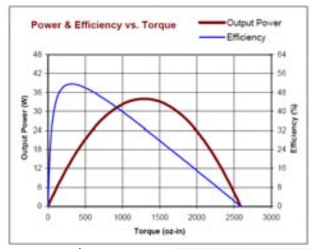


Pittman

What info is in this plot?

Motor operating regimes

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



Continuous torque

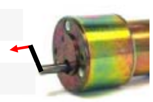
Example motor datasheet (detail)

GM9236S025

Lo-Cog® DC Servo Gearmotor

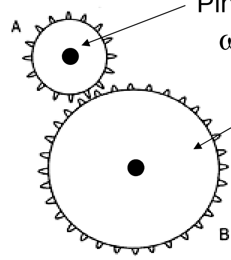
Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	12	
No-Load Speed	S_{NL}	rpm (rad/s)	71	(7.4)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	480	(3.4E+00)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	2585	(1.8E+01)
Weight	W_M	oz (g)	23.7	(671)
Motor Data				
Torque Constant	K_T	oz-in/A (N-m/A)	3.25	(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



Gearing Down

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



Pinion **A** (driver): ω_{in}, T_{in}

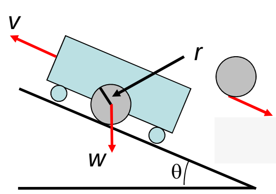
Wheel **B** (follower): ω_{out}, T_{out}

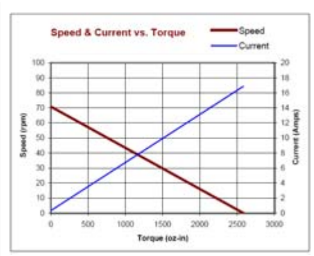
- Gear ratio

  R = # teeth_{out} **/** # teeth_{in}

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?

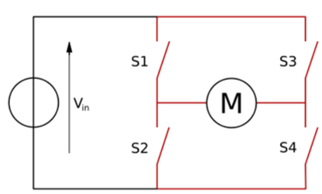




Microprocessor Control of DC Motor

- 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
  – 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

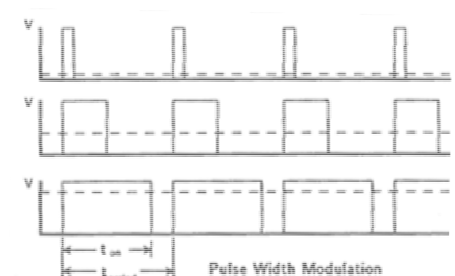
H-Bridge Circuit States

- Open
  - No voltage applied across motor M
- Forward
  - V_{in} applied
- Reverse
  - V_{in} applied

Wikipedia

PWM: Pulse Width Modulation

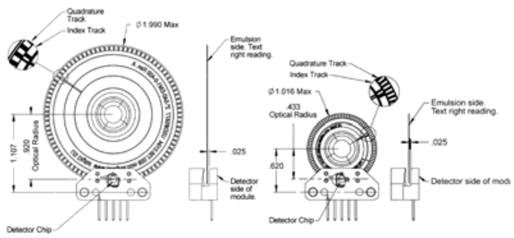
- Apply motor voltage as a *square wave* at *fixed* frequency (from 60Hz to 50KHz; Orc uses ~16KHz)
- Control motor speed/power by changing the *duty cycle* (or *pulse width*) of voltage signal
  - At 0% duty cycle, motor is off
  - At 100%, full power
  - At 50%, half power etc.
- Effectively produces a *time-averaged* voltage signal
- Inductive load of motor smoothes input signal in coils
- Duty cycle: Laptop sends 8-bit value (0..255) to μORC PSOC

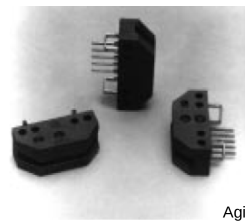


Clark and Owings

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





Agilent

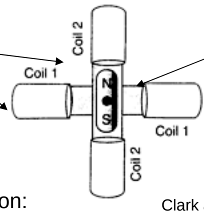
- Optical sensor detects codewheel region transitions
- Counting the pulses produced in any time interval yields *change* in shaft angle (how to compute distance traveled?)
- This is basic *odometry* used for control & “dead reckoning,” or estimation of *pose* relative to some starting point

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)

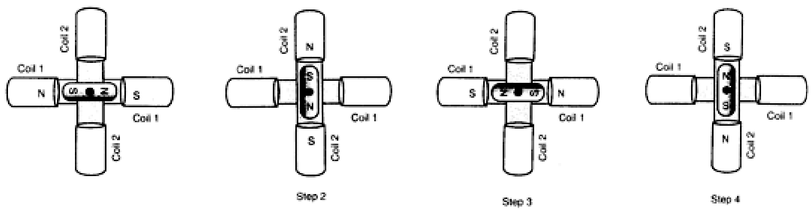


Rotor: permanent magnet(s) mounted on output drive shaft

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

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