UNIVERSITY·OF·MASSACHUSETTS·1863

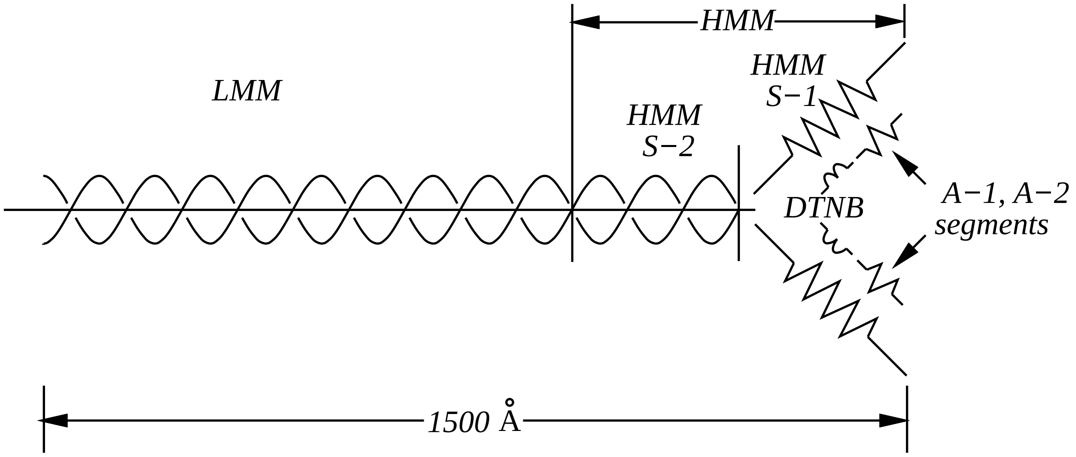
Actuators

...physical devices that transform electrical, chemical, or thermal energy into mechanical energy...

- muscle

- electric
  - stepper motors
  - permanent magnet DC motors
- hydraulic
- pneumatic
- artificial muscles
  - shape memory alloys
  - polymers
  - protein-based actuators
  - bucky tubes

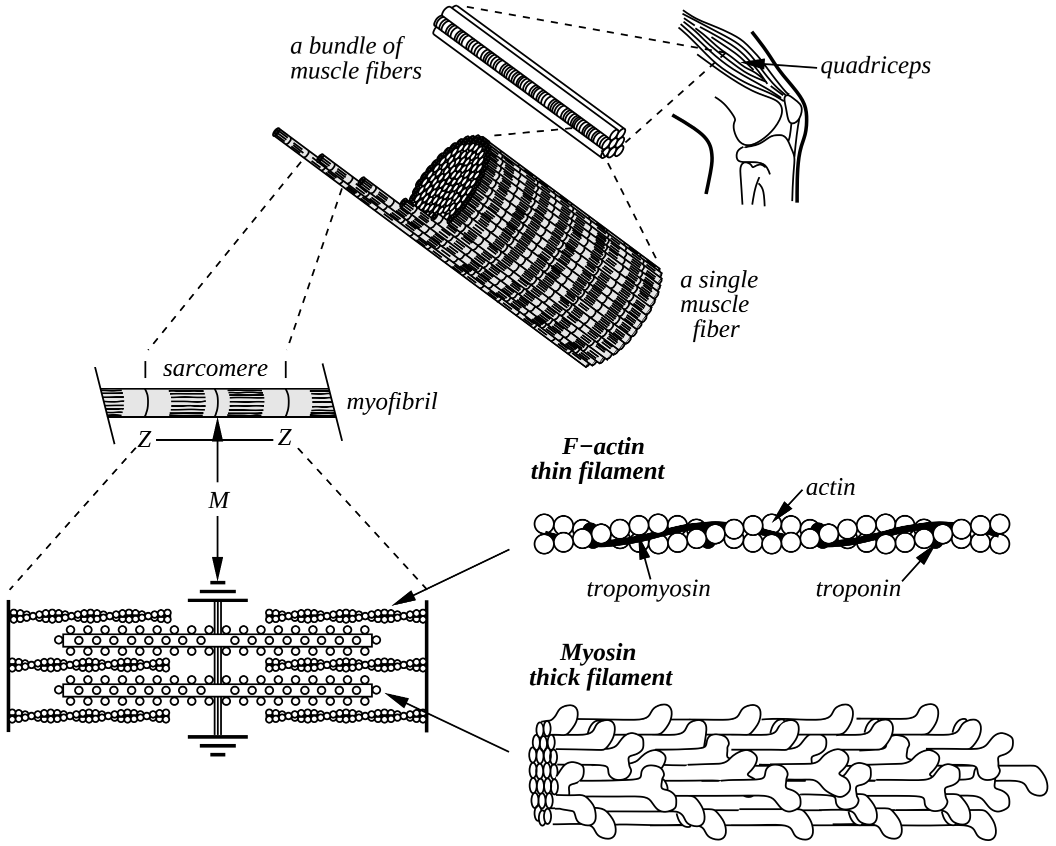
Muscle: Contractile Proteins



[adapted from Wilkie 1974, McMahon 1984]

Myosin molecules consist of multiple molecular subchains that participate in specialized roles.

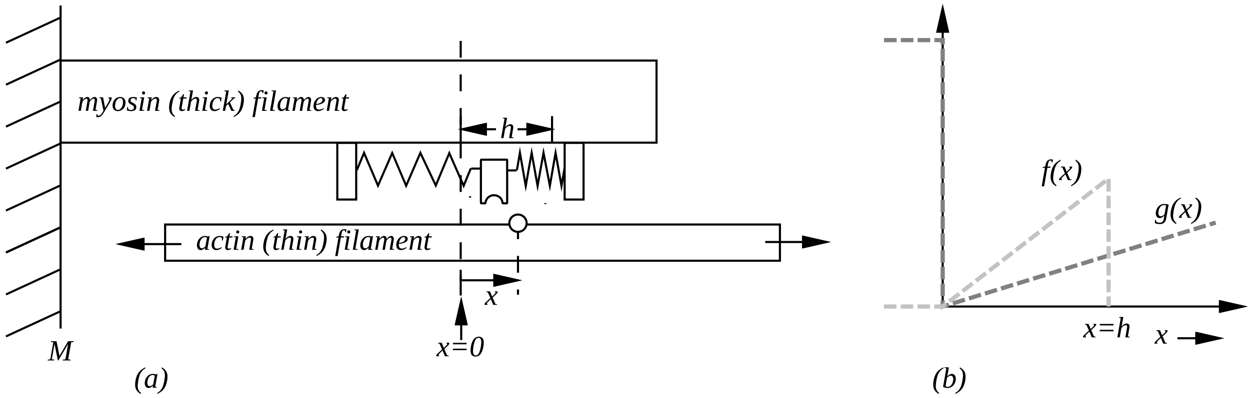
Muscle: Sliding Filament Model



[adapted from McMahon 1984]

- Neural stimuli causes actin to bind free Ca^{++} ions and thus prepare attachment sites for the S-1 subchain of myosin
- because of attachment, the head of the myosin changes shape and angle of attachment, producing a shear force between filaments
- the thin filament slides 50-100 angstroms relative to the thick filament causing the actin and myosin proteins to detach.

The Huxley Model (1957)



[adapted from McMahon 1984]

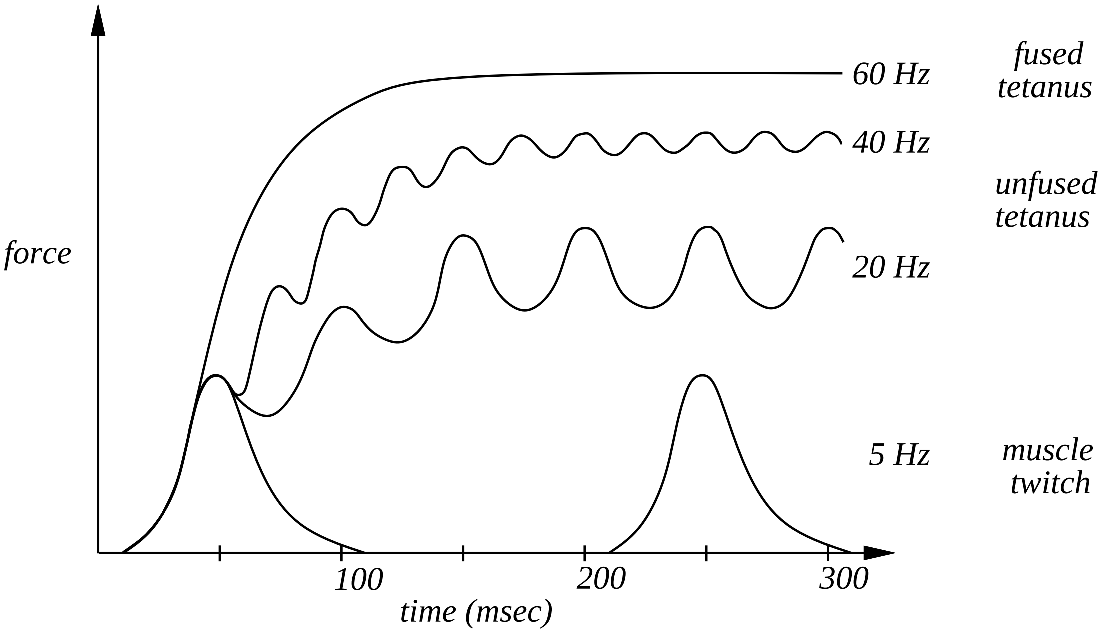
let $0 \leq n(x) \leq 1$ be the probability that a crossbridge exists at displacement x, then

$$\frac{dn(x)}{dt} = [1 - n(x)]\, f(x) - n(x)g(x),$$

where $f(x)$ is the probability of a new attachment and $g(x)$ describes the probability that an existing crossbridge will detach.

The shape of functions $f(x)$ and $g(x)$ is chosen so that muscles tend to shorten in response to neural excitation.

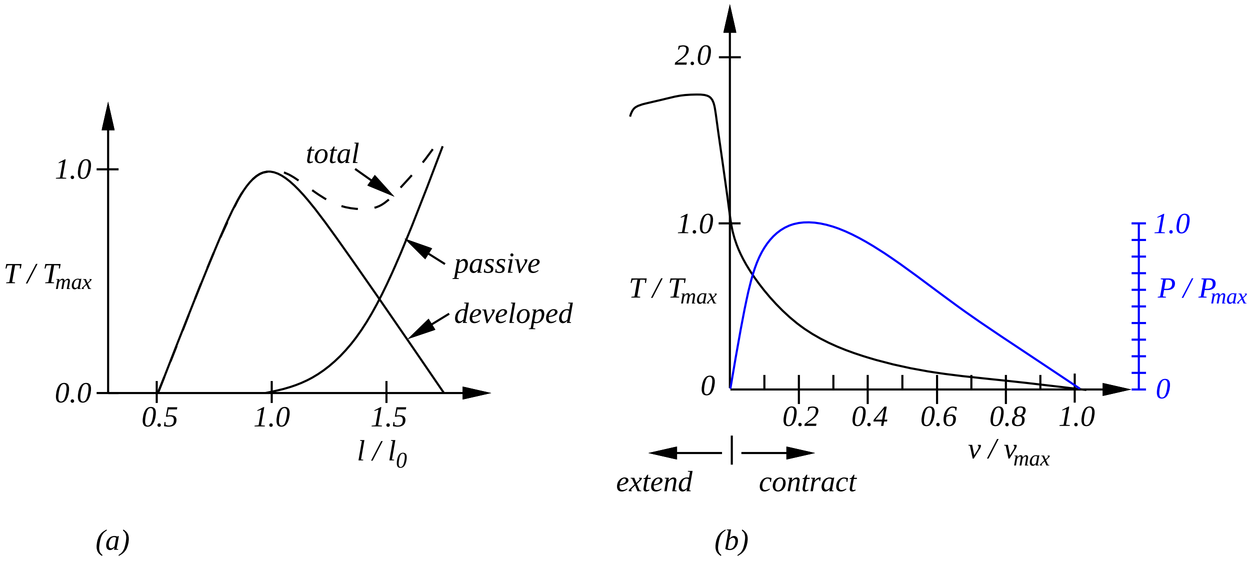
Twitch and Tetanic Responses



[adapted from McMahon 1984]

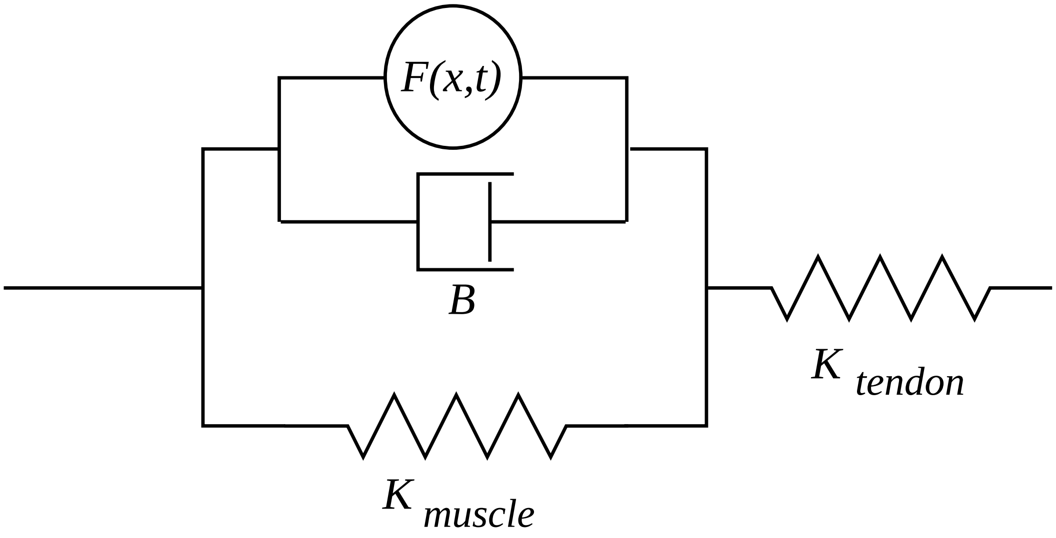
large mammalian muscles subject to periodic activation at 5, 20, 40, and 60 Hz.

Muscle Force Generation



The force capacity of muscle as a function of length and velocity. Tension is normalized by the maximum developed tension, length by muscle free length (l_0), and velocity by the maximum unloaded contractile velocity (v_{max}).

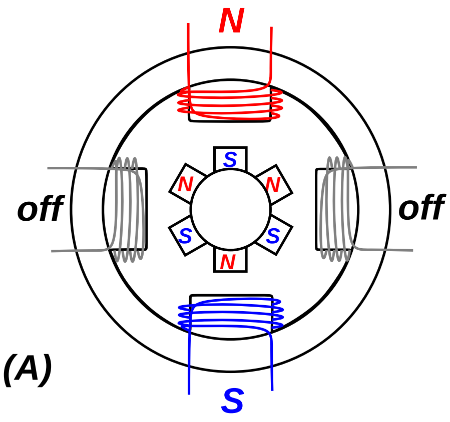
Muscle: Linear Model



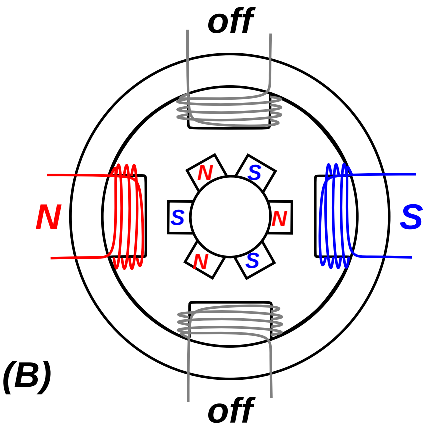
active and passive muscle dynamics

Actuators: Stepper Motors

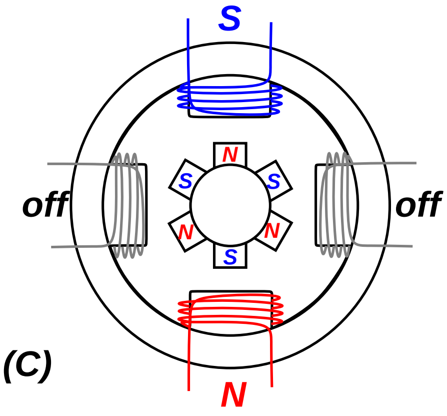
- precise (low torque), open-loop position control
- *resonance* - typically between 50 and 150 *steps/sec*
- *cogging*



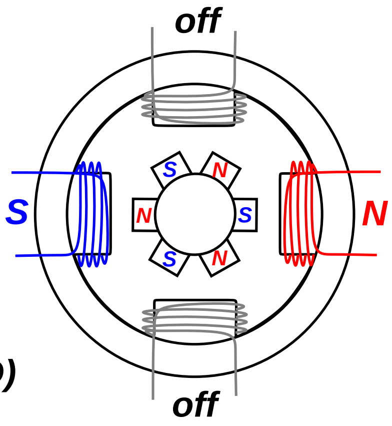
(A)



(B)



(C)

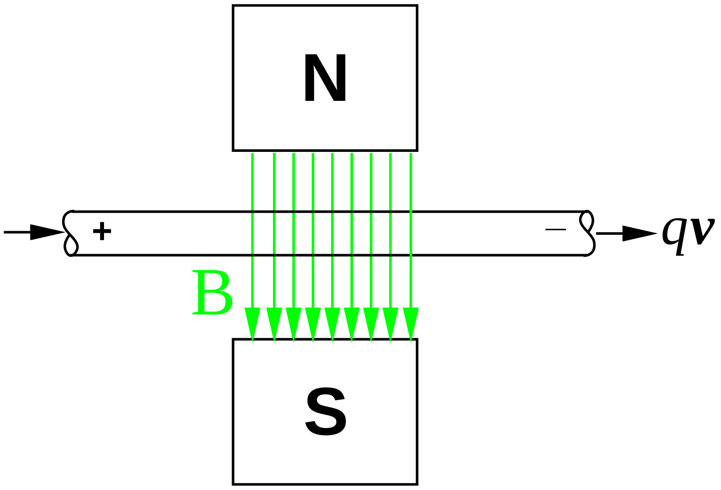


(D)

Permanent Magnet DC Motors

- run continuously in both directions
- closed-loop servo control w/position feedback
- reliable, good power/weight, high torques possible

Lorentz Force

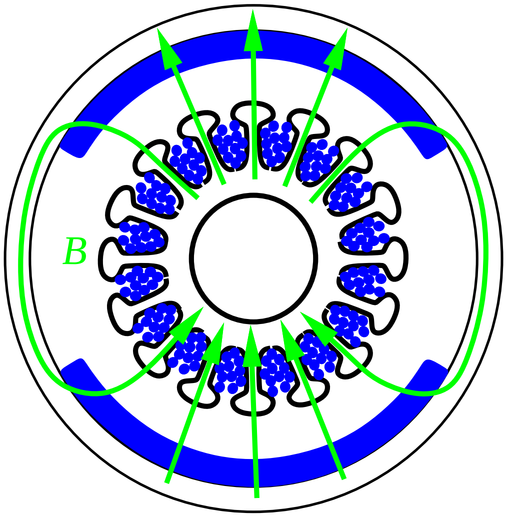


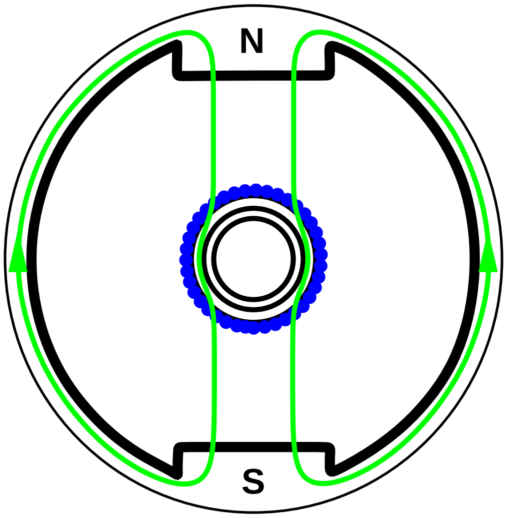
$$\mathbf{F} = q\boldsymbol{v} \times \mathbf{B}$$

Permanent Magnet DC Motor

Iron Core:

- high inertia, cogging
- very reliable
- cheap





Moving Coil:

- rare earth magnets - coil *is* rotor
- low rotor inertia - minimal *cogging*
- large torque
- can be thin (0.02″), large diameter (12″)
- *printed-circuit motors*
- very expensive

DC Motors - Electrodynamics

force: Newton $N = kg \cdot m/sec^2$

torque: the product of a force and a moment arm

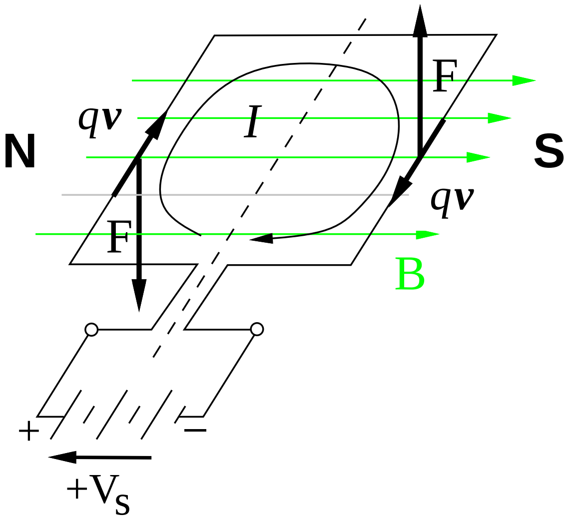
$$N \cdot m = \frac{kg \cdot m^2}{sec^2}$$

power: energy per unit time (Watts)

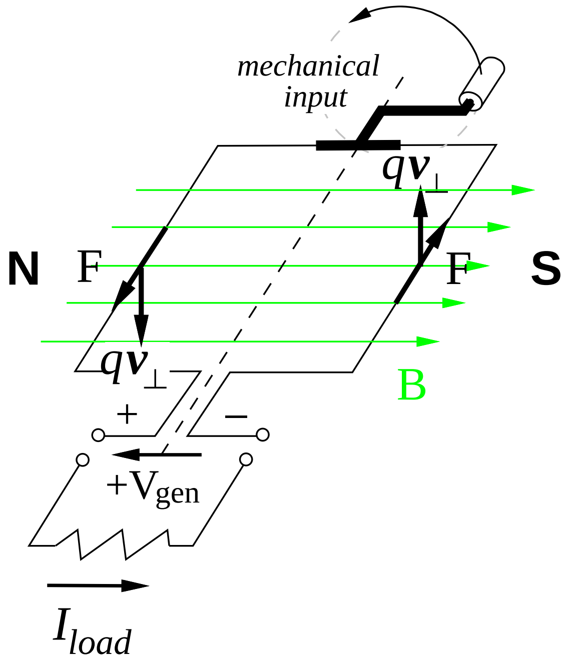
$$\begin{aligned} P &= VI(\text{electrical}) \\ &= \tau\omega(\text{mechanical}) \end{aligned}$$

$$Watt = \frac{volt \cdot coulomb}{sec} = \frac{Nm}{sec}$$

DC Motors - Electrodynamics



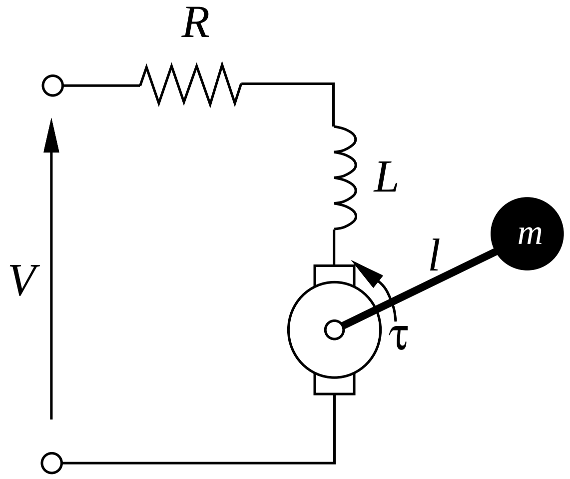
The Lorentz Force



Backward Electromotive Force (Back EMF)

- commutation - the rotor runs out of torque when the current loop is perpendicular to B, reversing the current can continue to provide torque in the same direction.
- K_m: overall motor torque constant - total number of current loops, magnetic field strength, supply voltage, rotor resistance
  - torque production: $\tau = K_m I$
  - back emf: $V_b = K_m \omega$

DC Motors - Electrodynamics (cont.)



ignoring rotor inductance L

forward current

$$\sum \tau = J\ddot{\theta} = K_m I = K_m \left[\frac{V}{R} - \frac{K_m \dot{\theta}}{R} \right]$$

back current

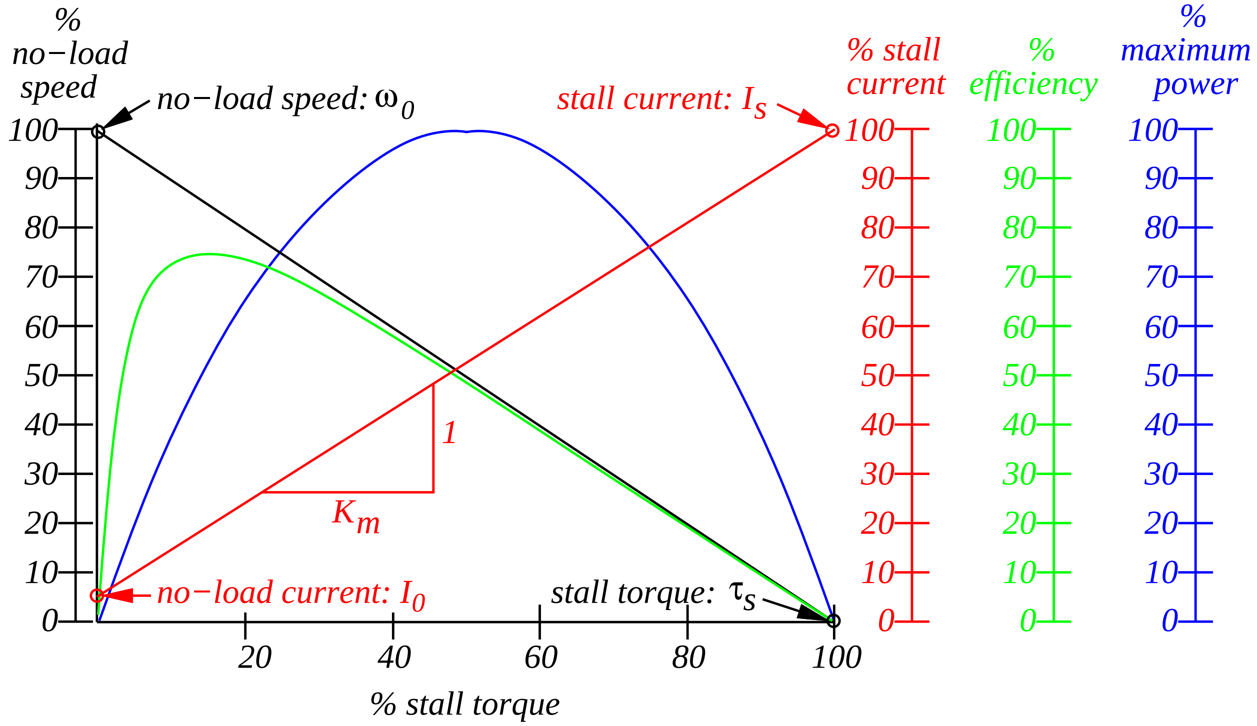
$$\ddot{\theta} + \frac{K^2}{JR}\dot{\theta} + \frac{KV}{JR} = 0$$

DC Motor Performance

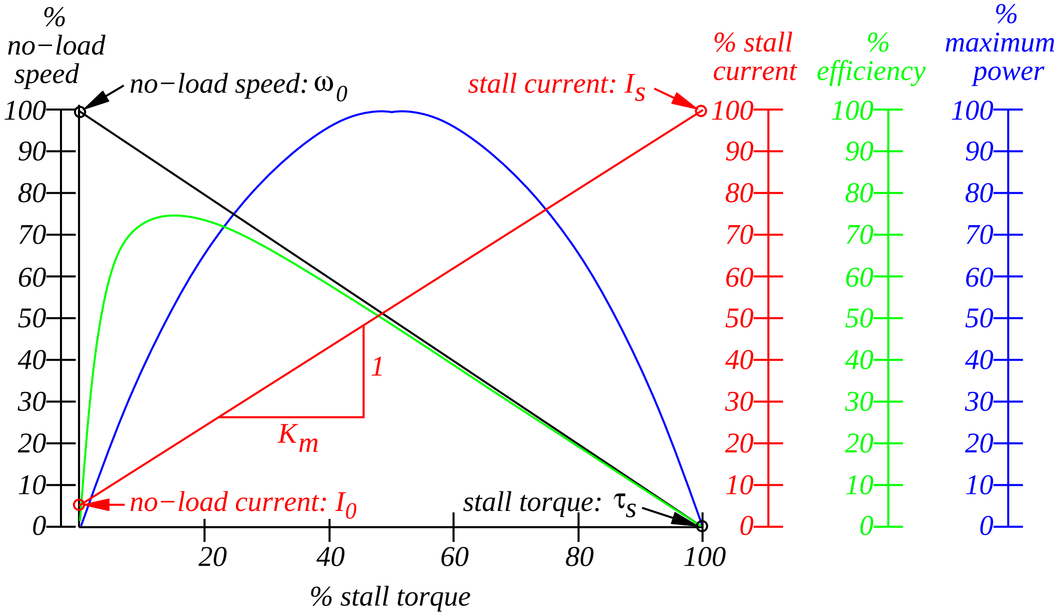
manufacturers publish physical parameters:
rotor inertia J, resistance R, inductance L, as well as overall mass and geometry of the motor package

and integrated motor performance data:

ω_0: no-load velocity
τ_s: stall torque
I_0: no-load current
I_s: stall current



DC Motor Performance



Power: the product of torque and speed ($\tau\omega$) for loads $[0, \tau_s]$

$$P_{out} = \tau_{load}\,\omega_\tau = \tau_{load}\left[\omega_0 - \frac{\Delta\omega}{\Delta\tau}\tau_{load}\right] = -\left(\frac{\Delta\omega}{\Delta\tau}\right)\tau_{load}^2 + (\omega_0)\tau_{load}$$

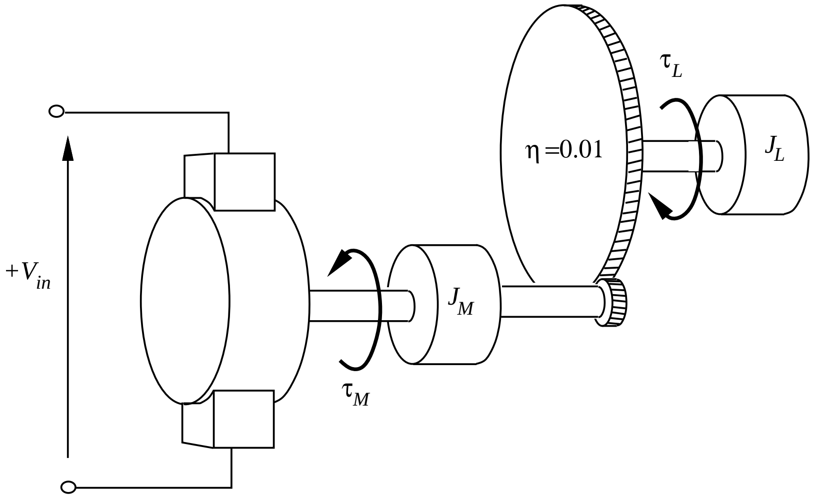
Efficiency: $\eta_\tau = \dfrac{\text{mechanical power out}}{\text{electrical power in}} = \frac{P_{out}}{V_s I}$

$$\eta_\tau = \frac{-\left(\frac{\Delta\omega}{\Delta\tau}\right)\tau_{load}^2 + (\omega_0)\tau_{load}}{V\left(I_0 + \tau_{load}/K_m\right)}$$

Roger's Motor Parameters

PARAMETER	wheel	shoulder	elbow	eye
ω_0 $[rad/sec]$ no-load speed	175.0	30.1	50.3	122.2
I_0 $[A]$ no-load current	0.38	0.26	0.17	0.12
τ_s $[N \cdot m]$ stall torque	475.0	205.3	120.7	2.7
K_m $\left[\frac{N \cdot m}{A}\right]$ $\left[\frac{V \cdot sec}{rad}\right]$ torque constant	0.105	0.623	0.364	0.163

DC Motors/Gearhead Combinations



if the transmission is perfectly efficient:

$$\begin{aligned} \tau_{out}\omega_{out} &= \tau_{in}\omega_{in} \\ \tau_{out}(\eta\omega_{in}) &= \tau_{in}\omega_{in} \\ \tau_{out} &= (1/\eta)\tau_{in} \end{aligned}$$

if $\eta = 0.01$, the output shaft carries one hundred times the torque at one hundredth the velocity of the input shaft

DC Motors/Gearhead Combinations — Compound Loads

dynamic equation of motion - equate the torque derived from Lorentz forces with the torques required to accelerate the load and to overcome viscous friction.

$$\tau_M = \left[J_M \ddot{\theta}_M \right] + \eta \left[J_L \ddot{\theta}_L \right]$$

but:

$$\begin{aligned} \theta_L &= \eta \theta_M, \\ \dot{\theta}_L &= \eta \dot{\theta}_M, \ \mathit{and} \\ \ddot{\theta}_L &= \eta \ddot{\theta}_M \end{aligned}$$

so:

$$\tau_M = \left[J_M + \eta^2 J_L \right] \ddot{\theta}_M$$

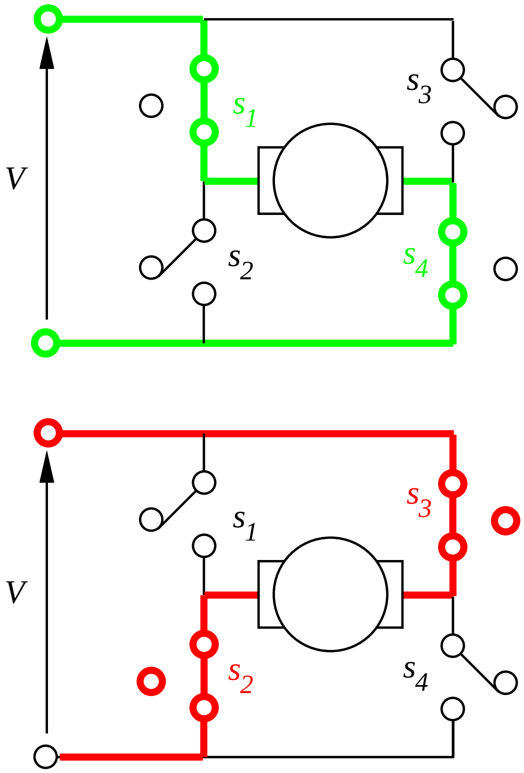
and:

$$J_{eff} = J_M + \eta^2 J_L$$

if $\eta = 0.01$, this means the relative influence of the motor dynamics is amplified 10,000 fold

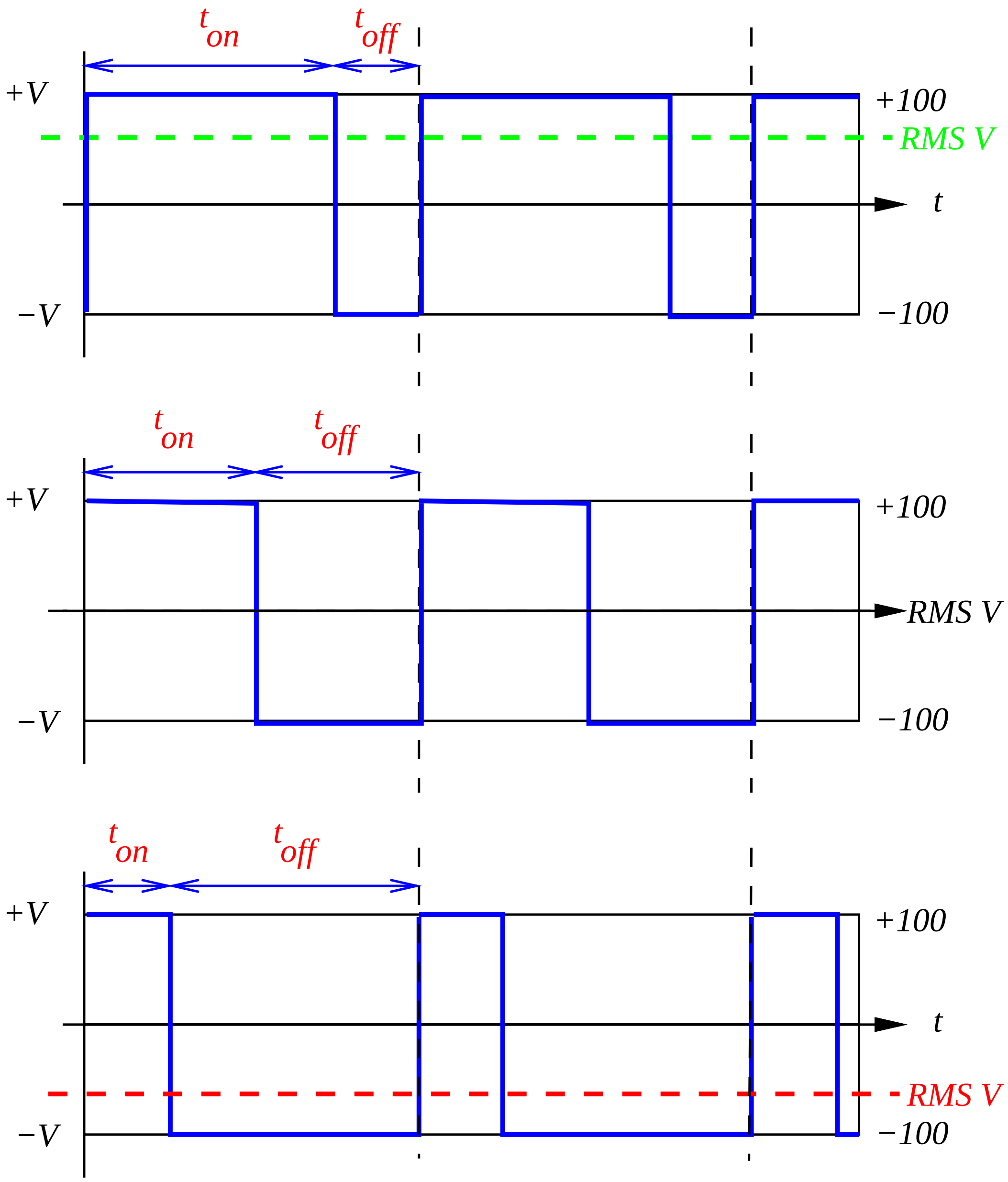
Driving DC Motors

H-Bridge

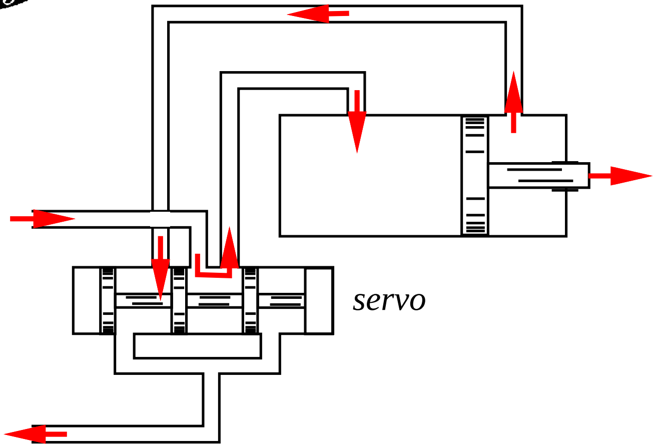


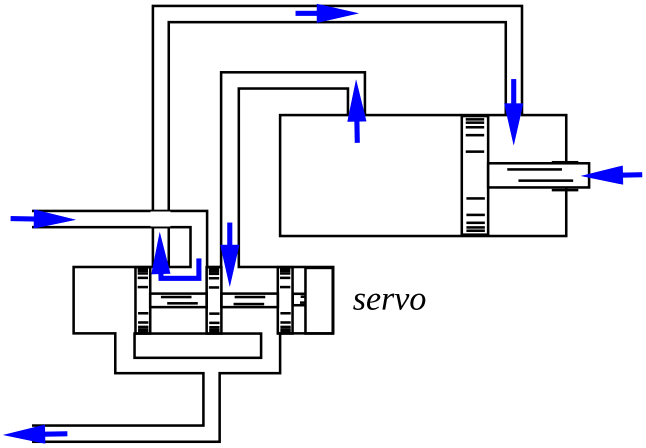
- continuous forward/backward speed control
- (s_1, s_2, s_3, s_4) open - freewheel
- (s_1, s_2, s_3, s_4) closed - (regenerative) braking
- RMS voltages - pulse width modulation (PWM)

Pulse Width Modulation



Actuators: Hydraulic





- energy in the high pressure fluid reservoir (1000-3000 psi)
- open-loop control - fork lifts, back hoes
- good bandwidth (5 KHz - fluid reverses direction 5 msec)

PROS

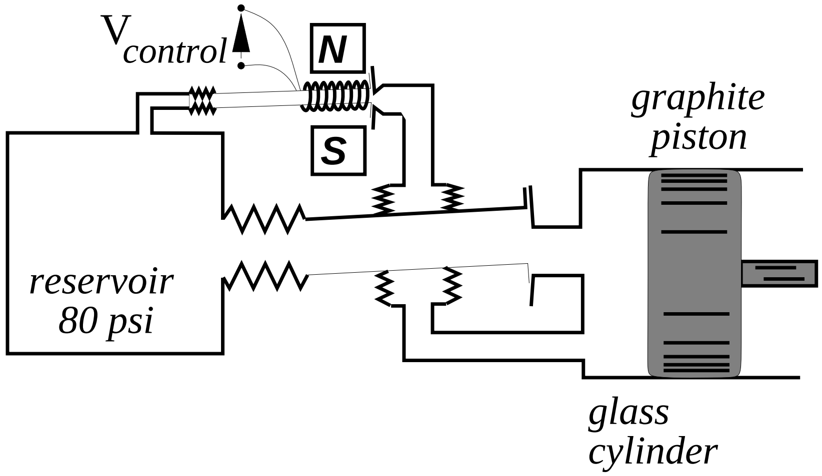
1. good power/weight
2. safe in explosive environments

CONS

1. expensive servos
2. messy
3. high maintenance

Actuators: Pneumatic

- compressible fluid (air)
- jet-pipe servo control



<u>PROS</u>

1. light and cheap
2. passively backdrivable

<u>CONS</u>

1. stiction
2. delicate

Artificial Muscles

McKibben Air Muscles - non-linear pneumatic actuators, attract interest because they are among the strongest and fastest of the “artificial” muscles.

Shape Memory Alloys - Nitinol “muscle wire” (nickel-titanium alloy) relatively slow, commercially available, a few grams force (similar to all options below this on in the list), low bandwidth (1Hz)

Polymers - electrostatic, chemical, and thermal, polymer gels can exhibit abrupt, reversible 1000 fold volume changes, forces up to 100 N/cm^2, contraction rates on the order of a second.

Synthetic Muscle - extracted actin and myosin protein, possibly avoiding tissue rejection

Bucky Tubes - Fullerenes (“Bucky Balls”) and nanotubes (“Bucky Tubes”), crystalline configurations of graphitic carbon.