Actuators

- The other side of the coin from sensors...
- Enable a microprocessor to modify the analog world.
- Examples:
  - speakers that transform an electrical signal into acoustic energy (sound)
  - remote control that produces an infrared signal to control stereo/TV operation
  - motors: used to transform electrical signals into mechanical motion
  -
- Actuator interfacing issues:
  - physical principles
  - interface electronics
  - power amplification
  - "advanced D/A conversion": How to generate an analog waveform from a discrete sequence?

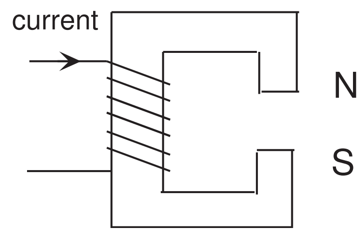
Motors

- Used to transform electrical into mechanical energy using principles of electromagnetics
- Can also be used in reverse to convert mechanical to electrical energy
  - generator
  - tachometer
- Several types, all of which use electrical energy to turn a shaft
  - DC motors: shaft turns continuously, uses direct current
  - AC motors: shaft turns continuously, uses alternating current
  - stepper motors: shaft turns in discrete increments (steps)
- Many many different configurations and "subtypes" of motors
- Types of DC motors
  - brush
  - brushless
  - linear
- We shall study brush DC motors, because that is what we will use in the laboratory
- References are [4], [2], [1], [3], [6], [5]

Electromagnetic Principles

Electromagnetic principles underlying motor operation:

- a flowing current produces a magnetic field whose strength depends on the current, nearby material, and geometry
  - used to make an electromagnet



  - motors have either permanent magnets or electromagnets

- a current, I, flowing through a conductor of length L in a magnetic field, B, causes a force, F, to be exerted on the conductor:

$$F = k_1 BLI$$

where the constant k_1 depends on geometry

  - idea behind a motor: use this force to do some mechanical work

- a conductor of length L moving with speed S through a magnetic field B has a potential difference between its ends

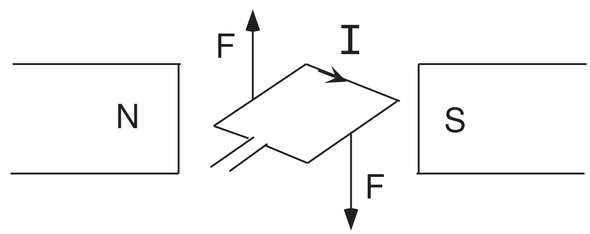
$$V = k_2 BLS$$

where the constant k_2 depends on geometry

  - idea behind a generator: use this potential difference to generate electrical power

Simplistic DC Motor

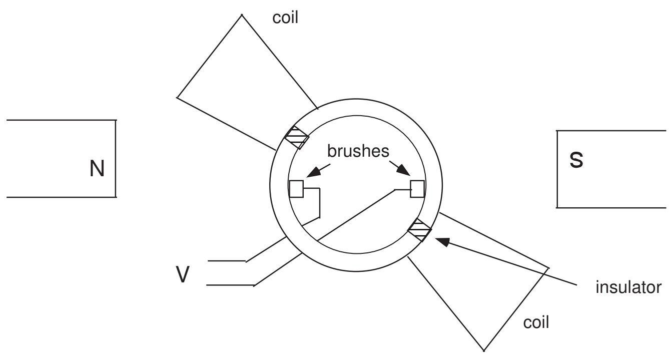
- A motor consists of a moving conductor with current flowing through it (the *rotor*), and a stationary permanent or electromagnet (the *stator*)
- consider a single loop of wire:



- combined forces yield a torque, or angular force, that rotates the wire loop
  - recall the "right hand rule" from physics
- Problems:
  - the force acting on the wire rotates it clockwise half the time, and counterclockwise half the time
  - if we want only CW rotation, we must turn off the current and let the rotor coast, during the time when the force is in the wrong direction
  - dead spot: there is one position where the force is zero

Brushes, Armature, and Commutator

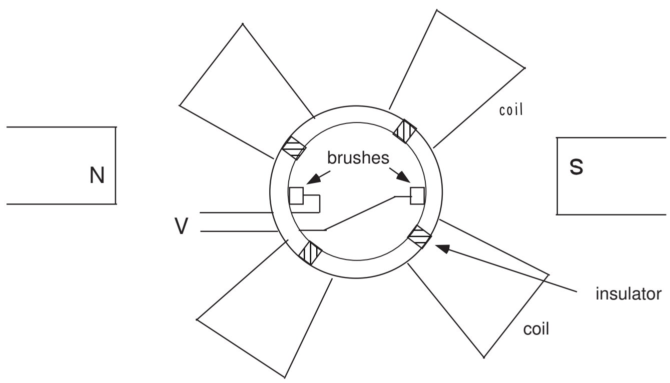
- Armature: the current carrying coil attached to the rotating shaft (rotor), which is divided into electrically isolated areas
- Commutator: uses electrical contacts (brushes) on the rotating shaft to switch the current back and forth
- Every time the brushes pass over the insulating areas, the direction of current flow through the coils changes, so that force is always in the same direction



- Problems:
  - still a dead spot, where no torque is produced.
  - torque varies greatly depending on geometry

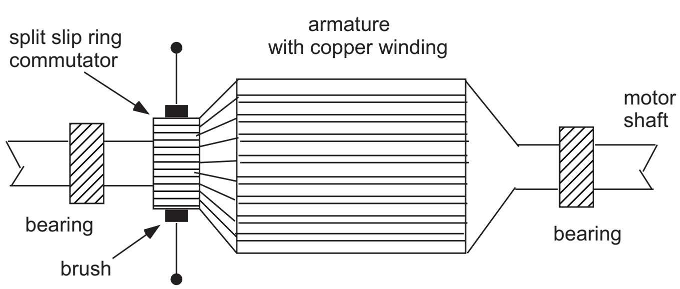
Practical Motor

- Adding more coils and brushes removes dead spot and allows smoother torque production



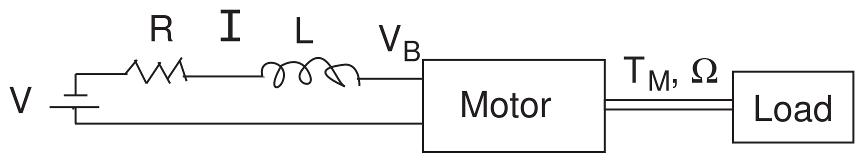
- disadvantages of brush DC motors
  - electrical noise
  - arcing through switch
  - wear

- More realistic diagram:



Motor Equations

- Mechanical variables on one side of motor, electrical variables on the other:



- Torque produced by motor as a result of current through armature:
$$T_M = K_M I$$
where T_M denotes motor torque, K_M is the torque constant, and I is the current through the armature.

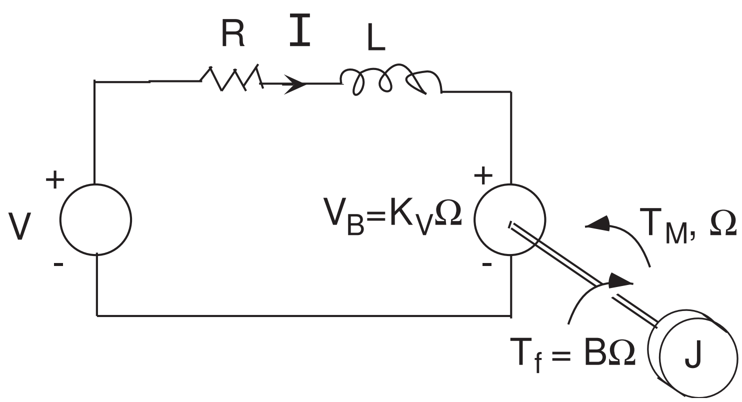
- Voltage produced as a result of armature rotation (called the *back EMF*):
$$V_B = K_V \Omega$$
where V_B is the back emf, K_V is the emf constant, and Ω is the rotational velocity

- Units:
  - T_M: motor torque, Newton-meters
  - I: current, Amps
  - V_B: back emf, Volts
  - Ω: rotational velocity, radians/second

- In these units, K_M (N-m/A) $=$ K_V (V/(rad/sec))

Circuit Equivalent

- Notation:
  - J: inertia of shaft
  - $T_f = B\Omega$: friction torque
  - R: armature resistance
  - L: armature inductance (often neglected)



- Current: $$V - V_B = RI + L\frac{dI}{dt} \tag{1}$$
- Torque: $$T_M = K_M I \tag{2}$$
- Back EMF: $$V_B = K_V \Omega \tag{3}$$
- In steady state ($\frac{dI}{dt} = 0$), substitute (2) into (1), rearrange, and apply (3):

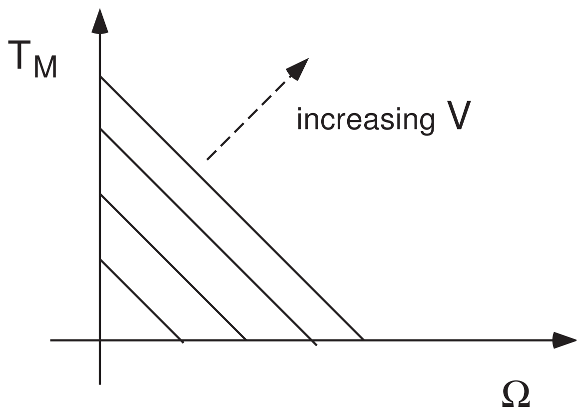
$$\begin{aligned} T_M &= \frac{K_M(V - V_B)}{R} \\ &= \frac{K_M(V - K_V\Omega)}{R} \end{aligned} \tag{4}$$

Torque-Speed Curves

- For a fixed input voltage V, the torque T_M produced by the motor is inversely proportional to the rotational speed Ω:

$$T_M + \left(\frac{K_M K_V}{R}\right)\Omega = \left(\frac{K_M}{R}\right)V \tag{5}$$

- Graphically:



- Maximum torque achieved when speed is zero:

$$T_M = \left(\frac{K_M}{R}\right)V$$

- Maximum speed achieved when torque is zero:

$$\Omega = \left(\frac{1}{K_V}\right)V$$

- Tradeoff between speed and torque should be familiar from riding a bicycle!

Load Torque

- Recall Newton's law for forces acting on mass:

$$\sum \text{forces} = ma$$

where m is the mass and a is acceleration.

- Analogue for rotational motion is

$$\sum \text{torques} = J\frac{d\Omega}{dt}$$

where J is inertia, and $\frac{d\Omega}{dt}$ is angular acceleration

- The shaft will experience
  - a torque T_M supplied by the motor,
  - a friction torque $T_f = B\Omega$ proportional to speed
  - a load torque T_L due to the load attached to the shaft[1]

- Generally load and friction torques are opposed to motor torque:

$$T_M - T_f - T_L = J\frac{d\Omega}{dt}$$

[1] We will assume load torque is constant, but it may also include a term proportional to angular velocity: $T_L = T_1 + T_2\Omega$.

Speed under Load

- Torque equation

$$T_M - B\Omega - T_L = J\frac{d\Omega}{dt}$$

- In steady state, $\frac{d\Omega}{dt} = 0$, and applied torque equals load torque plus friction torque:

$$T_M = T_L + B\Omega \tag{6}$$

- Recall torque equation

$$T_M = \frac{K_M(V - K_V\Omega)}{R} \tag{7}$$

- Setting (7) equal to (6) and solving for Ω shows that steady state speed and torque depend on the constant load T_L:

$$\Omega = \frac{K_M V - RT_L}{K_M K_V + BR} \tag{8}$$

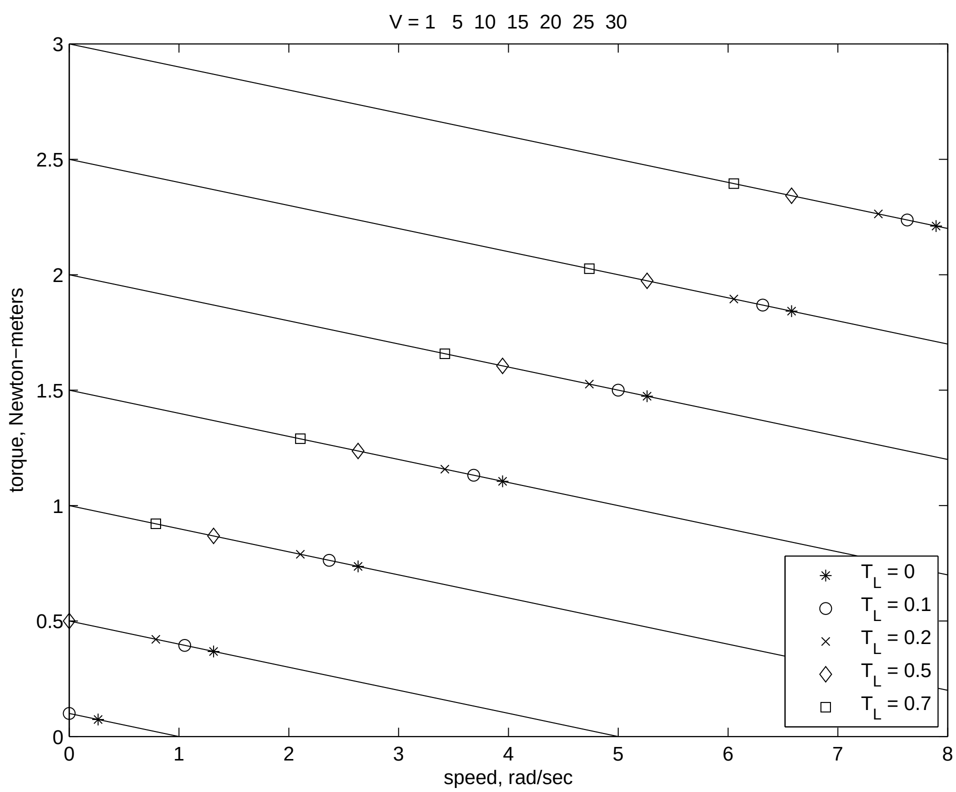
  Substituting (5) yields

$$T_M = \frac{K_M(VB + K_V T_L)}{K_M K_V + BR} \tag{9}$$

- Generally, load torque will decrease the steady state speed
- Motor will also produce nonzero torque in steady state
- Note: (8) and (9) must still satisfy torque-speed relation (5)
- Location on a given torque/speed curve depends on the load torque

Example

- Motor Parameters
  - $K_M = 1$ N-m/A
  - $K_V = 1$ V/(rad/sec)
  - $R = 10$ ohm
  - $L = 0.01$ H
  - $J = 0.1$ N-m/(rad/sec^2)
  - $B = 0.28$ N-m/(rad/sec)
- Input voltage: $V = \begin{bmatrix} 1 & 5 & 10 & 15 & 20 & 25 & 20 \end{bmatrix}$
- Load torque: $T_L = \begin{bmatrix} 0 & 0.1 & 0.2 & 0.5 & 0.7 \end{bmatrix}$
- Torque-speed curves[2]



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[2] MATLAB plot `torque_speed_curves.m`

Motor as a Tachometer

- We think of applying electrical power to a motor to produce mechanical power.
- The physics works both ways: we can apply mechanical power to the motor shaft and the voltage generated (back emf) will be proportional to shaft speed:

$$V_B = K_V \Omega$$

  $\Rightarrow$ we can use the motor as a tachometer.
- Issues:
  - brush noise
  - voltage constant drift

References

[1] D. Auslander and C. J. Kempf. *Mechatronics: Mechanical Systems Interfacing*. Prentice-Hall, 1996.

[2] W. Bolton. *Mechatronics: Electronic Control Systems in Mechanical and Elecrical Engineering, 2nd ed.* Longman, 1999.

[3] C. W. deSilva. *Control Sensors and Actuators*. Prentice Hall, 1989.

[4] G.F. Franklin, J.D. Powell, and A. Emami-Naeini. *Feedback Control of Dynamic Systems*. Addison-Wesley, Reading, MA, 3rd edition, 1994.

[5] C. T. Kilian. *Modern Control Technology: Components and Systems*. West Publishing Co., Minneapolis/St. Paul, 1996.

[6] B. C. Kuo. *Automatic Control Systems*. Prentice-Hall, 7th edition, 1995.