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:

$$F = k_1 B L I$$

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

$$V = k_2 B L S$$

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:

![Diagram of a single loop with forces N S F I S]

- 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

![Diagram of brushes, armature, and commutator]

- **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:

\[ V \quad R \quad I \quad L \quad V_B \quad \text{Motor} \quad T_M, \Omega \quad \text{Load} \]

- 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 \( \Omega \) is the rotational velocity.

- Units:
  - \( T_M \): motor torque, Newton-meters
  - \( I \): current, Amps
  - \( V_B \): back emf, Volts
  - \( \Omega \): 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)

\[ V - V_B = RI + L\frac{dI}{dt} \quad (1) \]

- Torque:
  \[ T_M = K_M I \quad (2) \]

- Back EMF:
  \[ V_B = K_V\Omega \quad (3) \]

- In steady state ($\frac{dI}{dt} = 0$), substitute (2) into (1), rearrange, and apply (3):

\[ T_M = \frac{K_M(V - V_B)}{R} \]

\[ = \frac{K_M(V - K_V\Omega)}{R} \quad (4) \]
Torque-Speed Curves

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

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

- 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:

\[ T_M = T_L + B\Omega \]  \hspace{1cm} (6)

- Recall torque equation

\[ T_M = \frac{K_M(V - K_V\Omega)}{R} \]  \hspace{1cm} (7)

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

\[ \Omega = \frac{K_M V - RT_L}{K_M K_V + BR} \]  \hspace{1cm} (8)

Substituting (5) yields

\[ T_M = \frac{K_M(VB + K_VT_L)}{K_M K_V + BR} \]  \hspace{1cm} (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:** $V = [1 \ 5 \ 10 \ 15 \ 20 \ 25 \ 30]$
- **Load torque:** $T_L = [0 \ 0.1 \ 0.2 \ 0.5 \ 0.7]$
- **Torque-speed curves$^2$**

$^2$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:

\[ V_B = KV\Omega \]

\[ \Rightarrow \] we can use the motor as a tachometer.

- Issues:
  - brush noise
  - voltage constant drift
References


