MECH 420

Sensors and Actuators

Presentation Part 10

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Part 10: Continuous-drive Actuators

- **DC Motors (Brushed and Brushless)**
- **AC Motors (Induction and Synchronous)**
- **Hydraulic Actuators**

Plan

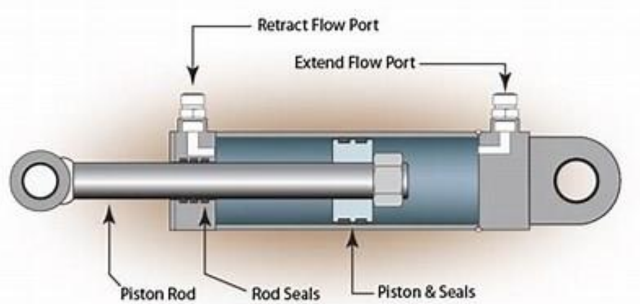
- **Types of continuous-drive actuators**
- **DC Motors (Brushed and Brushless)**
- **AC Motors (Induction and Synchronous)**
- **Hydraulic Actuators**
- **Physical Principles**
- **Control Issues**

Continuous Drive Actuators

- **DC Motors (Brushed and Brushless)**
- **AC Motors**
  - **Induction motors**
  - **Synchronous Motors**
- **Hydraulic and Pneumatic Actuators**






Electric Motor Comparison

Similarities:

- All have rotors and stators
- All electric motors generate magnetic forces/torques
- There is a corresponding rectilinear configuration (linear actuator)
- Similar selection/sizing process (mainly uses Torque vs Speed curve)
- Servo motors use a motion sensor for feedback control
- Control Issues

Differences

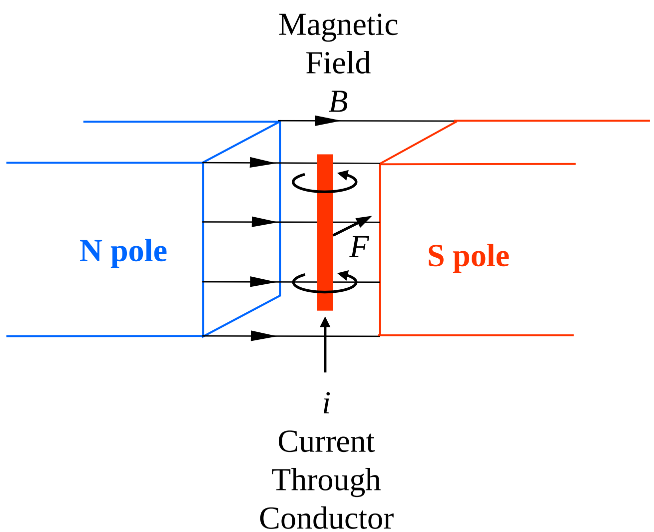
- Nature of power supply (DC or AC, single phase or multi-phase)
- Nature of rotor (permanent magnet, soft-iron, wound, powered coil, shorted coil—no power)
- Commutation (required or not, mechanical or electronic)
- Control methods (voltage, frequency, pulsed, etc.)
- Drive system (linear amplifiers, PWM amplifiers, frequency converters, etc.)

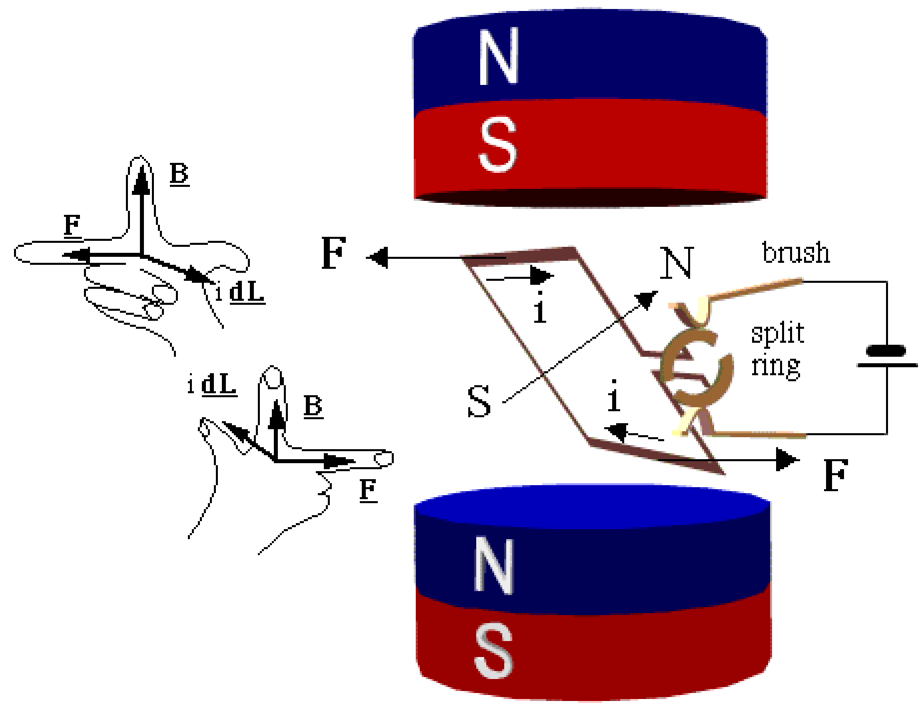
DC Motors

DC Motors

- Converts DC electrical energy into rotational mechanical energy
- Much of generated torque is available to drive a load
- Features
  - High torque
  - Speed controllability over a wide range
  - Well behaved speed-torque characteristics
  - Adaptability to various types of control methods
- Applications
  - Multi-axis positioning stages
  - Robotic manipulators
  - Disk drives
  - Machine tools
  - Valve actuators (e.g., servo-valves)

Principle of Operation





Lorenz's Law: Force $F = Bil$

Lenz's Law: Back emf $v_b = Blv$

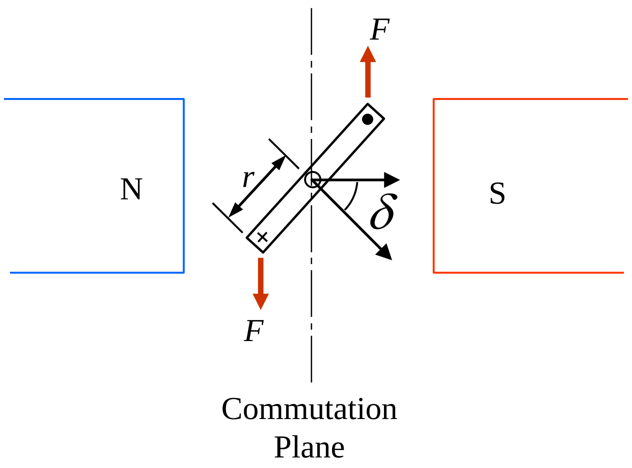
B - Flux density; v - velcity

i - Current through the conductor

l - length of the conductor

Compare with tacho generator

Torque Characteristics

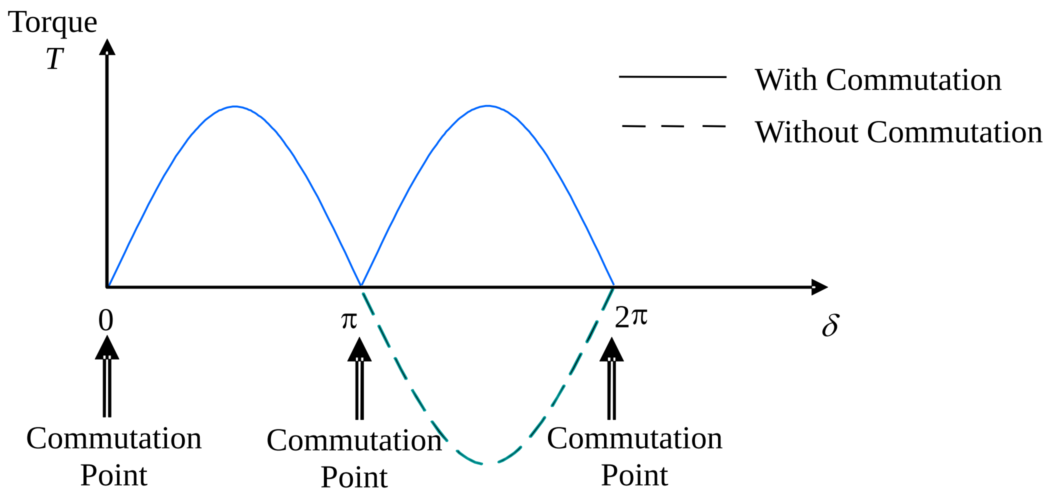


(a)

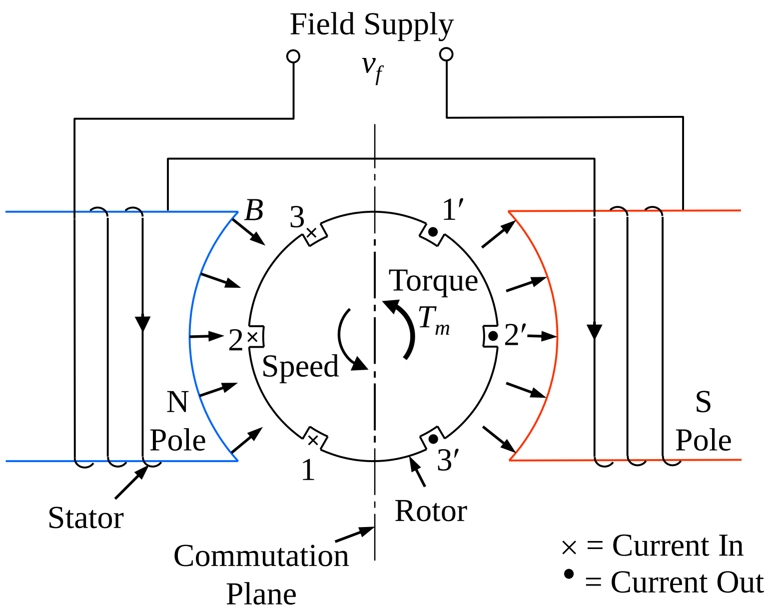
$$T = F \times 2r \sin \delta$$

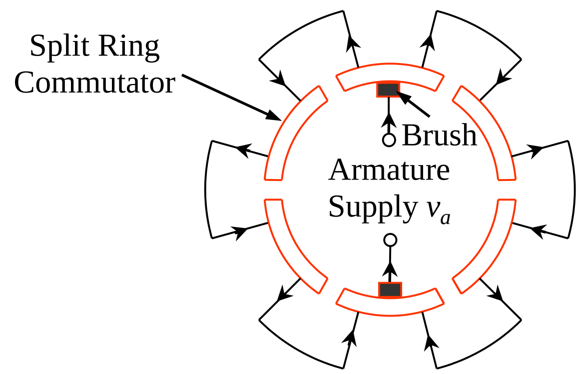
$$T = Bi_a l \times 2r \sin \delta$$

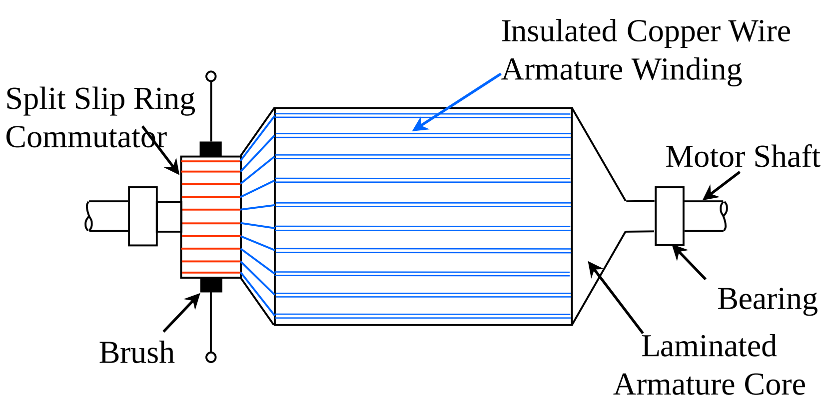
$$T = Ai_a B \sin \delta$$

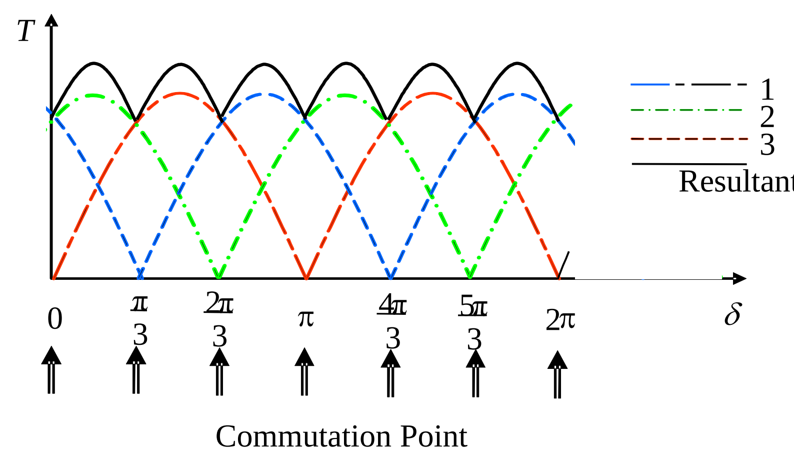


Commutation (With Brushes)

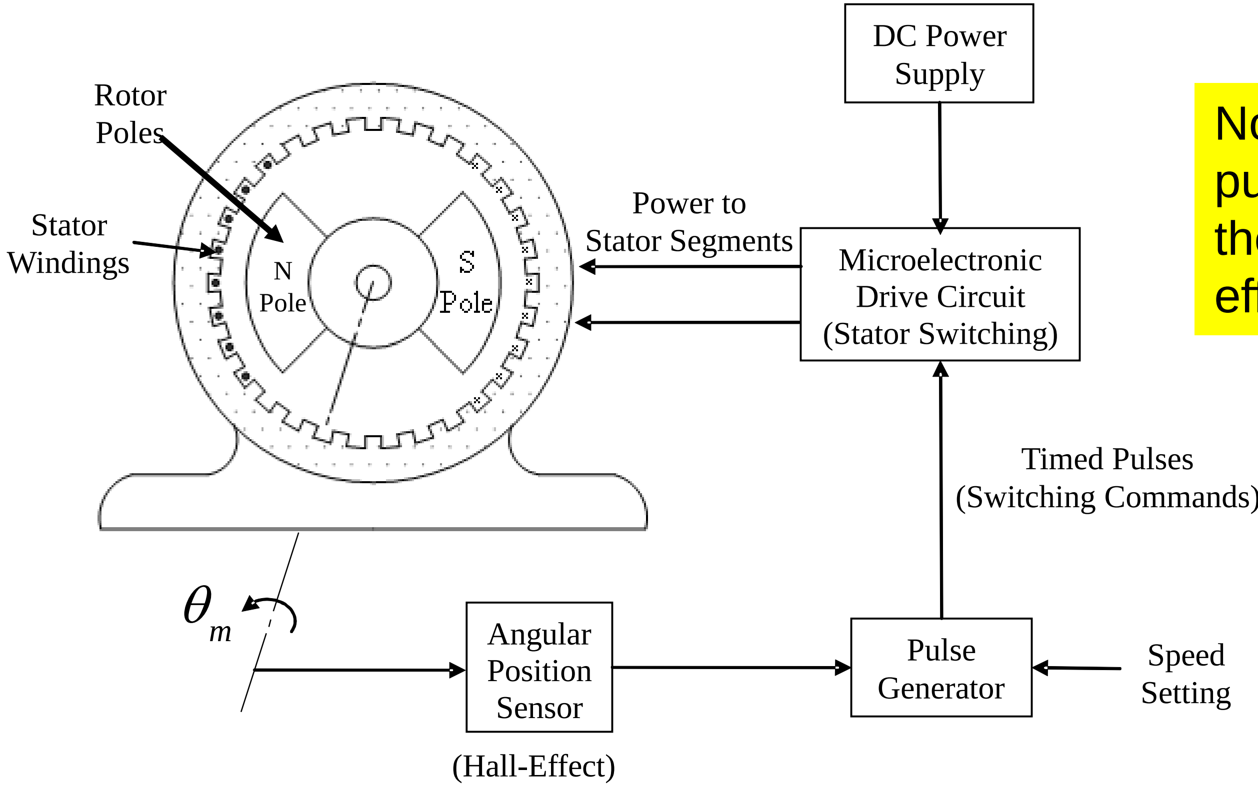








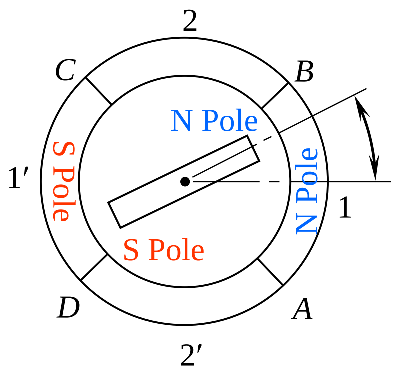
Brushless DC Motors

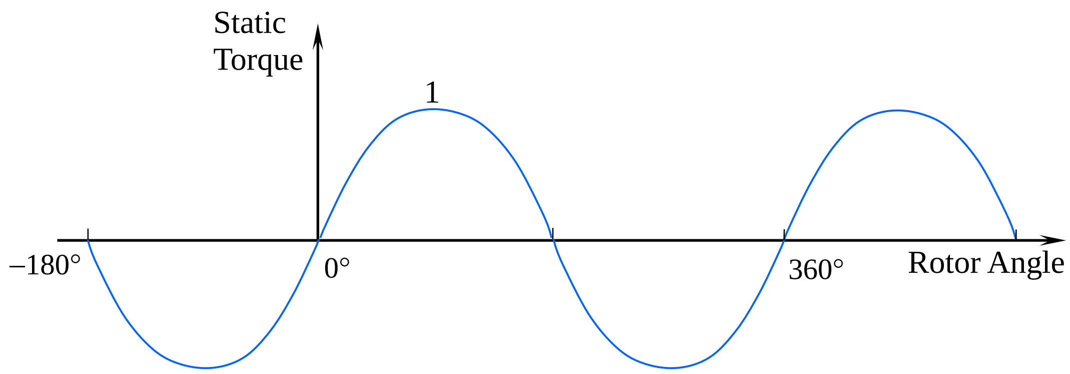


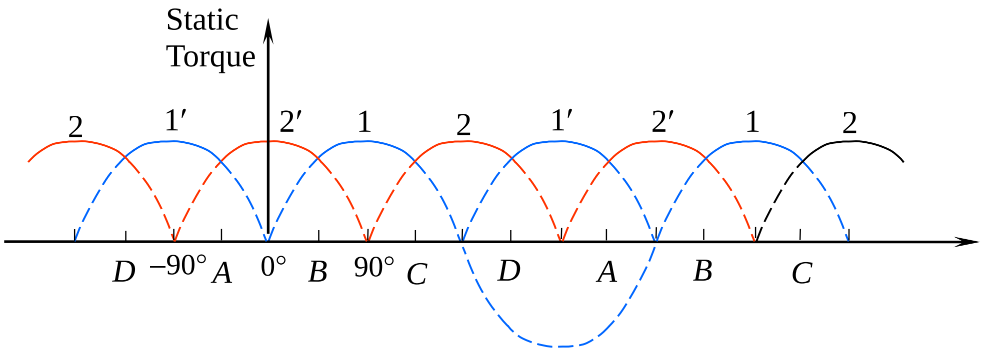
Note the purpose of the Hall-effect sensor

- **Rotor:** Multi-pole permanent magnet (2-pole rotor is shown in figure)
- **Stator:** Has pole windings
- **Commutation:** Electronically switching the current in pole windings depending on the rotor position
- **Rotor Position:** Sensed by Hall-effect sensor or optical encoder

Electronic Commutation







Question

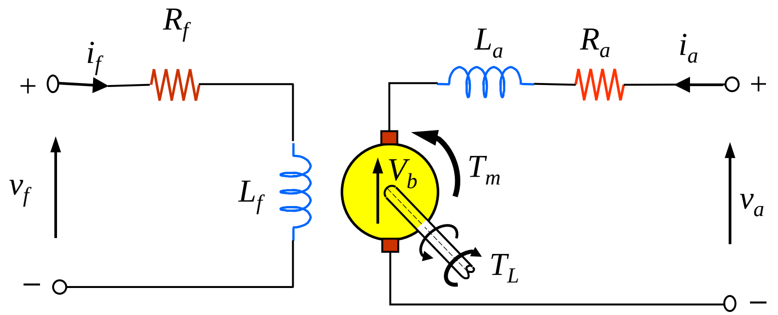
Compare the Operation of Brushed DC Motor and Brushless DC Motor.

Brushed Motor:

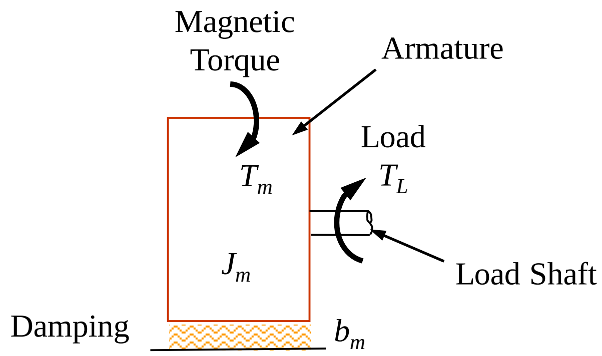
Brushless Motor:

DC Motor Equations

DC Motor Equations



Stator (Field) Circuit **Rotor (Armature) Circuit**



Rotor and Load

$$F = Bil \quad \Rightarrow \quad T_m = k i_f i_a \quad \leftarrow \text{Lorenz}$$

$$v_b = Blv \quad \Rightarrow \quad v_b = k' i_f \omega_m \quad \leftarrow \text{Lenz}$$

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + v_b$$

$$J_m \frac{d\omega_m}{dt} = T_m - T_L - b_m \omega_m$$

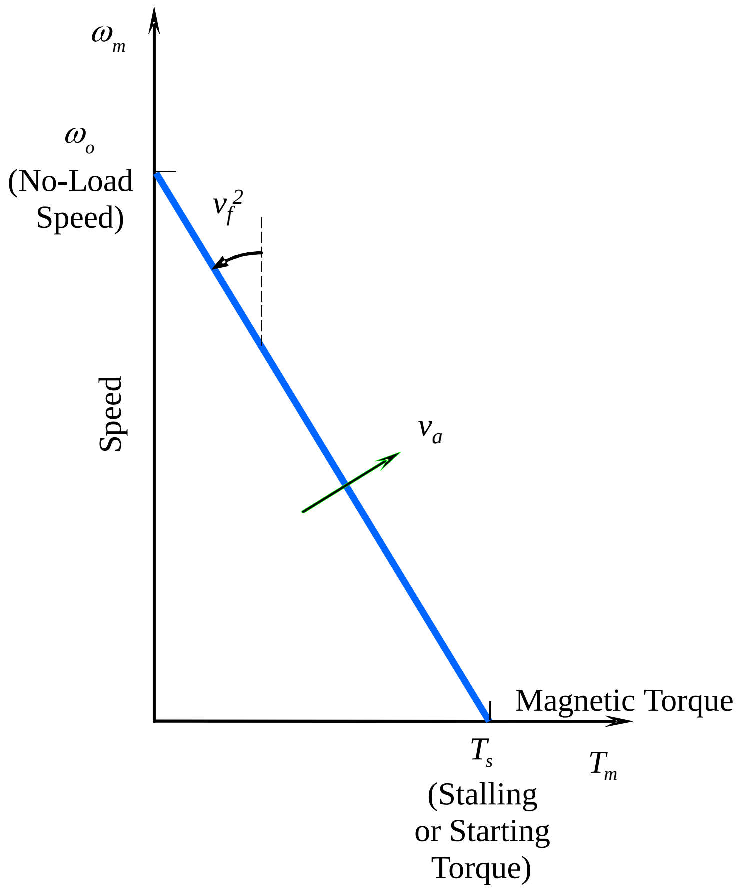
Note: With perfect energy conversion, $k = k'$

Why?

Natural frequency and damping ratio?

Steady-state Characteristics

- **In selecting a motor for a given application, its steady-state characteristics are a major determining factor**



$$v_f = R_f i_f \qquad v_a = R_a i_a + v_b$$

$$\frac{R_a R_f^2}{kk' v_f^2} T_m + \omega_m = \frac{R_f v_a}{k' v_f}$$

$$\frac{\omega_m}{\omega_o} + \frac{T_m}{T_s} = 1$$

Where is motor damping?

Mechanical Load:

$$J_m \frac{d\omega_m}{dt} = T_m - T_L - b_m \omega_m$$

Output Power of a DC Motor

$$p = T_m \omega_m \quad \textbf{and} \quad \frac{\omega_m}{\omega_o} + \frac{T_m}{T_s} = 1$$

→

$$p = T_s \left[1 - \frac{\omega_m}{\omega_0} \right] \omega_m$$

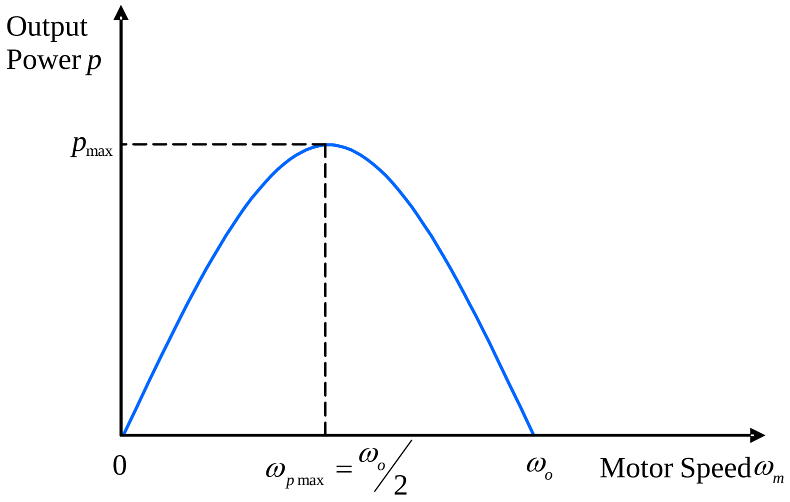
→ **Quadratic shape**

To obtain maximum power and corresponding speed:

$$\frac{dp}{d\omega_m} = T_s \left(1 - \frac{\omega_m}{\omega_o}\right) - \frac{T_s}{\omega_o}\omega_m = T_s \left(1 - 2\frac{\omega_m}{\omega_o}\right) = 0$$

→

$$\omega_{\text{pmax}} = \frac{\omega_o}{2} \quad \textbf{and} \quad p_{\max} = \frac{1}{4} T_s \omega_o$$



Motor-Load Matching

Stable and Unstable Operating Points

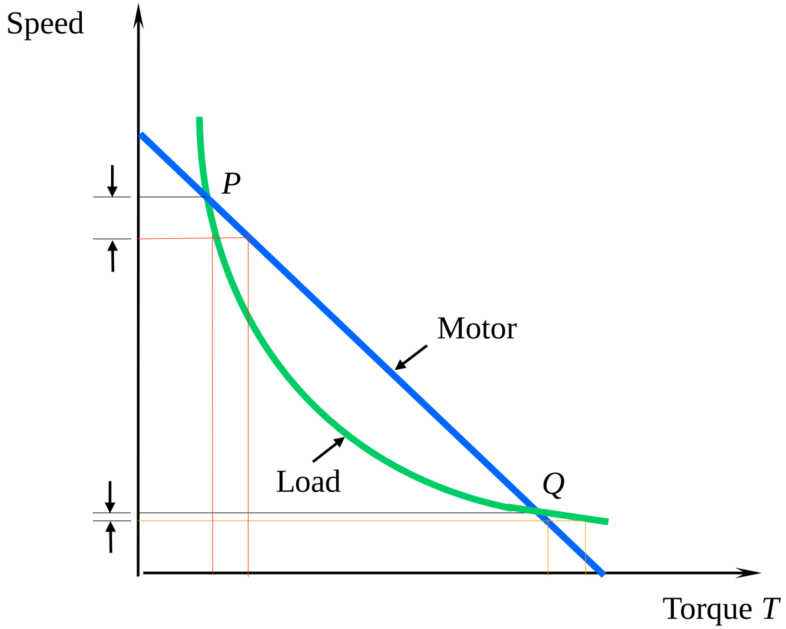
Example:

Constant-power load

DC motor under steady-state operation

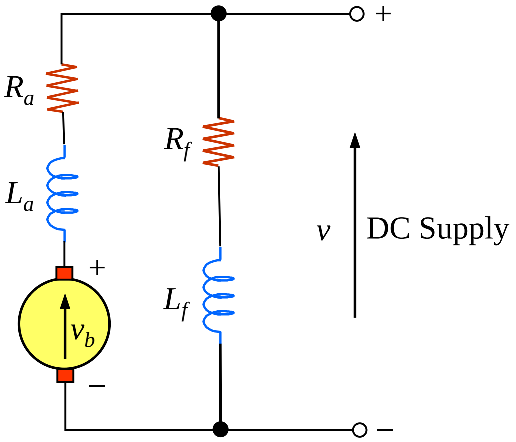
Two operating points are possible (*P* and *Q*)

***P* is stable; *Q* is unstable** Why?

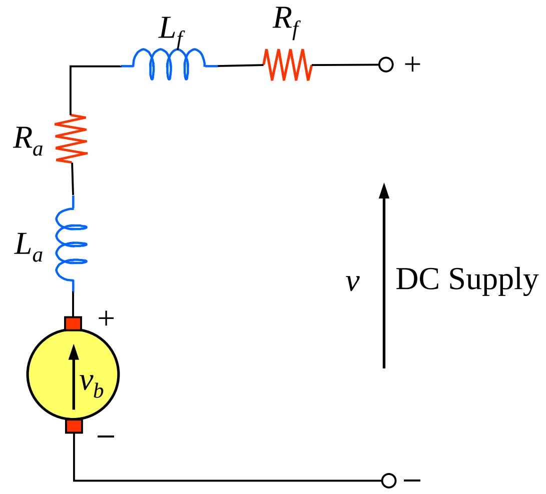


Torque-Speed Characteristics

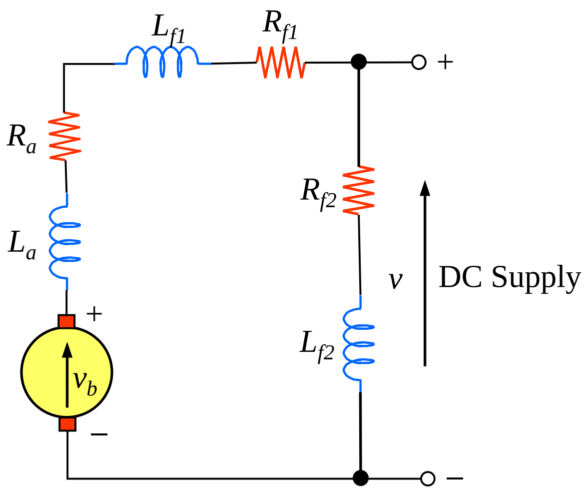
Motor Windings, Combined Excitation



Shunt Wound Motor



Series Wound Motor



Compound Wound Motor

Torque-Speed Equations (Steady-state)

Shunt Wound Motor:

$$\omega_m + \left(\frac{R_a R_f^2}{kk'v^2}\right) T_m = \frac{R_f}{k'}$$

Series Wound Motor:

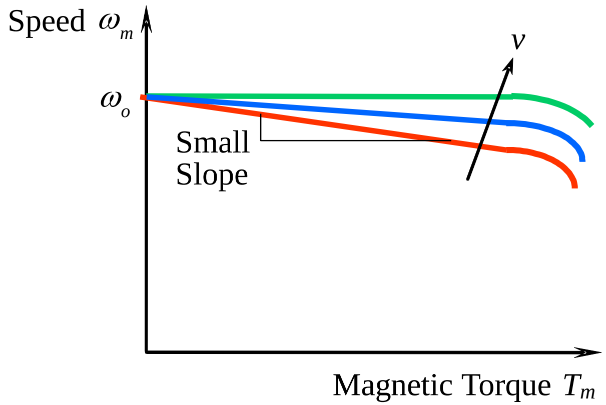
$$\omega_m = \frac{v}{k'}\sqrt{\frac{k}{T_m}} - \frac{R_a + R_f}{k'}$$

Compound Wound Motor:

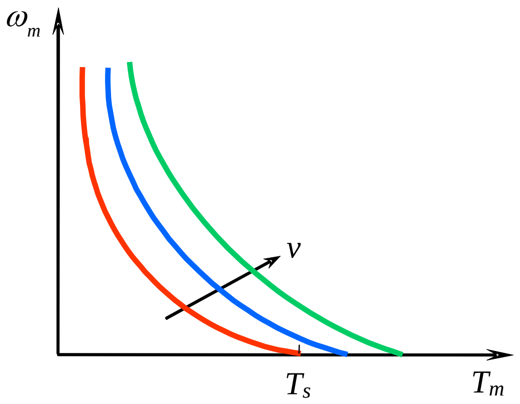
$$T_m = \frac{kv^2\left(\frac{1}{R_a + R_{f1}} + \frac{1}{R_{f2}}\right)\left[1 - k'\omega_m\left(\frac{1}{R_a + R_{f1}} + \frac{1}{R_{f2}}\right)\Big/\left(1 + \frac{k'\omega_m}{R_a + R_{f1}}\right)\right]}{\left(R_a + R_{f1}\right)\left(1 + \frac{k'\omega_m}{R_a + R_{f1}}\right)}$$

$$= \frac{kv^2\left(\frac{1}{R_a + R_{f1}} + \frac{1}{R_{f2}}\right)\left(1 - \frac{k'\omega_m}{R_{f2}}\right)}{\left(R_a + R_{f1}\right)\left(1 + \frac{k'\omega_m}{R_a + R_{f1}}\right)^2}$$

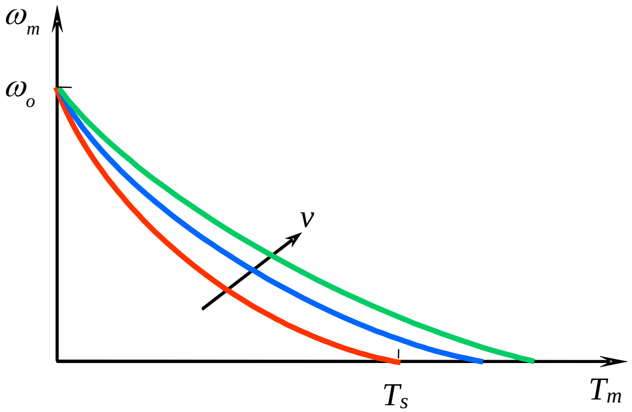
Torque-Speed Curves



Shunt Wound Motor



Series Wound Motor



Compound Wound Motor

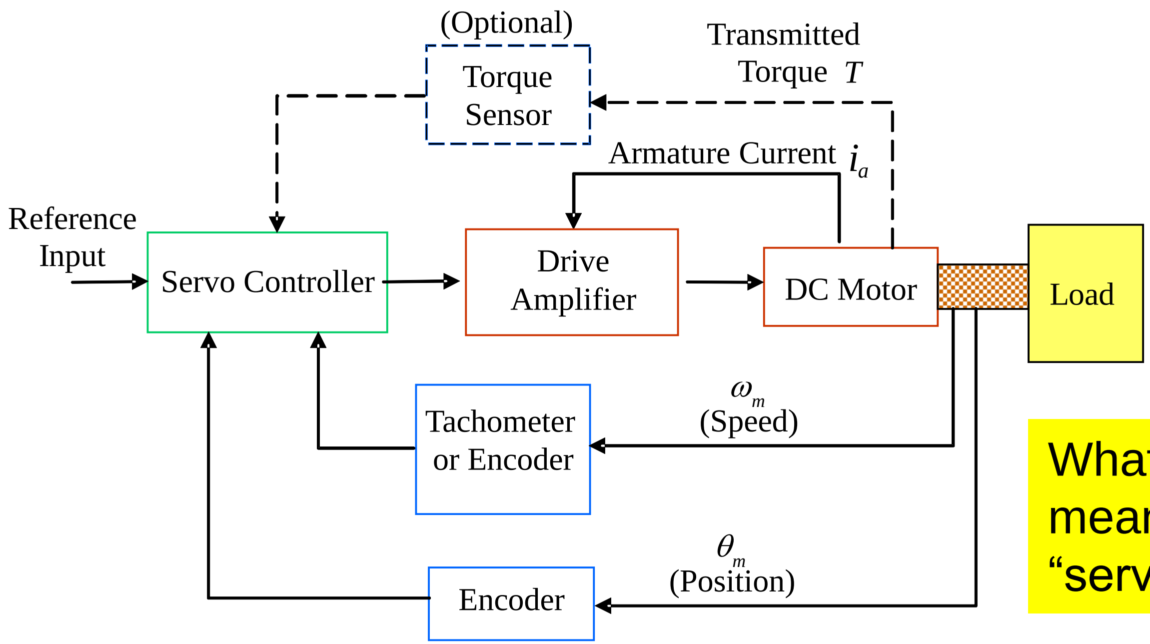
Winding Configuration and Characteristics

DC Motor Type	Speed Regulation	Starting Torque
Shunt-wound	Good	Average
Series-wound	Poor	High
Compound-wound	Average	Average

DC Motor Control

Control of DC Motors, Servo Motor

- **Armature Control**
- **Field Control**



What is the meaning of "servoing"?

***Note*: Drive amplifier can be: 1. Linear amp (simpler control, less efficient; 2. PWM amp (nonlinear, very efficient)**

Armature Control

Torque: $T_m = k_m i_a$

Back emf: $v_b = k'_m \omega_m$

Mechanical: $T_m - T_L = (J_m s + b_m)\omega_m$

Electrical: $v_a - v_b = (L_a s + R_a) i_a$

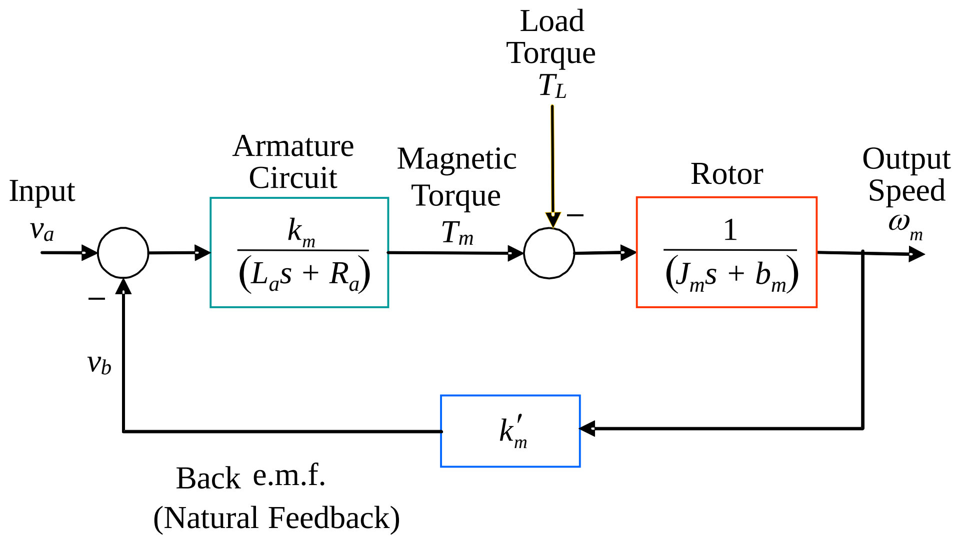
I-O Relation (Transfer Functions): $\omega_m = \dfrac{k_m}{\Delta(s)} v_a - \dfrac{(L_a s + R_a)}{\Delta(s)} T_L$

Characteristic Polynomial: $\Delta(s) = (L_a s + R_a)(J_m s + b_m) + k_m k'_m$

Why?

Time constants?

Block Diagram:



***Note*: Controls have to be added to this system**

Field Control

Torque: $T_m = k_a i_f$ **Field Voltage:** $v_f = (L_f s + R_f) i_f$

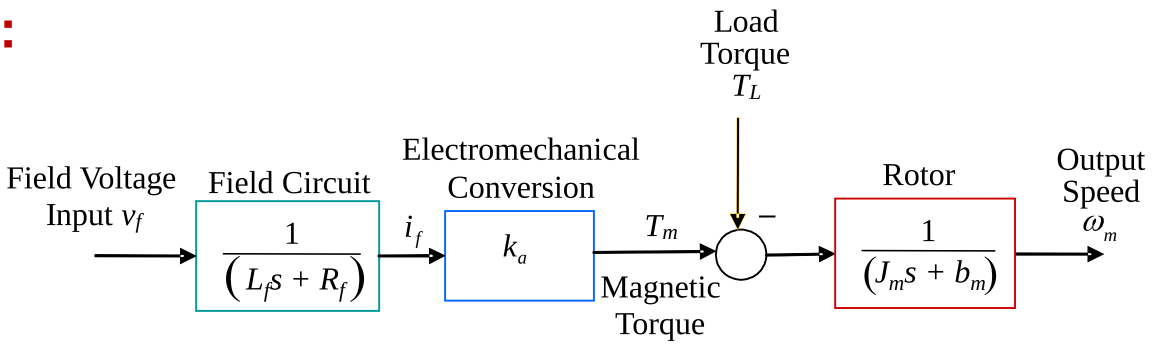
Motor Mechanical Equation: $T_m - T_L = (J_m s + b_m)\omega_m$

I-O Relation (Transfer Functions):

$$\omega_m = \frac{k_a}{(L_f s + R_f)(J_m s + b_m)} v_f - \frac{1}{(J_m s + b_m)} T_L$$

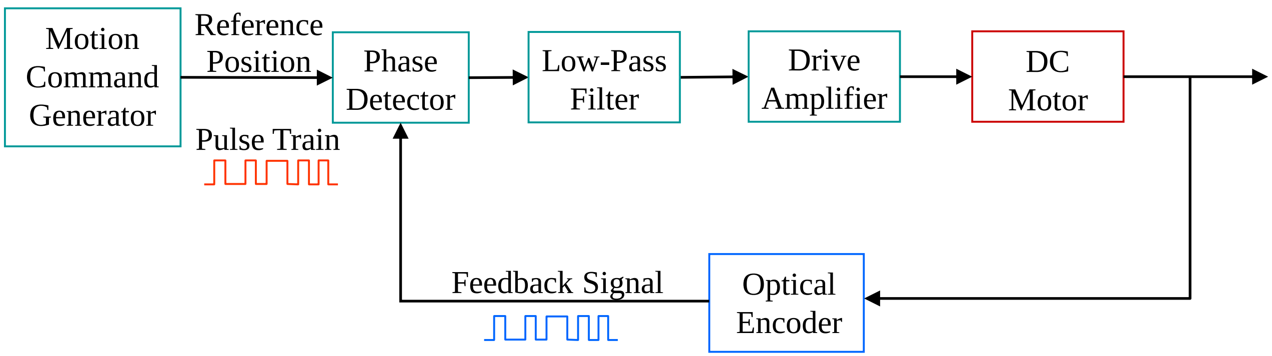
Time constants?

Block Diagram:



***Note*: Controls have to be added to this system**

Phased Locked Control



Question

Compare a Servo Motor and a Non-servo Motor.

Non-servo Motor:

Advantages

Disadvantages

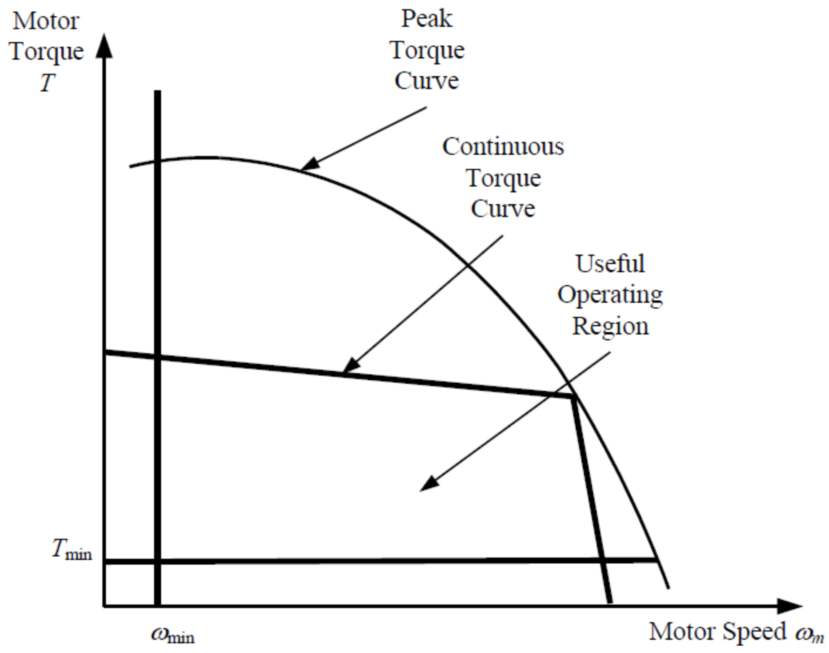
Servo Motor:

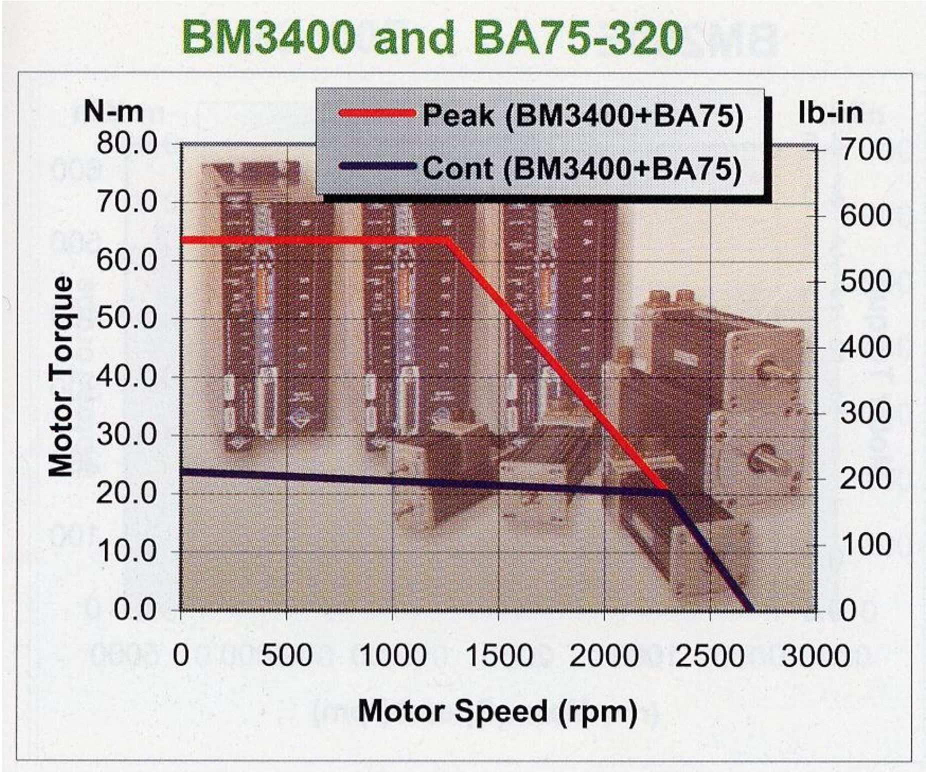
Advantages

Disadvantages

DC Motor Selection (Sizing)

- Similar to stepper motor selection
- Torque vs speed curve is key





Question: Servo Motor Over Stepper Motor

Advantages: Justify each

- **Continuous/Smooth/Quiet Operation**
- **High Power (Output) and Efficiency**
- **Can Operate for Long periods without Overheating**

Disadvantages: Justify each

- **More Costly**
- **Need Sensors**
- **Control is More Complex**
- **Gearing may be Required**

Electric Linear Actuator

Note**:** **"Linear" means "Rectilinear" (Moving along a Straight Line)**

Typical Principle of Operation:

- **Same as Rotary Motor**
- **Rotation is Converted into Rectilinear Motion by a Leadscrew and Nut (or Rack and Pinion)**

Question

Disadvantages of the Linear Motor Design Given in Previous Slide:

Another Possible Design of a Linear Motor:

AC Motors:

1. Induction Motors
2. Synchronous Motors

AC Motors

Advantages

- Cost-effective
- Convenient power source – standard power grid (for single-phase and three-phase ac supply)
- Typically, no commutator and brush mechanisms needed
- No electric spark generation or arcing (no brushes and slip rings) ➔ Less hazardous (e.g., in chemical environments)
- Capability of accurate constant-speed operation without needing servo control (with synchronous AC motors)
- High capacity, reliability and robustness; easy maintenance; long life

Applications

- **Heavy-duty:** Rolling mills, presses, elevators, cranes, material handlers
- **Continuous Motion:** Conveyors, mixers, extruders, pulping machines
- **Household and Industrial:** Refrigerators, pumps, compressors, fans

Main Principle: Generation of a rotating magnetic field

Induction Motors

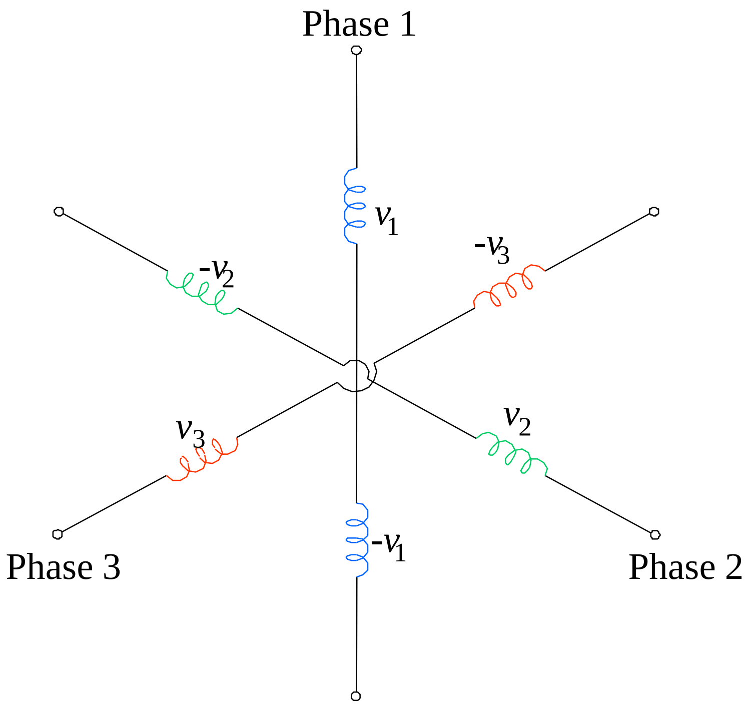
Rotating Magnetic Field:

(3-phase example)

$$v_1 = a\cos\omega_p t$$

$$v_2 = a\cos\left(\omega_p t - \frac{2\pi}{3}\right)$$

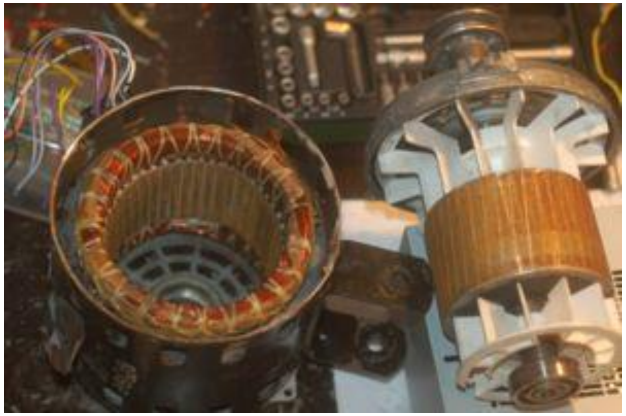
$$v_3 = a\cos\left(\omega_p t - \frac{4\pi}{3}\right)$$



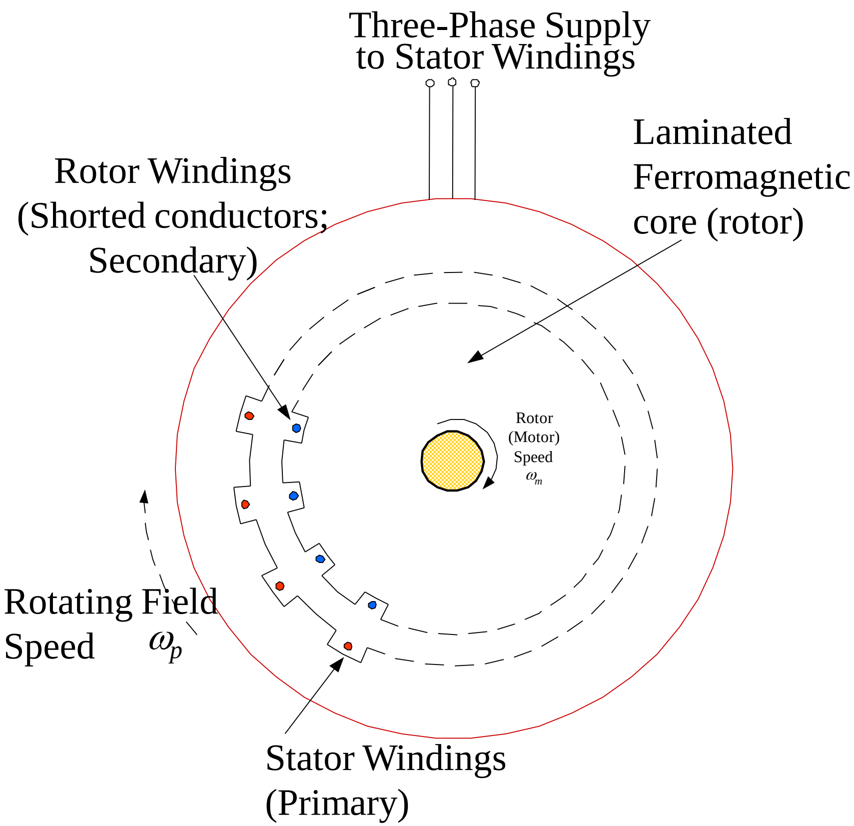
Angular speed of rotating magnetic filed $\Rightarrow$ $\omega_f = \dfrac{\omega_p}{n}$

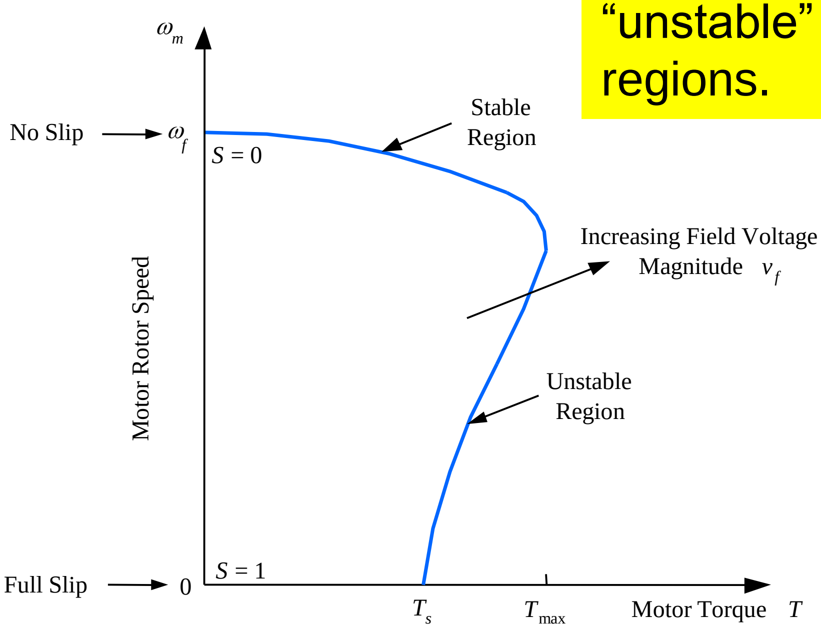
ω_p = line frequency (frequency of AC supply)

***n* = number of pole pairs per phase**



Induction Motor Characteristics





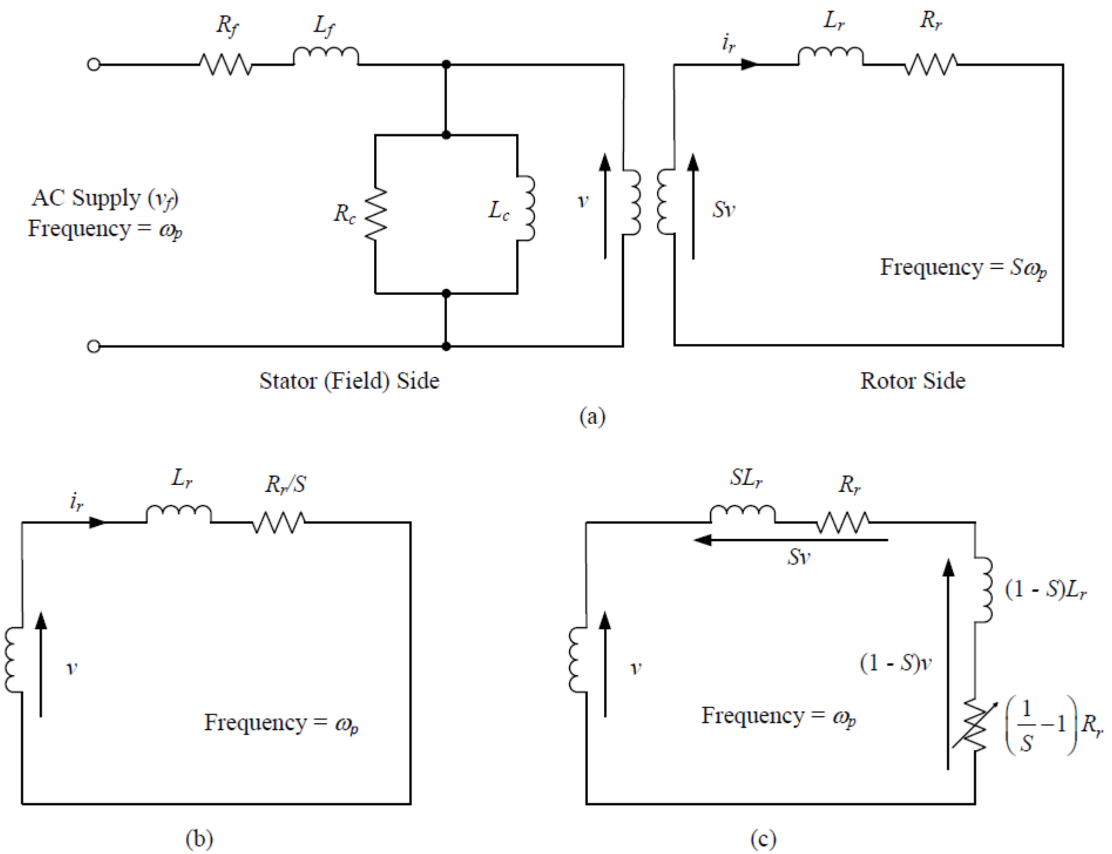
Explain the reasoning for "stable" and "unstable" regions.

Slip $$S = \frac{\omega_f - \omega_m}{\omega_f}$$

Induction Motor Characteristics (Cont'd)

Steady-state Torque-speed Relation

Circuits for One Phase:



Try to understand what is happening In these circuits

(a) Stator and rotor circuits for an induction motor; (b) Rotor circuit referred to the stator side; (c) Representation of available mechanical power using the rotor circuit.

Induction Motor Control

Steady-state Torque-speed Characteristic:

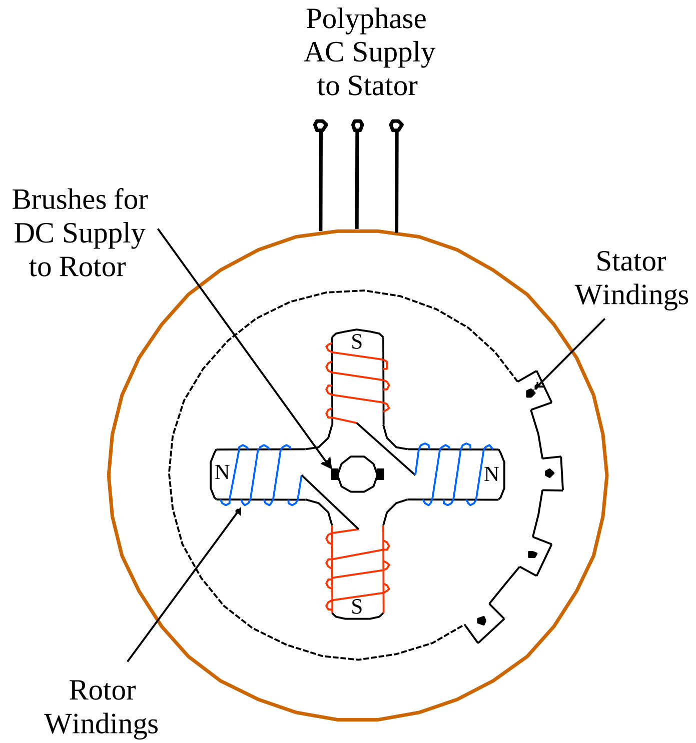
$$T_m = \frac{pnv_f^2 S R_r}{\omega_p (R_r^2 + S^2 \omega_p^2 L_r^2)}$$

Control Methods:

1. **Excitation frequency control (*ω_p*)**
2. **Supply voltage control (*v_f*)**
3. **Field Vector (Flux Vector) Control (Control both magnitude and phase of each phase. Behaves like a DC motor ➔ best torque characteristics)**
4. **Rotor resistance control (*R_r*)**
5. **Pole changing (*n*)**

Synchronous Motors

- Rotor of a synchronous AC motor rotates in synchronism with the rotating magnetic filed



- Rotor coil is powered by DC: Use, 1. Separate DC supply; 2. AC supply and rectifier (AC→ DC converter); 3. As rotor rotates, switch to small, built-in DC generator
- Rotor speed = rotating field speed = synchronous speed
- Good for constant-speed applications

Question

Compare Operation and Control of DC Motor and AC Motor.

DC Motor:

Advantages

Disadvantages

AC Motor:

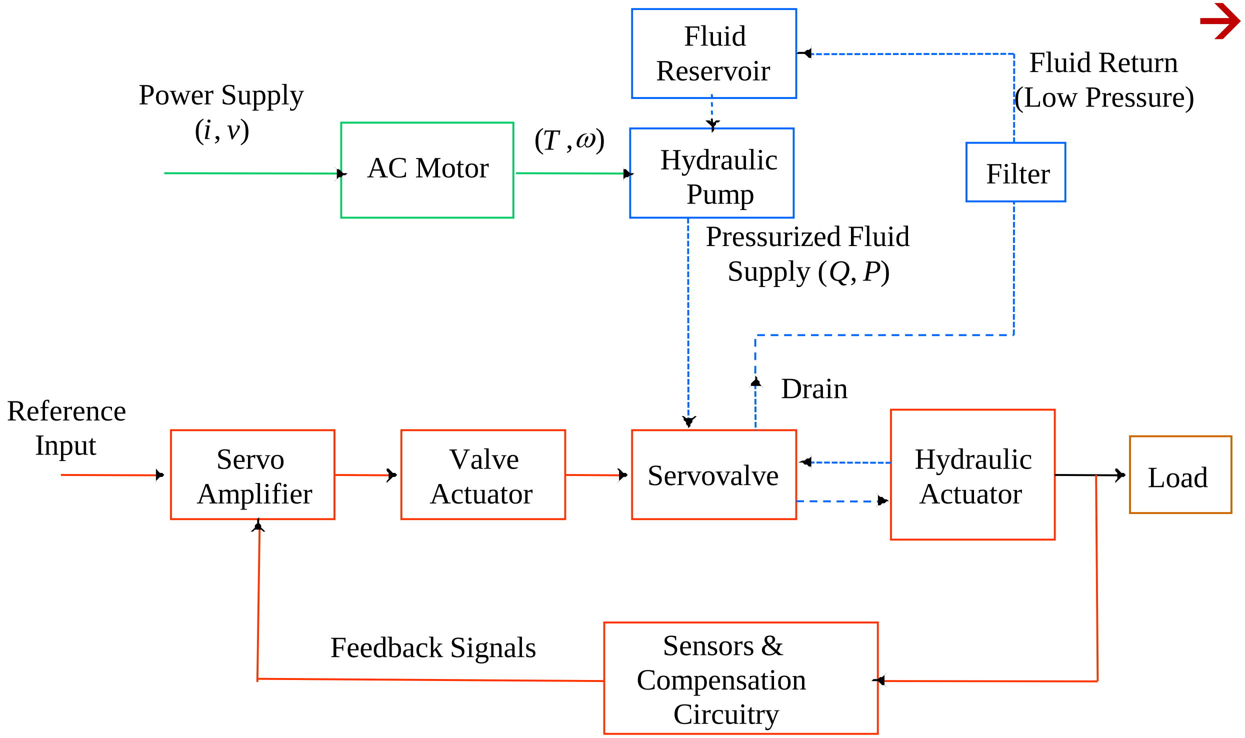
Advantages

Disadvantages

Hydraulic Systems

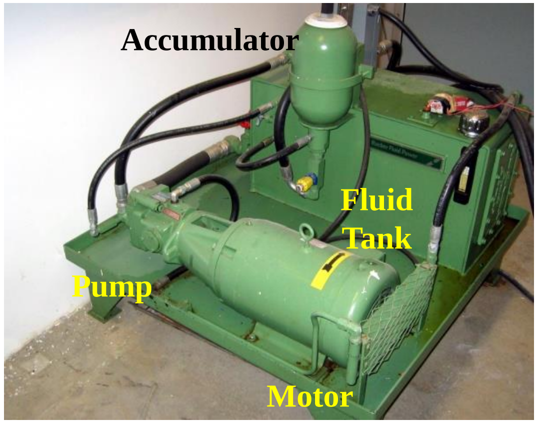
Hydraulic Systems

Electric power → Mech power → Fluid power → Mech power



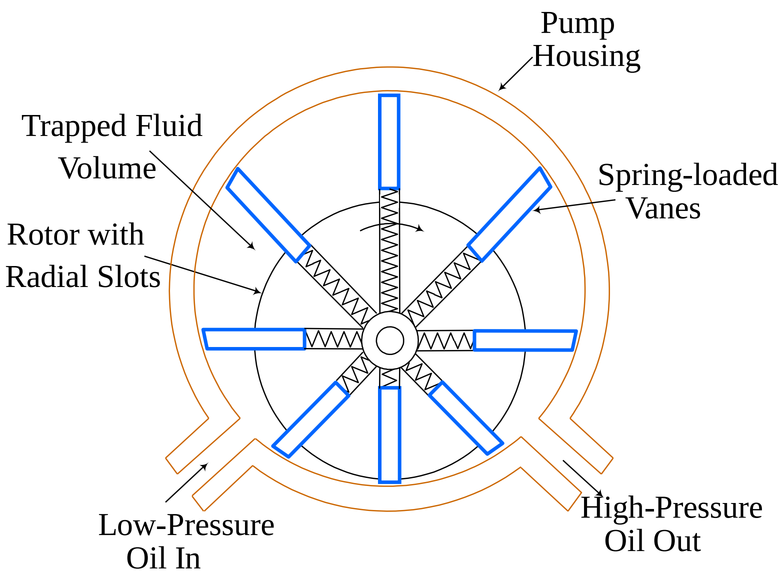
See Lab 5 Video

3-roll Calender Machine with Hydraulic Actuators (produces plastic sheets)
Hydraulic pump uses an induction motor

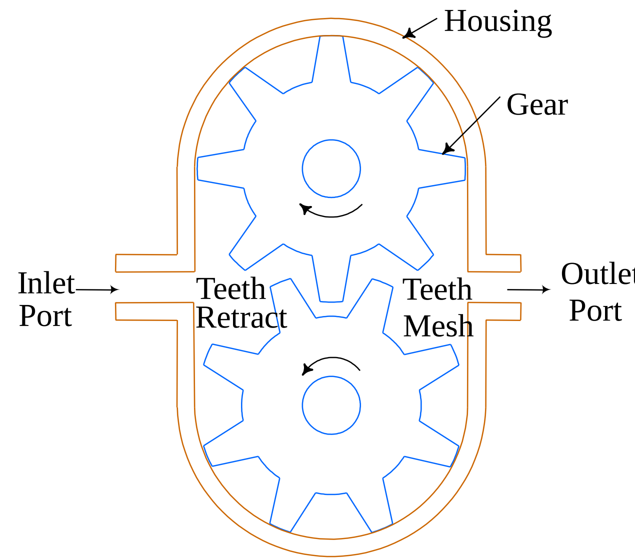


Typical Hydraulic Supply

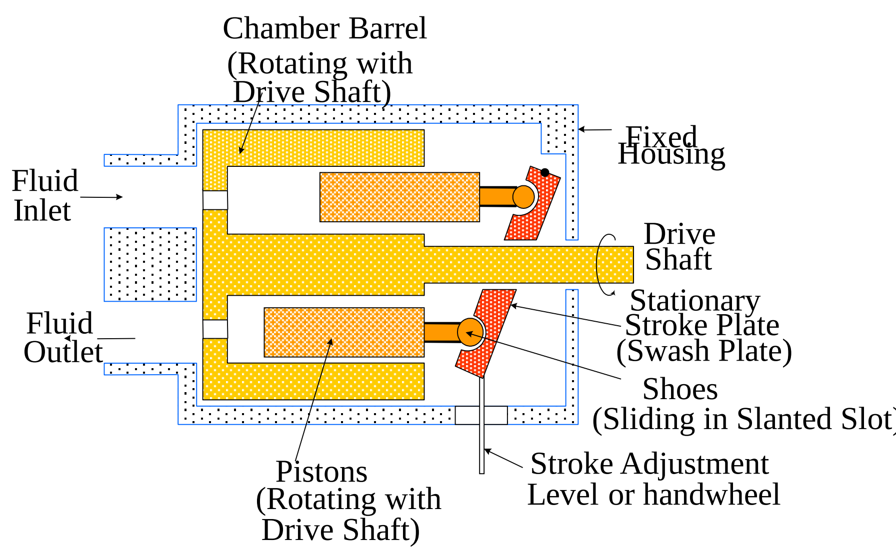
Hydraulic Pumps (Mechanical → Fluid)



Vane Pump



Gear Pump

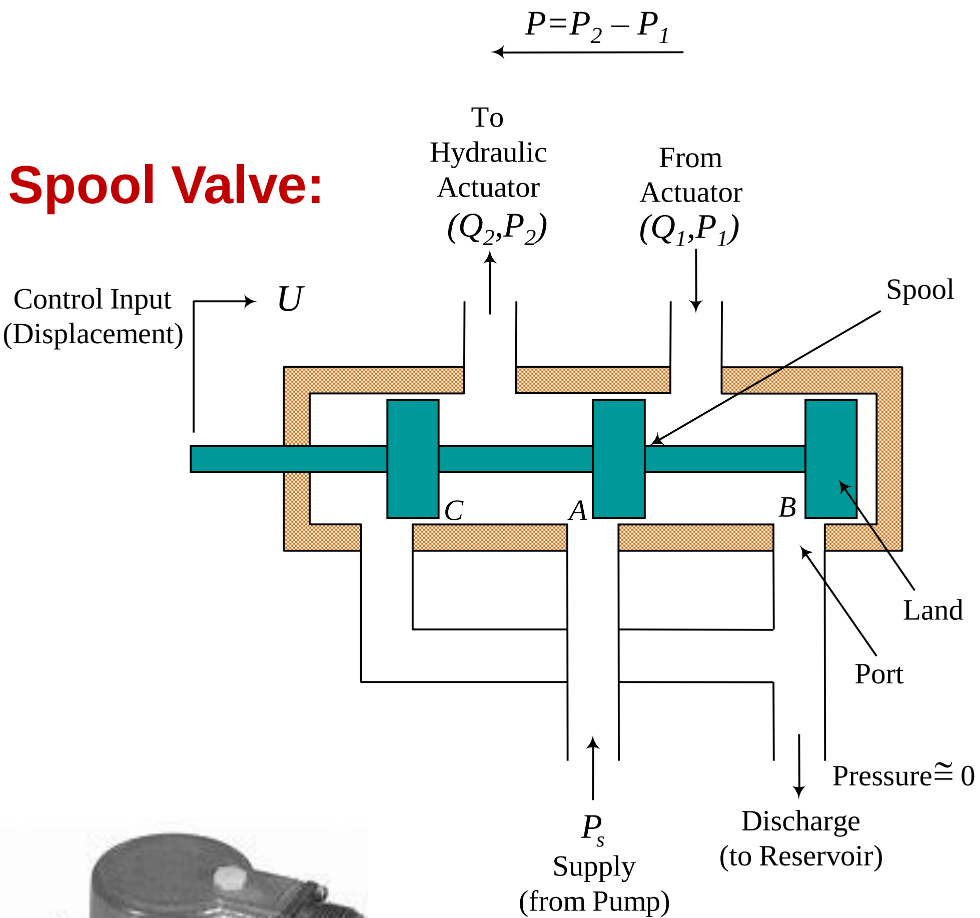


Piston Pump

Pump Efficiency $$\eta_p = \frac{PQ}{\omega T}$$

Hydraulic Servo-valve

Spool Valve:



Flow-Pressure-Spool Displacement Equations:

$$\delta Q_2 = k_q \delta U - k_c' \delta P_2$$

$$\delta Q_1 = k_q \delta U + k_c' \delta P_1$$

$$Q = \frac{Q_1 + Q_2}{2} \; ; \; P = P_2 - P_1 \; ; \; k_c = \frac{k_c'}{2}$$

Spool Valve Equation:

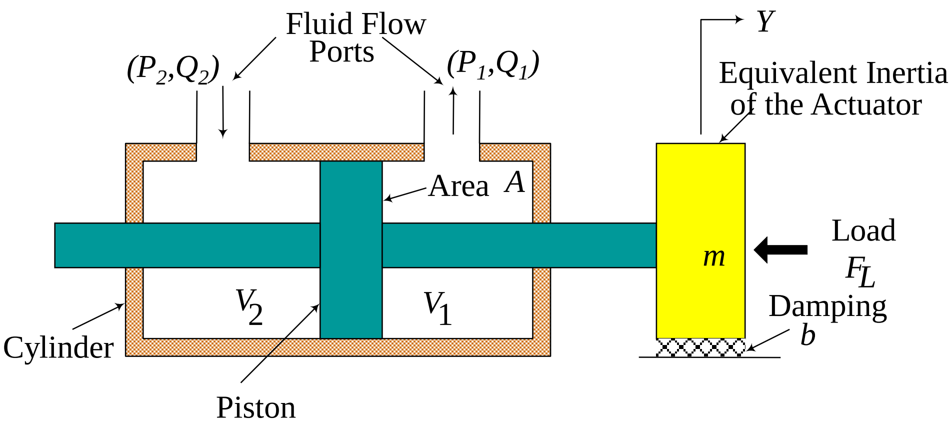
$$\delta Q = k_q \delta U - k_c \delta P$$

Flow Gain: $$k_q = \frac{\partial Q}{\partial U}$$

Flow-Pressure Coefficient: $$k_c = -\frac{\partial Q}{\partial P}$$

Pressure Sensitivity: $$k_p = \frac{\partial P}{\partial U} = \frac{k_q}{k_c}$$

Hydraulic Actuator



- **Flow rate into the chamber**
  - **Chamber volume**
  - **Pressure (compressibility)**
- **Bulk Modulus:** $\beta = -V \dfrac{\partial P}{\partial V}$

Load Equation:

$$m\frac{d^2Y}{dt^2} + b\frac{dY}{dt} = A(P_2 - P_1) - F_L$$

→

$$m\frac{d^2\delta Y}{dt^2} + b\frac{d\delta Y}{dt} = A\delta P - \delta F_L$$

Flow Equations:

$$Q_2 = A\frac{dY}{dt} + \frac{V_2}{\beta}\frac{dP_2}{dt} \quad \textbf{and} \quad Q_1 = A\frac{dY}{dt} - \frac{V_1}{\beta}\frac{dP_1}{dt}$$

For incremental changes about the operating point $V_2 = V_1 = V$:

$$\delta Q_2 = A\frac{d\delta Y}{dt} + \frac{V}{\beta}\frac{d\delta P_2}{dt} \quad \textbf{and} \quad \delta Q_1 = A\frac{d\delta Y}{dt} - \frac{V}{\beta}\frac{d\delta P_1}{dt}$$

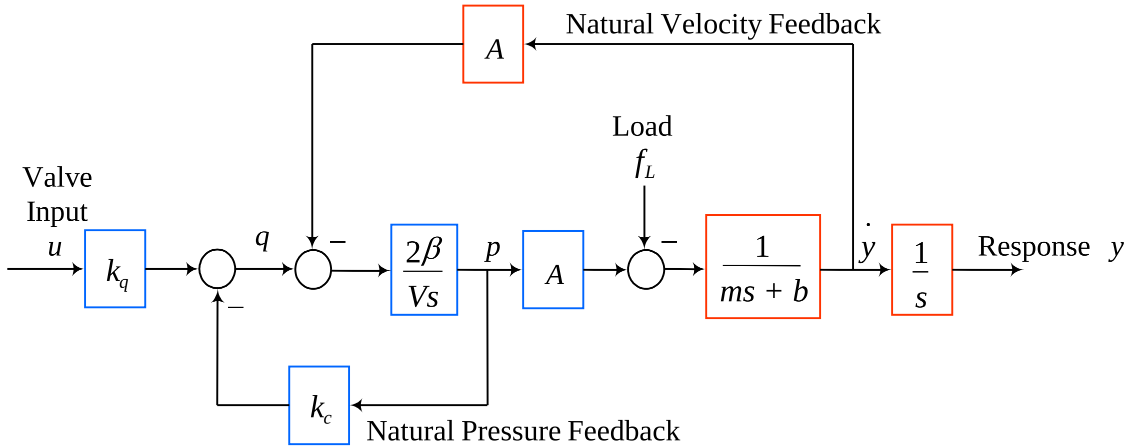
→

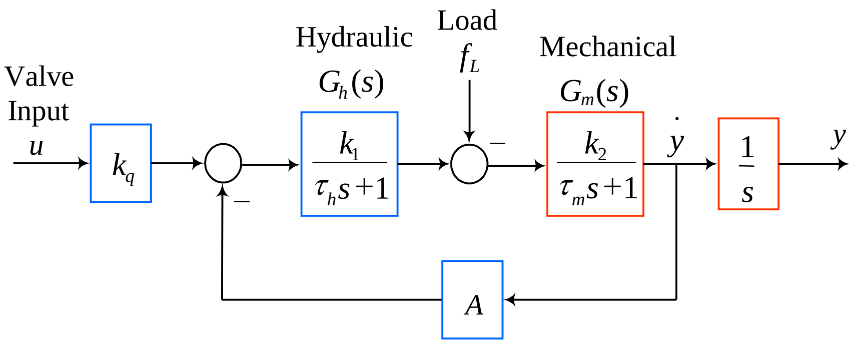
$$\delta Q = A\frac{d\delta Y}{dt} + \frac{V}{2\beta}\frac{d\delta P}{dt}$$

With $Q = \dfrac{Q_1 + Q_2}{2}$ **and** $P = P_2 - P_1$

Hydraulic Control System

Valve: $q = k_q u - k_c p$; **Hydraulic Actuator:** $q = A\dfrac{dy}{dt} + \dfrac{V}{2\beta}\dfrac{dp}{dt}$; **Load:** $m\dfrac{d^2y}{dt^2} + b\dfrac{dy}{dt} = Ap - f_L$





Advantages

When compared with electro-magnetic actuators:

- **Higher torque/mass ratio**
- **Greater flexibility of providing multiple actuators at different physical locations using the same power source**
- **Stiffer system with greater bandwidth**
- **More efficient heat removal and reduced thermal problems**
- **Self-lubricating**
- **Less hazardous**

***Note*: Pneumatic actuators are similar except the fluid—gas is more complex (compressible and temperature dependent). Also, the fluid is normally not circulated (exhausted to the atmosphere)**

Question

Outline the Design/Operation of a “Rotary” Hydraulic Actuator.

MECH 420 Roadmap—Review