Actuators

Introduction

- Electric motors (전기)
  - Servomotors : DC / AC
  - Stepper motors
  - Direct drive electric motors
- Hydraulic actuators (유압)
- Pneumatic actuators (공압)

Characteristics of Actuating Systems

1. Power to Weight Ratio

Pneumatic < Electric < Hydraulic

(stepper < servo)

2. Stiffness vs. Compliance
   - Stiffness (강성) : resistance of material against deformation
   - Stiffer system
     - Requires a larger load to deform
     - More responsive and more accurate
     - More damage to other systems when contact or collide

Pneumatic < Electric < Hydraulic

Characteristics of Actuating Systems

3. Reduction Gears
   - Electric motor 의 torque 를 증폭시키기 위하여 사용

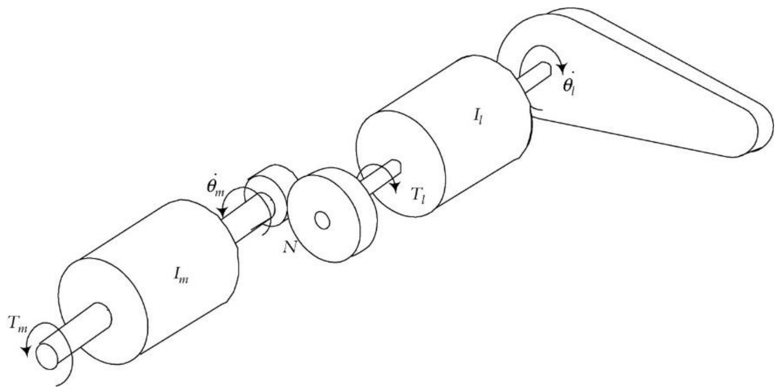
     Torque up / Speed down
   - Power 가 큰 hydraulic actuator, direct-drive motor 에서는 사용하지 않음

➢ 단점
   - Higher weight, more space, more cost
   - **Increase backlash**
   - More noise

➢ 장점
   - Increase resolution
   - **Increase inertia** → 제어를 용이하게 함

Characteristics of Actuating Systems

- Inertia and torque relationships



$$\dot{\theta}_l = \frac{1}{N}\dot{\theta}_m$$
$$T_l = N\,T_m$$

$$\begin{aligned}
T_m &= I_m\ddot{\theta}_m + b_m\dot{\theta}_m + \frac{1}{N}T_l \\
&= I_m\ddot{\theta}_m + b_m\dot{\theta}_m + \frac{1}{N}\left(I_l\ddot{\theta}_l + b_l\dot{\theta}_l\right) \\
&= I_m\ddot{\theta}_m + b_m\dot{\theta}_m + \frac{1}{N^2}\left(I_l\ddot{\theta}_m + b_l\dot{\theta}_m\right) \\
&= \left(I_m + \frac{1}{N^2}I_l\right)\ddot{\theta}_m + \left(b_m + \frac{1}{N^2}b_l\right)\dot{\theta}_m \qquad // \quad I_l = I_l(\theta), b_l = b_l(\theta) \\
&\approx I_m\ddot{\theta}_m + b_m\dot{\theta}_m
\end{aligned}$$

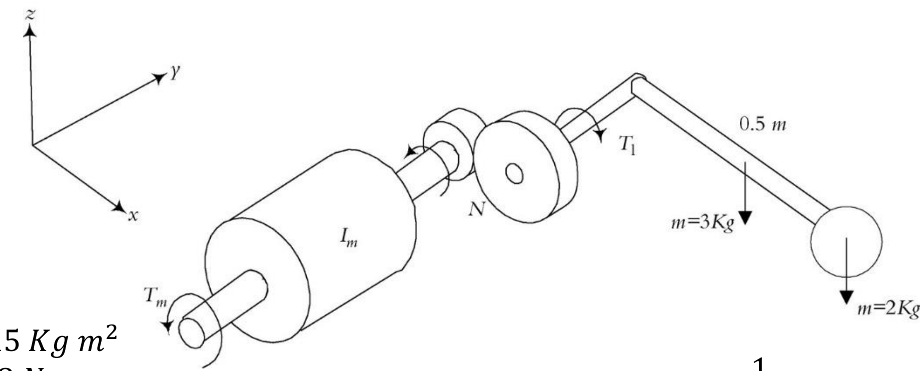
// motor 의 inertia 증가 효과

// non-linear system →linear system

$$I_{Effective} = \frac{1}{N^2}I_l \quad \text{and} \quad I_{Total} = \frac{1}{N^2}I_l + I_m$$

Characteristics of Actuating Systems

(Example)



$I_m = 0.015\ Kg\ m^2$
$T_m = 8\ Nm$

$$I_l = I_{arm} + I_{mass} = \frac{1}{3} \times 3 \times 0.5^2 + 2 \times 0.5^2 = 0.75\ Kg\ m^2$$

$$I_{total} = \frac{1}{N^2} I_l + I_m$$

(a) N=3

$$I_{total} = \frac{1}{9} \times 0.75 \quad +0.015 = 0.098$$

$$\ddot{\theta}_m = \frac{T_m}{I_{total}} = \frac{8}{0.098} = 81.6\ rad/s^2$$

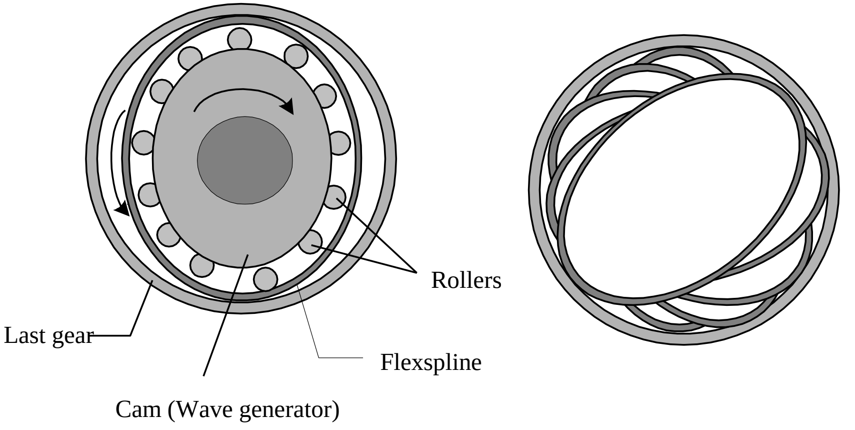
(b) N=30

$$I_{total} = \frac{1}{900} \times 0.75 \quad +0.015 = 0.0158$$

$$\ddot{\theta}_m = \frac{T_m}{I_{total}} = \frac{8}{0.0158} = 506.3\ rad/s^2$$

Harmonic Drive

- Backlash 최소화
  - a flexspline gear is used to overcome interference between gears



Harmonic Drive

https://www.youtube.com/watch?v=nj1vO3cP7ug

Comparison of Actuating Systems: Hydraulic

- \+ Good for large robots and heavy payload
- \+ Highest power/weight ratio
- \+ Stiff system, high accuracy, better response
- \+ No reduction gear needed
- \- May leak; not fit for clean room applications
- \- Requires pump, reservoir, motor, hoses, and so on
- \- Can be expensive and noisy; requires maintenance
- \- Viscosity of oil changes with temperature
- \- Very susceptible to dirt and other foreign material in oil
- \- Low compliance

Comparison of Actuating Systems: Electric

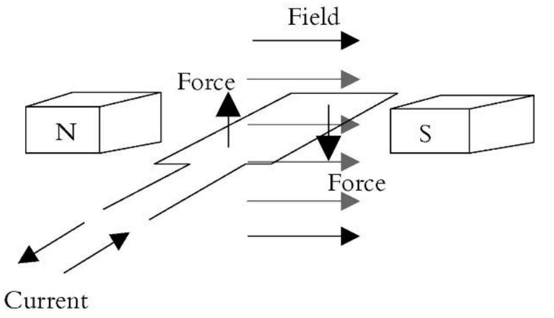
- + Good for all sizes of robots
- + Better control, good for high precision robots
- + Higher compliance than hydraulics
- + Does not leak, good for clean room
- + Reliable, low maintenance
- + Can be spark-free. Good for explosive environments
- - Low stiffness
- - Needs reduction gears, increased backlash, cost, weight, and so on

Comparison of Actuating Systems: Pneumatic

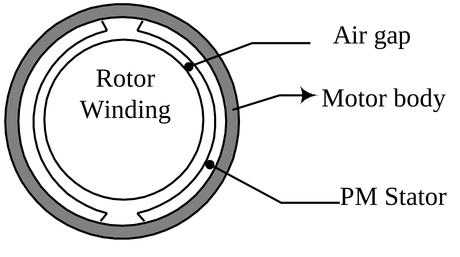
- + No leaks or sparks
- + Inexpensive and simple
- + Low pressure compared to hydraulics
- + Good for on-off applications and for pick and place
- + Compliant systems
- - Noisy
- - Require pressurized air, filter, and so on
- - Difficult to control their linear position
- - Very low stiffness Inaccurate response
- - Lowest power to weight ratio

Electric Motors

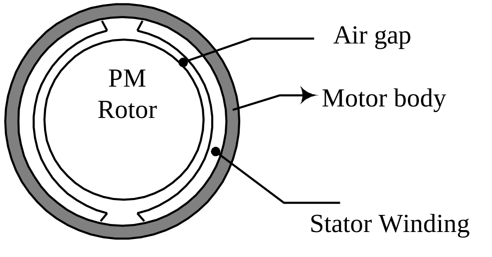
- 동작원리 : 플레밍 왼손법칙



- Stator (고정자) vs. Rotor (회전자)
  - DC Motor : Stator = PM (자석) , Rotor = Winding
  - AC Motor : Stator = Winding , Rotor = PM



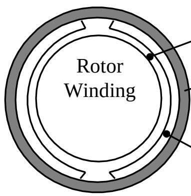
DC motor



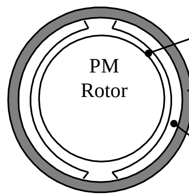
AC motor

Electric Motors

- Heat dissipation path



DC motor



AC motor

Winding 에서 열 발생

$$P_{electric} = i^2 R = \frac{T^2}{K_t^2} R_t$$

1) DC Motor

   Rotor → airgap → stator → body

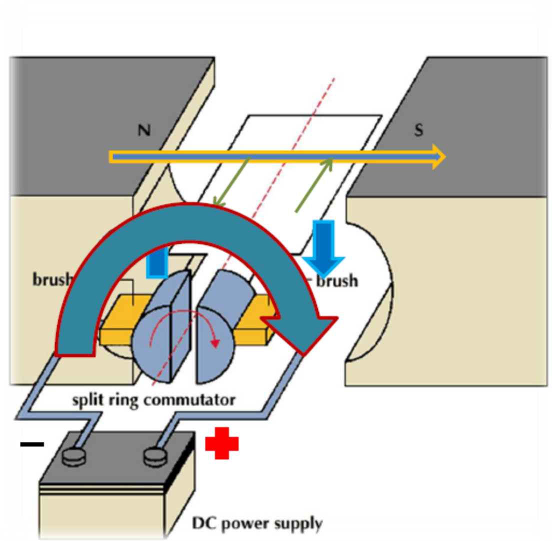
2) AC Motor

   Stator → body

❖ AC Motor 의 stator 에 더 많은 전류를 흘릴 수 있음
→ More powerful

DC Motor

- 원리



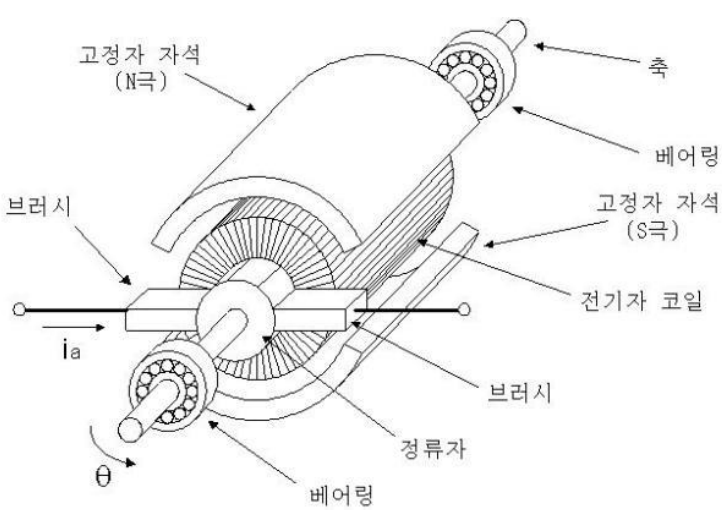
1. 모터내부의 자기장 형성

2. 전압이 인가되어 전류가 흐르면

3. 플레밍의 왼손법칙에 따라 회전력이 발생

4. 로터가 시계방향으로 회전

- 구조



Commutator(정류자):
rotor 가 한 방향으로 계속 회전할 수 있도록 전류 흐름 유지

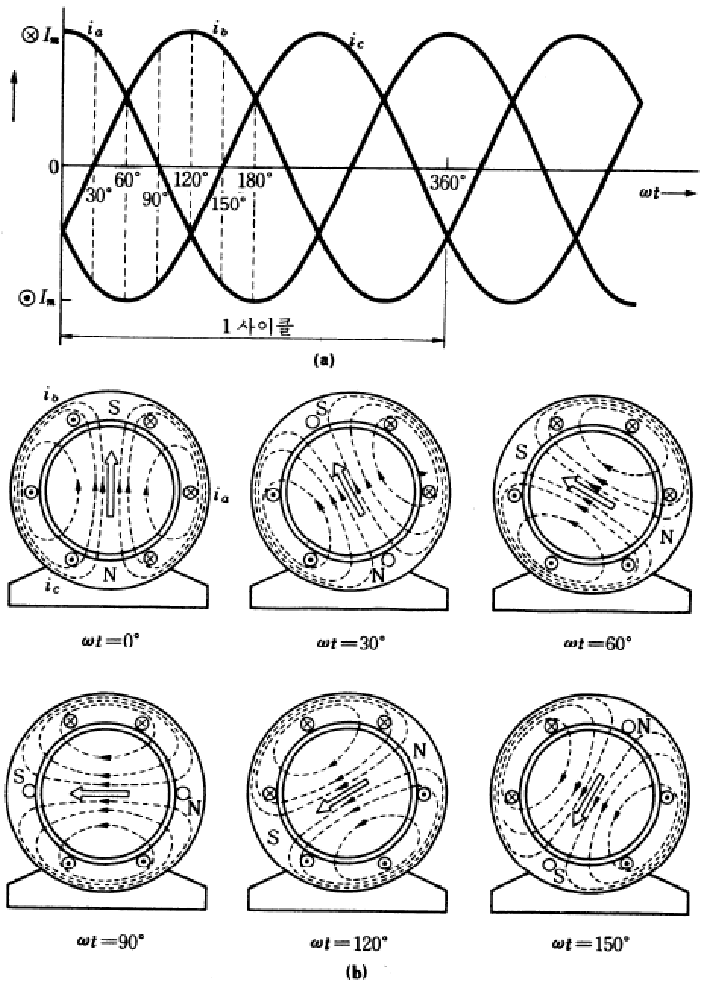
Commutator 와 Brush 간의 마찰 발생
→ Brush 마모 및 noise
→ Brush 교환 필요

DC Motor

https://www.youtube.com/watch?v=LAtPHANEfQo

AC Motor

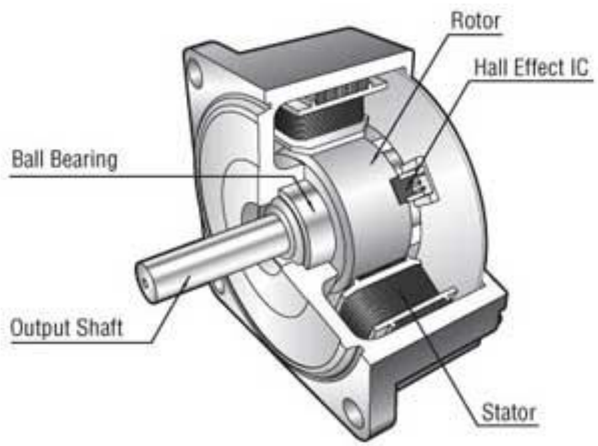
- 회전자계 (rotating flux)



https://www.youtube.com/watch?v=FQRe7K1m8RU

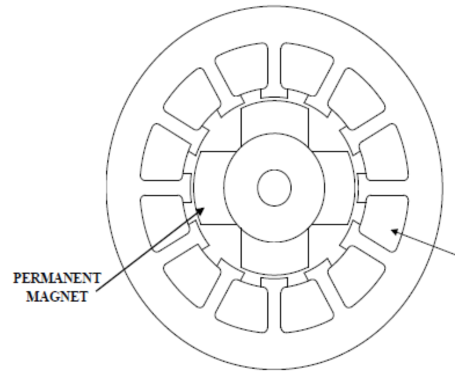
AC Motor

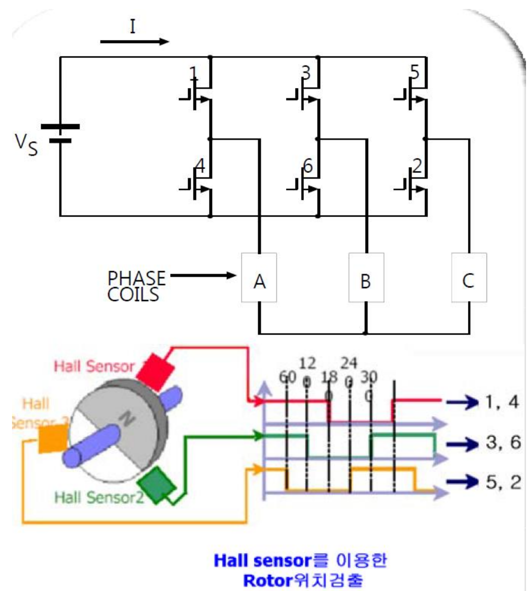
- 특징
  - The rotor is permanent magnet,
  - The stator houses the windings
  - No brushes or commutators
  - Changing flux is provided by the AC current
  - Speed is a function of line frequency
  - Can dissipate heat more favorably than DC motors; more powerful



Brushless DC Motor

- 원리
  - DC motor 특성
    - DC 전원 공급
  - AC motor 특성
    - Rotor : PM
    - No brush / commutator





3상 BLDC Motor에 사용되는
스위칭 소자를 이용한 구동회로

Brushless DC Motor

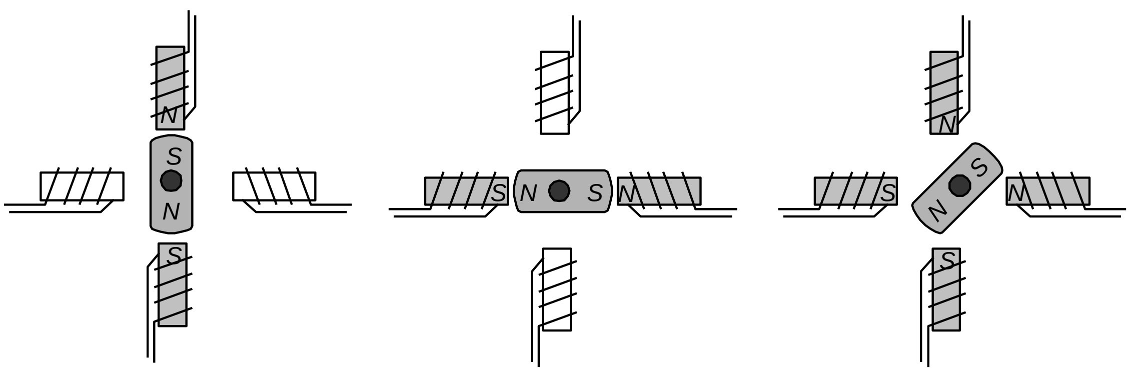
https://www.youtube.com/watch?v=bCEiOnuODac

Brushless DC Motor

항목	일반 DC모터	BLDC 모터
기본 구조	• 회전전기자형	• 회전계자형
회전자 위치 검출	• 브러시의 기계적인 위치	• 위치 검출 소자 및 Logic 회로
정류방법	• 브러시와 정류자 접촉에 의한 기계적인 스위칭	•반도체 소자를 이용한 전자 스위칭
역회전방법	• 단자전압의 극성 변경	• 스위칭 순서의 변경
특징	• 대응성 및 제어성이 우수 • 정기적인 보수 필요 • 전기 기계적인 잡음 발생 • 브러시/정류자 사용으로 고속운전 불가능 • 외형이 크고 구조 복잡	• 장기간 사용가능 • 보수 불필요 • 전기 기계적인 잡음 없음 • 고속운전 가능 • 소형화, 박형화가 가능

Stepper Motor

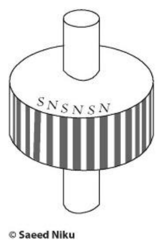
- 특성
  - Stepper motors are versatile, robust, and simple motors.
  - They require a drive circuitry, but no feedback.
  - Each step provides a known angle of motion.
  - Unless a step is missed, speed and positional control is easy.
  - Stepper motors have soft iron or PM rotors.
  - Their stators house multiple windings.
  - Construction is similar to AC-type motors. (no brush)



(a) (b) (c)

Stepper Motor

- Rotor & Stator 예



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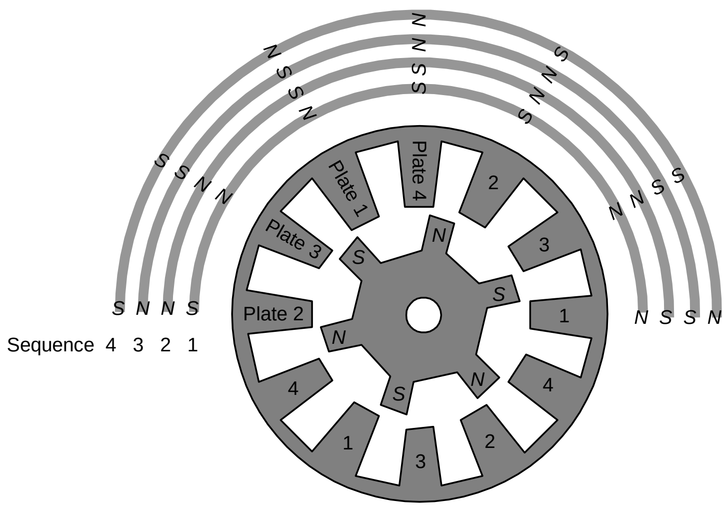
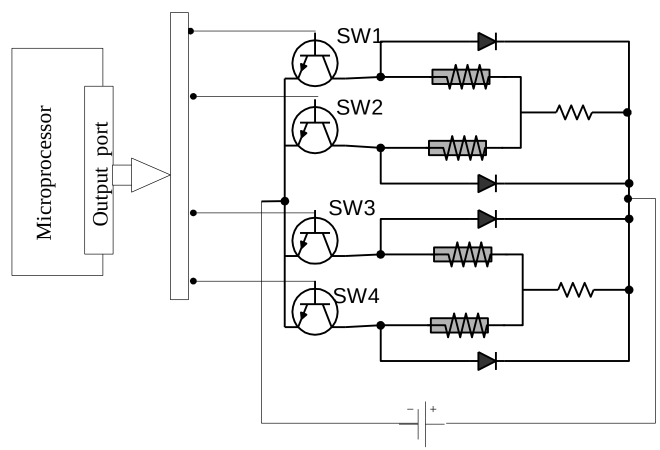
- Rotating pattern 예





https://www.youtube.com/watch?v=eyqwLiowZiU

Stepper Motor

https://www.youtube.com/watch?v=eyqwLiowZiU

DC Motor Modeling

- DC 모터의 모델
  - 입력: 전압(voltage)
  - 출력: 관성부하(inertial load)의 회전속도(rotational velocity)
  - SISO(Single Input Single Output) system
  - 주요 물리량: 저항(R), 인덕턴스(L)

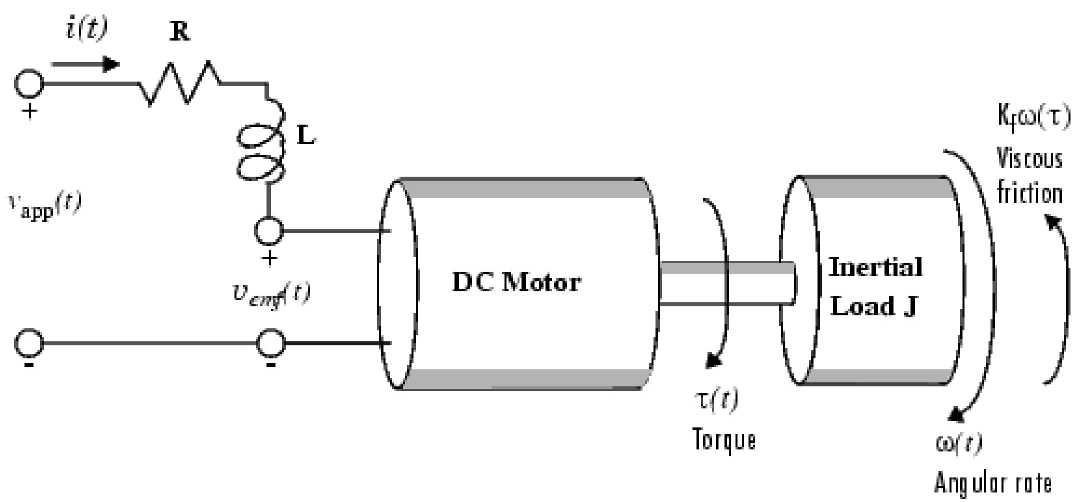


그림 7.2 DC 모터의 모델

DC Motor Modeling

- For armature-controlled moter

the motor torque is

$$T_m(s) = K_t I(s) \qquad (7.1)$$

back electromotive-force voltage(EMF)

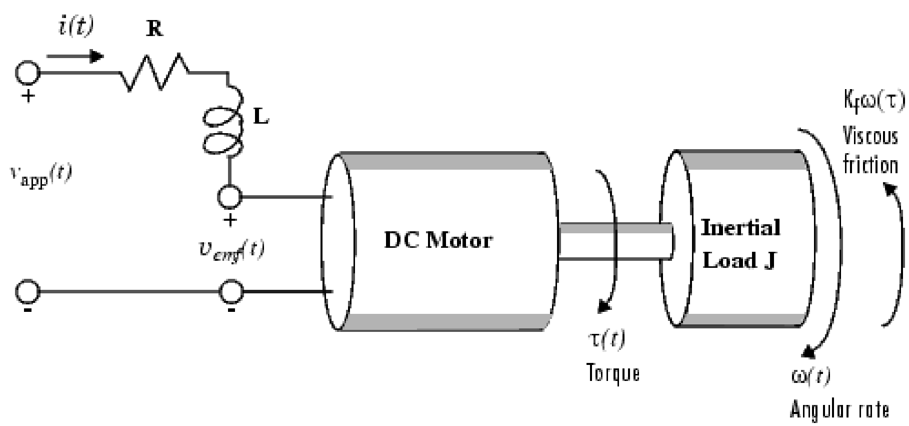
$$V_e(s) = K_e \omega(s) \qquad (7.2)$$

the equation of motion of motor

$$Js\omega(s) + b\omega(s) = T_m(s) \qquad (7.3)$$

and,

$$\omega(s) = \frac{1}{Js+b} T_m(s) \qquad (7.4)$$



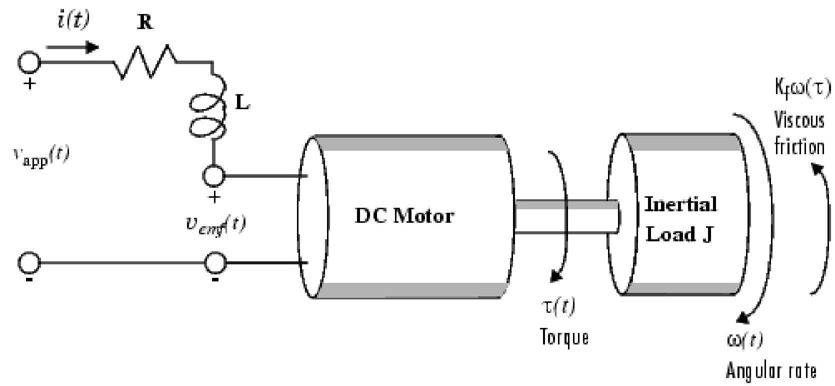
DC Motor Modeling

- **For armature-controlled motor**

$$V(s) - V_e(s) = RI(s) + LsI(s) \qquad (7.5)$$

and,

$$I(s) = \frac{V(s) - V_e(s)}{Ls + R} \qquad (7.6)$$



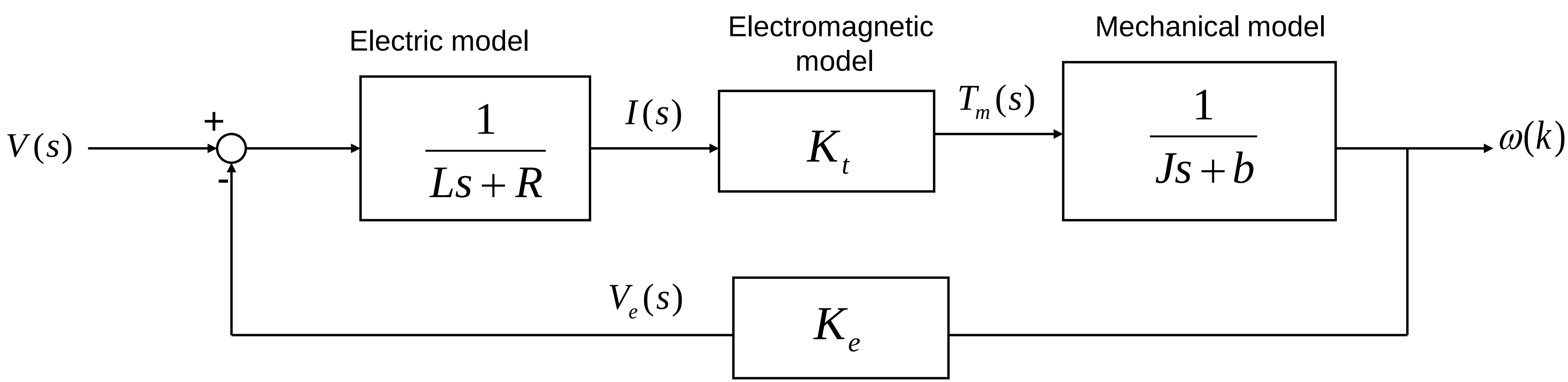


그림 7.3 모터의 동적 모델 블록도

DC Motor Modeling

$$\frac{\omega(s)}{V(s)} = \frac{K_t}{(R+Ls)(Js+b)+K_eK_t}$$

: 2차 시스템

since physically $L << R$

we can make the first order model as

$$\frac{\omega(s)}{V(s)} = \frac{K_t}{RJs+Rb+K_eK_t}$$

: 1차 시스템

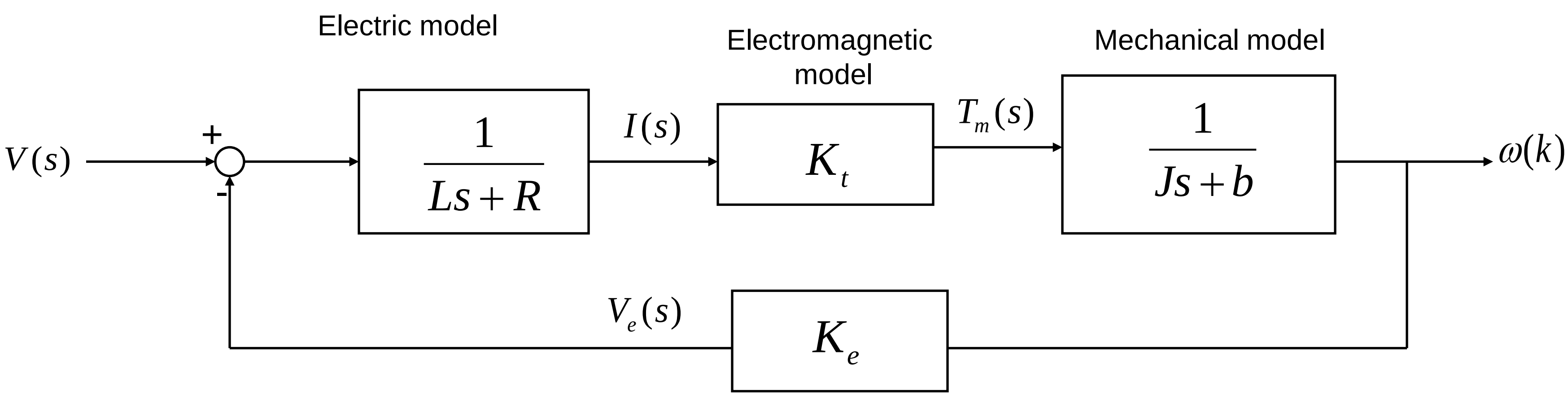


그림 7.3 모터의 동적 모델 블록도

DC Motor Modeling

$$\frac{\omega(s)}{V(s)} = \frac{K}{\tau s + 1}$$

전압-속도는 1차 시스템

$$\frac{\theta(s)}{V(s)} = \frac{K}{s(\tau s + 1)}$$

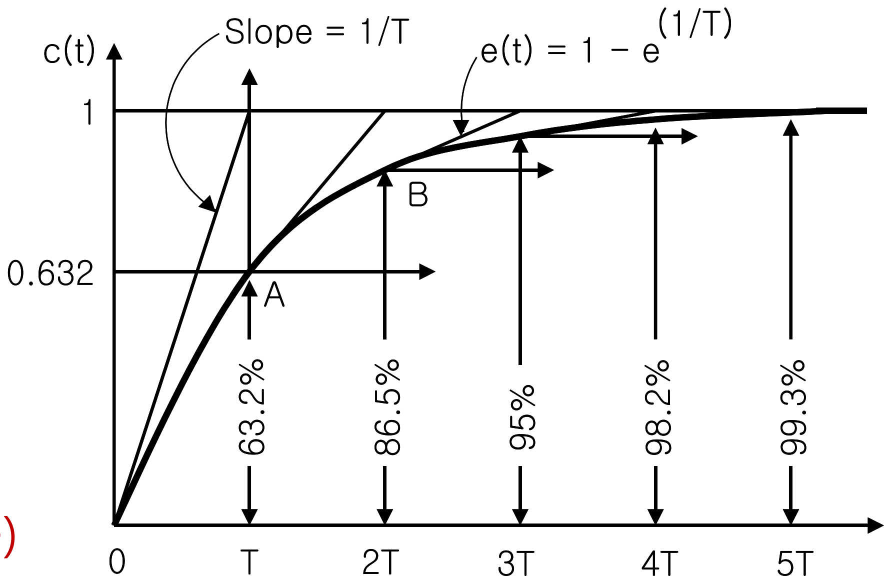
전압-위치는 2차 시스템

where

$$\tau = \frac{RJ}{Rb + K_e K_t}$$

$$K = \frac{K_t}{Rb + K_e K_t}$$

τ : time constant (시상수)



DC Motor Modeling

Physical model of motor

$R = 16.4\Omega$

$J = 3.8 \times 10^{-7} kgm^2$

$K_e = 3.2086 \times 10^{-2} V \sec/ rad$

$K_t = 3.21 \times 10^{-2} Nm / A$

By (7.11) and (7.12)

Continuous model of motor

$$\tau = \frac{RJ}{Rb + K_e K_t} = \frac{16.4 \times 3.8 \times 10^{-7}}{0 + 3.2086 \times 10^{-2} \times 3.21 \times 10^{-2}} \sec = 6.051 \times 10^{-3} \sec$$

$$K = \frac{K_t}{Rb + K_e K_t} = \frac{1}{3.2086 \times 10^{-2}} = 31.1662 rad / \sec$$

By (7.19) to (7.22)

model of motor

$$\frac{\omega(s)}{V(s)} = \frac{31.1662}{0.006051 s + 1}$$