Mech 1751: Introduction to Mechatronics

Actuators

Dr. Stefan B. Williams

Schedule of Events

Week	Date	Content	Assignment Notes
1	09/3	Introduction	
2	16/3	Design Process	
3	23/3	System Modelling and Control	
4	30/3	Actuators	
5	6/4	Sensors	**Assignment 1 Due**
		Break	
6	20/4	Computer – Hardware	
7	27/4	Computer – Software	
8	4/5	Active Sensing Systems	
9	11/5	Digital vs. Power Electronics	**Assignment 2 Due**
10	18/5	Case Study : Formula SAE	
11	25/5	Case Study : Unmanned Air/Land/Sea Vehicles	
12	1/6	Guest Lecture	
13	8/6	Review	**Major Assignment Due**
14	15/6	Spare	

What is an actuator?

- a mechanical device for moving or controlling something
- Electric Motors and Drives
- Hydraulic Drives
- Pneumatic Drives
- Internal Combustion hybrids
- Actuators of the future

Electric Actuators and Drives

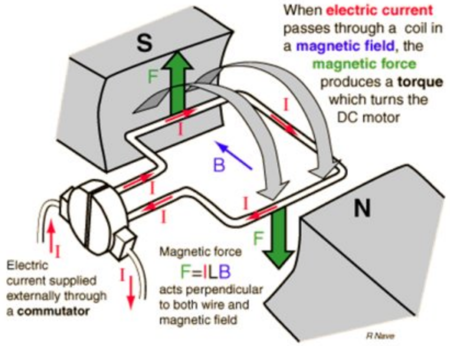
Electrical energy transformed to mechanical energy

- DC Motors
- AC Motors
- Linear Motors
- Stepper Motors

DC-Motors

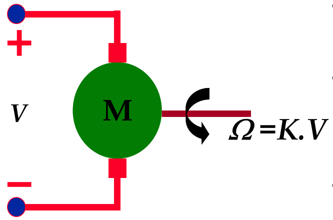
- Rotary actuators
- Power range: Fractions of watts to 100s of Kw.
- Power supply by grid, diesel generator, or batteries
- Easy to control accurately

Basic Operating Principle



Basic Operating Principle

DC-Motors



- Apply a voltage to armature
- Armature rotates in magnetic field
- Speed control by:
  - Armature voltage
  - Field Strength
- Speed proportional to Voltage
- Torque proportional to current
- Power=Speed x Torque

DC Motors: Basic Rules I

Torque proportional to current

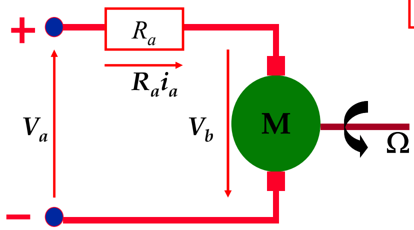
$$T = K_T i_a$$

Torque Constant

Current flowing in Armature

DC Motors: Basic Rules II

Voltage Balance in Armature



$$R_a i_a + V_b = V_a$$

$$R_a i_a + K_b \Omega = V_a$$

Voltage generated by motion of armature in field (like a Generator)

Back EMF Constant

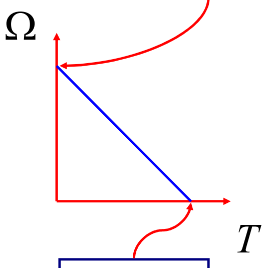
DC Motors: Basic Rules III

Torque and Speed

$$T = K_T i_a$$

$$R_a i_a + K_b \Omega = V_a$$

$$\Omega = -\frac{R_a}{K_b K_T} T + \frac{1}{K_b} V_a$$

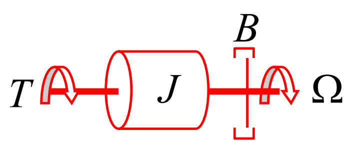


No-load Speed

Stall Torque

DC Motors Behaviour I

Equations of Motion: Torque Drives a Load



$$T = \frac{K_T V_a}{R_a} - \frac{K_b K_T}{R_a} \Omega$$

+

$$T = J \frac{d\Omega}{dt} + B\Omega$$

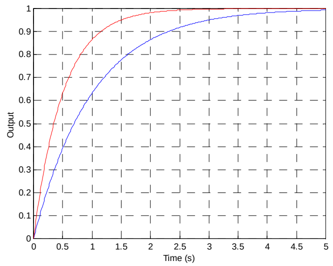
$$J \frac{d\Omega}{dt} + \left(B + \frac{K_b K_T}{R_a} \right) \Omega = \frac{K_T V_a}{R_a}$$

DC Motors: Behaviour II

$$J\frac{d\Omega}{dt}+\left(B+\frac{K_bK_T}{R_a}\right)\Omega=\frac{K_T}{R_a}V_a$$

$$\frac{d\Omega(t)}{dt}+K_1\Omega(t)=K_2V(t)$$

$$\Omega(t)=K_2e^{-K_1t}V(t)$$



Step response of motor speed with varying load

DC Servo Motors

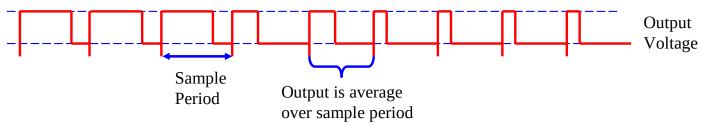
- Power range: few W to few kW: for disc drives, X-Y recorders, instruments, robot arms
- Speed: very low to very high 10000 rpm (use gear boxes)
- Time-constants (ms): Electrical, Mechanical and thermal
- Friction: Coulomb, viscous, stiction
- Often in-built encoders or tachometers

Permanent Magnet DC Motors

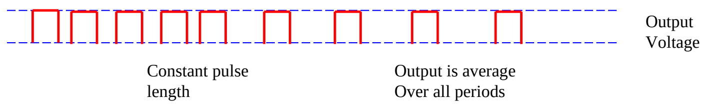
- Many DC Servos are now brushless PM-DC motors because of advances in:
  1. **High energy ceramic and rare earth magnets**
  2. **Development of high power switching semiconductors**
- No field windings
- Result is motors which are smaller and linear
- Motor is inside-out (magnets rotate).

Digital Control of DC Motors

Pulse-Width-Modulated (PWM)



Pulse-Rate-Modulated (PRM)



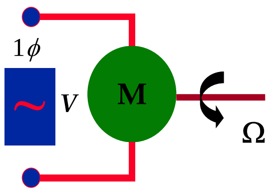
When to use a DC Motor

- Accurate position or velocity control
- Low noise, high efficiency
- Cost not too critical
- Speed and power payoff (gearing)

Some Examples

- Consumer Products:
  - CDs, disk drives
  - Fans, drills, etc
- Manufacturing
  - Robots
  - CNC machines
- Aerospace
  - Sensor pointing
  - Fly-by-wire inputs
- Cars:
  - Windscreen wipers
  - Fuel management

AC-MOTORS: An Introduction

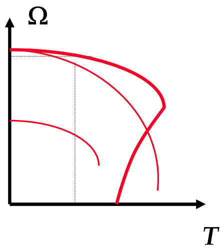


- Single or three phase motors
- 100 Watts – MW
- High power high torque applications
- Brushless, durable, easy to maintain
- Now fully digital vector controlled

AC-MOTORS: An Introduction

AC-MOTORS: Main Features

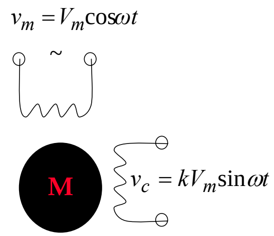
- Brush free full digital control
- Requires sophisticated algorithms to control speed (hence recent)
- Frequency control via power converter (field control)
- Suitable for high speed and/or high power applications
- Complex structure, heavy weight



Multi-phase AC servo motors

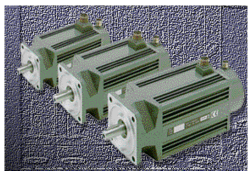
- Drive voltages out of phase
- Multi-phase induction
- Better control and power density
- Transfer function is second order

$$\frac{\theta_r}{v_c} = \frac{k}{s(\tau_m s + 1)}$$



When to Use an AC Motor

- High power required
- Complex control profiles:
  - Point to point
  - Velocity
- Load Demand
  - High duty cycle
  - Efficiency
  - Reliable

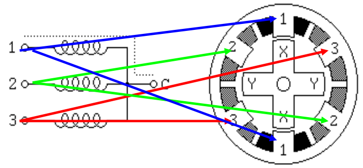


Applications of AC Drives

- Large Cranes or material handling systems
- Belts or conveyors
- High Speed Trains
- Electric Drive Haul Trucks (930E)

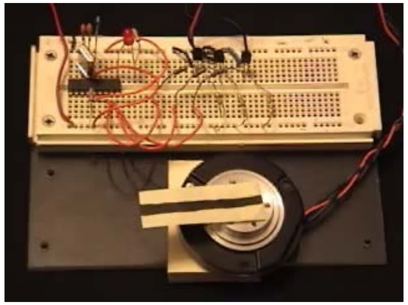
Stepper Motors

- Motors that cause angular shift correspondence to a number of pulses
  - 1st method: providing a fixed number of pulses, motion proportional to number of pulses
  - 2nd method: synchronising rotations with the input pulse frequency



Stepper Motors

- PM type: permanent magnets rotor
- VR (variable reluctance) type: salient poles rotor, torque is generated from difference of magnetic resistance
- Applications: Electronic typewriters and printers, magnetic disk drives

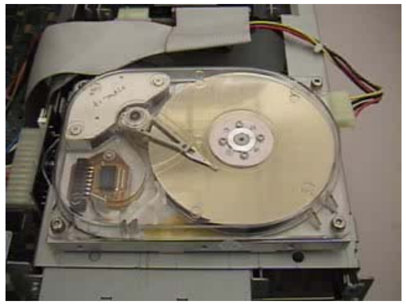


Voice Coil

- Voice coil is an actuator based on similar principles to a motor – current appplied to coil induces magnetic field
- Uses closed loop feedback servoing to dynamically position heads in a computer hard drive
- Name voice coil comes from resemblance to technology used to drive audio speaker

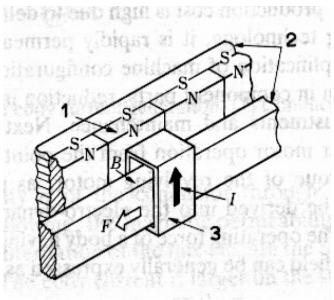
Computer Hard Drive

- Hard drive uses 3 phase AC motor to turn disk
- Originally used stepper motors to position read head
- Modern hard drives use voice coil to position read head



Linear Motors: Brief Introduction

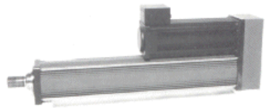
- Slider (rotor), stationary part (stator), and gap are extended in a straight line
- Linear DC motors, stepping motors, induction motors, etc.
- Relatively expensive and large for power output

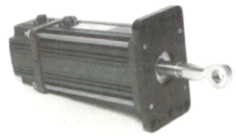


$$F = iB$$

Linear Motors: Brief Introduction

- Miniature & simple structure, low power factor & efficiency
- Linear DC motors: rare earth PMs, two yokes, moving coil
- Linear induction motors: eddy current is developed in a good electrical conductor to obtain thrust





Summary of Electric Motors

Servo Motor	Advantages	Disadvantages	Applicable capacity
DC servo motor:	Easy to use, Low priced control device	Brush replacement. Has restrictions in respect of operating environment	0.1 - few 100 Watts
Brushless motor (PM synchronous) **Synchronous motor (vector control)**	No brush maintenance Excellent environment resistivity	Control device is expensive due to its complexity Detector is necessary	from few W to few kW
Induction motor (vector control)	Durable construction	Complicated control system	More than few W
Stepping motor	Open loop control, large static torque	Dropped out of step. Large weight/capacity ratio	Below few 10 W

Hydraulic Systems and Actuators

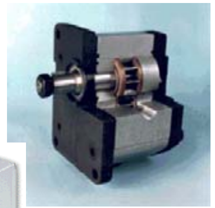
- Hydraulics: Use of fluids to transmit power:
  - Pumps are power generators
  - Inverse pumps or cylinders are power drain
  - Valves used for control
- Traditionally High Power applications
- Now use integrated electronics and sensing

Pump or Rotary motor

Linear Actuator (Cylinder)

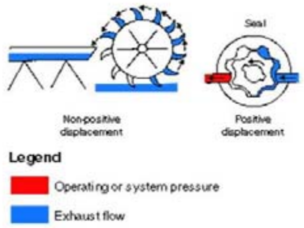
Hydraulic Circuits

- Hydraulic Power Units:
  - Pumps
  - Accumulators (fluid capacitors)
  - Check valves to isolate hydraulic systems
  - Reservoirs
- Piping and Fittings
- Proportional/servo valves
- Hydraulic actuators

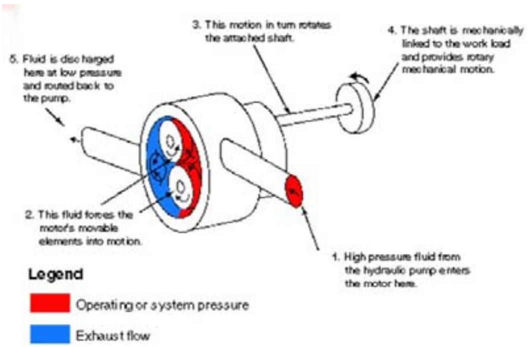



Rotary Hydraulic Pumps and Motors

- General Operating principles:
  - Fluid is compressed by pump on which mechanical work is done
  - Fluid does work in motor producing mechanical power
- Two Types:
  - Vane/gear pumps
  - Piston/swash-plate

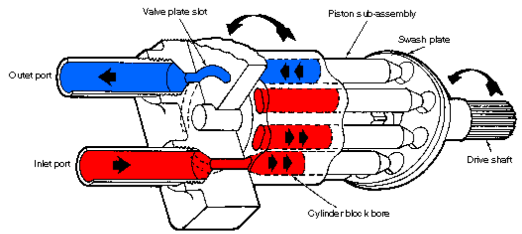


Hydraulic Motor



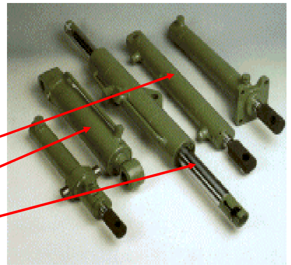
Piston and Swash-plate Pumps/Motors

- Pistons connected to swash plate
- Swash plate is angled
  - **Swash plate rotates and pumps fluid**
  - **Fluid flow rotates swash plate**



Hydraulic Cylinder Actuators

- Piston in cylinder acted on by hydraulic pressure
- Force generated by rod:
  - Single acting
  - Double acting
  - Double cylinder
  - Double rod
- Efficiency governed by friction,
- Small internal leakage: hold static load



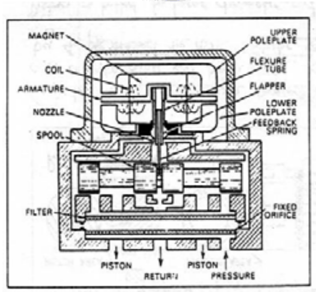
Pressure

Force → $F_c = \lambda \Delta P A_c$ ← Area

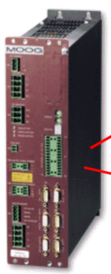
Friction

Hydraulic Valves

- Three main valve types:
  - On/off valves for manual control
  - Proportional valves: Control of volume flow rate
  - Servo valves: Accurate control of flow and pressure
- Control Mode:
- Electric over hydraulic
- Hydraulic over hydraulic (pilot)
- Manual

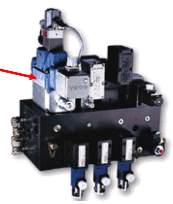


Digital Flow Control



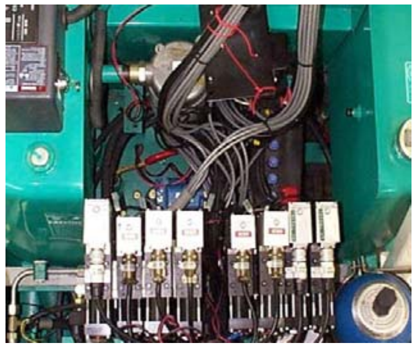
Fully Digital Controller

Integrated Valve



Integrated Manifold

Electro-hydraulic System Example

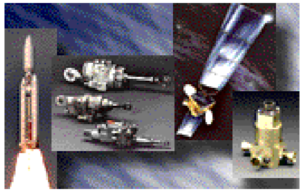


When to use Hydraulics

- Large Force, High Power applications
- High power density
- Accurate control
- Rugged environments (explosive, dusty,etc)
- Now use integrated electronics and sensing
- Wide range of applications:
  - www.moog.com
  - www.rexroth-hydraulics.com

Applications of Hydraulic Systems

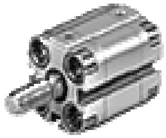
- Heavy Plant
  - Steel press
  - Large-scale precision motion tables
- Mobile Systems
  - Steering, brakes
  - Propulsion and transmission
- Aerospace
  - Aerolon actuation in aircraft
  - Fin actuation in missiles/rockets

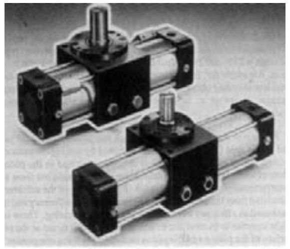


Pneumatic Systems

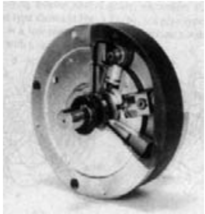
- Many of the same principles as hydraulics except working fluid is compressed air
- Compressed air widely available and environmentally friendly,
- Piping installation and maintenance is easy
- Explosion proof construction
- Major disadvantage is compressibility of air, leading to low power densities and poor control properties (usually on/off)
- Pneumatic systems are suitable for light and medium loads (30N-20kN) with temperature -40 to 200 degrees Celsius

Pneumatic Actuators





Oscillating actuator
(Rack and pinion type)



Air motors
(multi-stroke radial piston type)

Modern Pneumatic Systems

Dual check valves

Linear drive

Twin cylinder piston vacuum pump or compressor 250 W motor developing 2.8 bar with flow to 8.7 m^3/hr

Servovalve offers closed loop control of acceleration, velocity, positioning and force

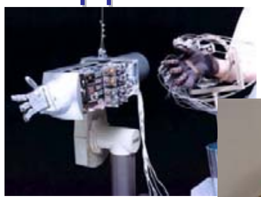
Angular Toggle Gripper

When to use Pneumatics

- Low cost and easy to install
- Clean and easy to maintain
- Low power densities
- Only on/off or inaccurate control necessary

Pneumatic Applications

- Manufacturing
  - Robot grippers
  - Movement of parts
  - Assembly operations
- Medical Systems
  - Drills/cutting tools
  - Suction and clamping
- Robotics
  - Animatronics
  - Grippers
  - Subsea

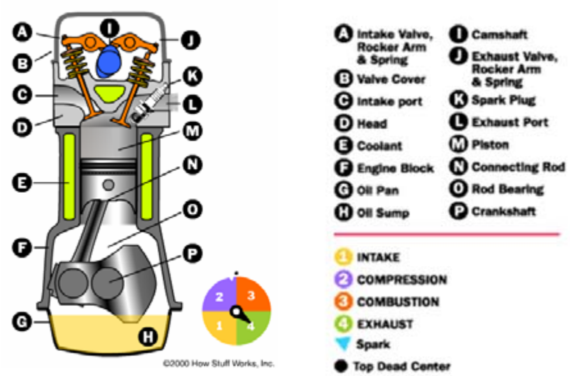


Internal Combustion Engine

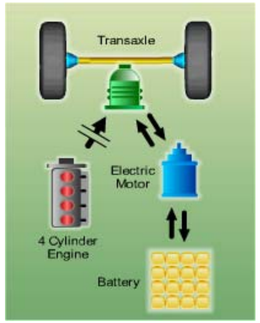
Fuel energy transformed to mechanical energy

- Petrol Engine
- Diesel
- Hybrid

Internal Combustion Engine

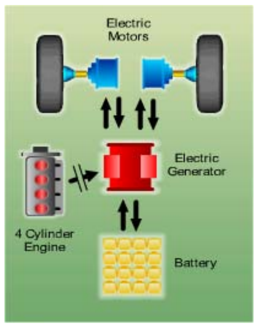


Hybrid Electric Drives - Parallel



- Both gas engine and electric motor connected to drivetrain
- Improved fuel economy and reduced emissions
- Regenerative braking supplements battery charging

Hybrid Electric Drives - Series

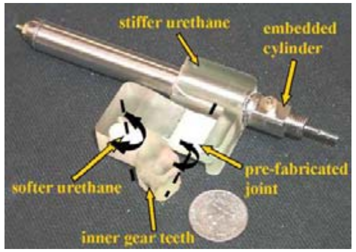


- Charge batteries with combustion engine and generator
- Combustion engine efficiency increased by operating at a single optimised speed
- Energy density of fuels higher than current battery technologies

Future Actuators...

- Actuators using functional materials
  – Piezoelectric element actuator
  – Ultrasonic Motors
  – Actuators of shape memory alloys
- Plasma motors
- Bio-actuators
- …..and many more !

Piezo Micro Actuators



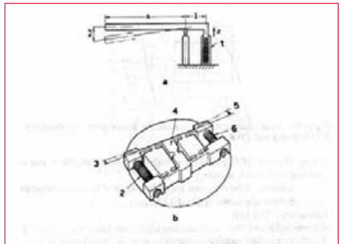
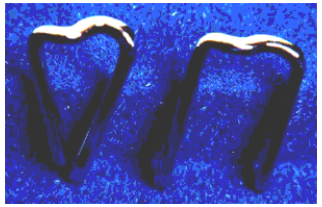


Fig 10.9 Mechanical magnification mechanism; (a) Displacement magnification with piezoelectric element actuator; (b) Construction of device for micropositioning rotation; (1) Laminated piezoelectric element; (2) Piezoelectric element A; (3) Rotation; (4) Flexible hinge; (5) Rotation; (6) Piezoelectric element B

http://www.piezo.com/bendedu.html

Shape Memory Alloys (SMA)

- SMA=TiNi alloy
- Height 160mm
- Weight 0.06kg
- Changes shape on (electric) heating



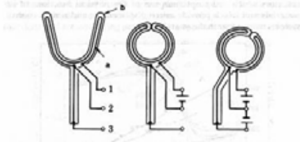


Fig 10.20 Operation and construction of shape memory micro-manipulator; (a) TiNi wire; (b) Silicon rubber

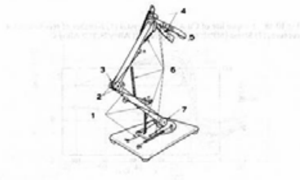
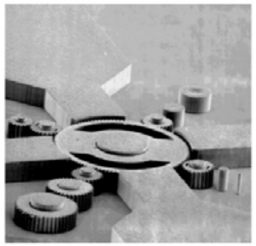
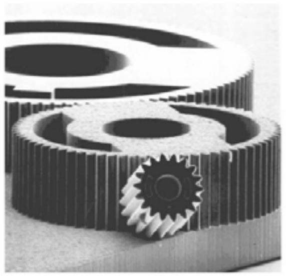


Fig 10.21 Assembly diagram of micro-robot operating with shape memory alloy (Height 160mm, Weight 0.06kg); (1) TiNi alloy wire; (2) Idler; (3) Elbow part; (4) TiNi alloy coil; (5) Finger part; (6) Bias spring; (7) Shoulder part

And finally….MEMs





Summary

- There are many types of actuators available today
- Selecting the right actuators is a critical part of the design cycle
- Requires an understanding of
  - Type of motion
  - Precision of motion
  - Magnitude of motion
  - Operating conditions

Questions?