Week 9 – Actuators II

Advanced Mechatronics System Design – MANU2451

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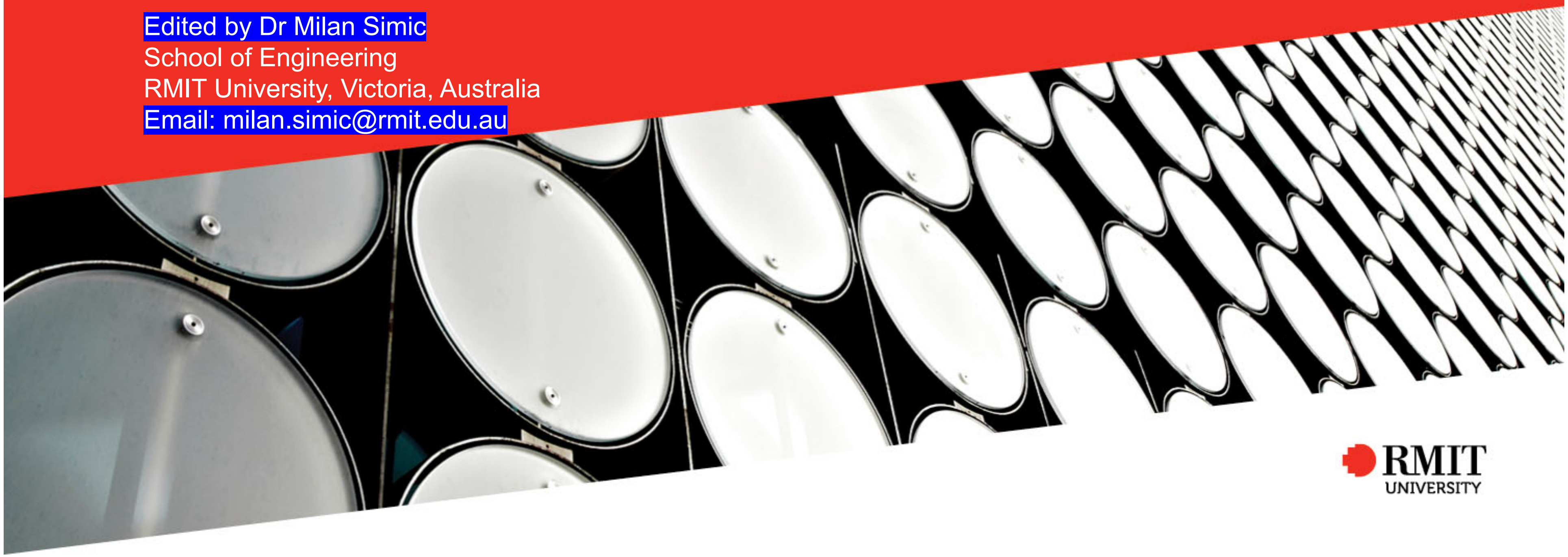

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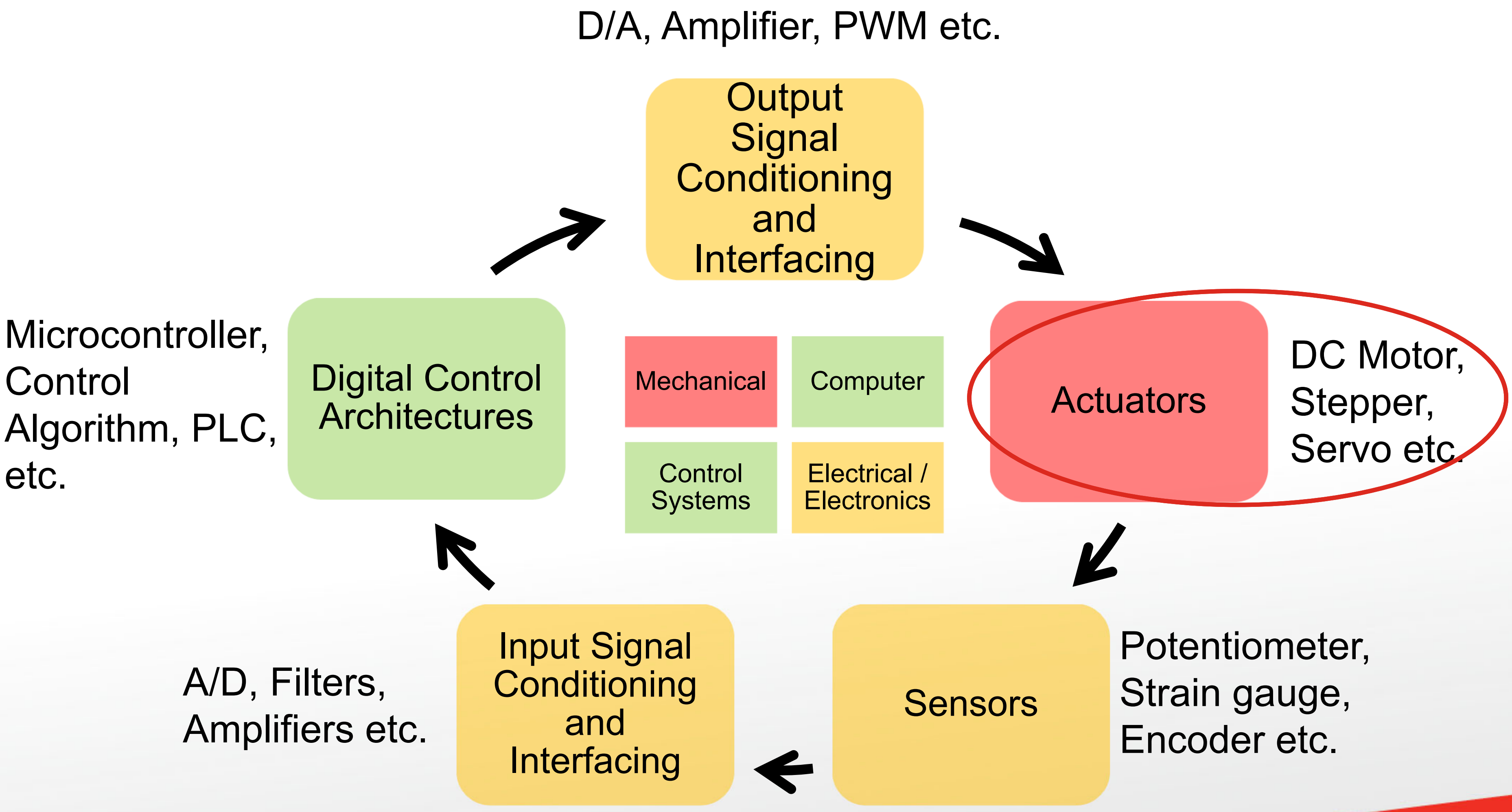
New Teaching Schedule

Week		Class Activity Before	Lecture	Class Activity During or After
1			Introduction to the Course / Introduction to LabVIEW	LabVIEW Programming
2			Introduction to LabVIEW / Data Acquisition	LabVIEW Programming
3			Gripper / Introduction to Solidworks / Safety	Gripper Design
4			Sensors I	myRIO Programming for Sensor Signal Reading / Gripper Design
5			Sensors II	myRIO Programming for Sensor Signal Reading
6			Actuators I	LabVIEW Tutorial
7		LabVIEW Assessment.	DC Motors I	Matlab Simulink Simulation
8		Design report submission	DC Motors II	Matlab Simulink Simulation / myRIO Programming for Control
9			Actuators II	Matlab Simulink Simulation
10			Modeling and System Identification	Matlab Simulink Simulation
11			Artificial Intelligence I	Matlab Simulation
12		Gripper Simulation / Submission of Report	Artificial Intelligent II	Revision

Mechatronics System Components



Mechatronics System Components

Sensors:
Encoder at
each joint

→ Input signal interfacing

↓

Robot controller:

- Generate desired motion trajectory
- Calculate current end-effector position based on angular position (kinematics)
- Calculate desired angular position for desired end-effector position and trajectory (inverse kinematics)
- Control algorithm
- Safety, collision detection etc.

↓

Output signal interfacing

←

Actuators:
Geared motor
at each joint

Industrial Robots

https://commons.wikimedia.org/wiki/File:Float_Glass_Unloading.jpg

Contents

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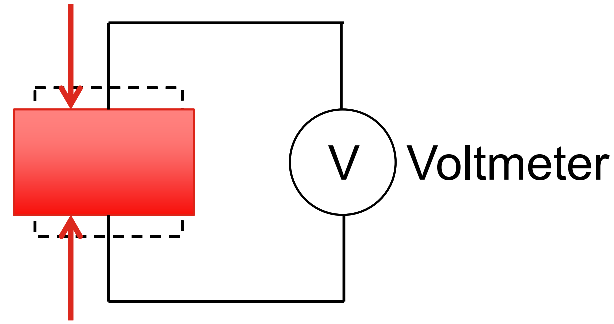
Contents

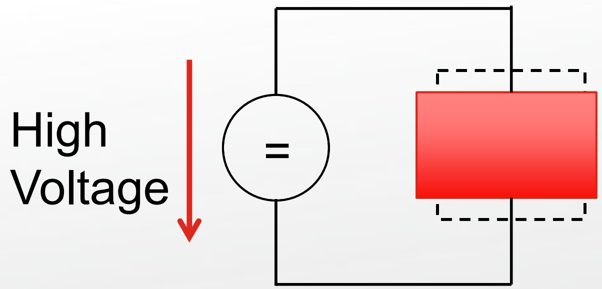
The Piezoelectric Effect

https://www.youtube.com/watch?v=fHp95e-CwWQ

- Certain crystals such as Quartz, Sodium Chlorate, cane sugar and Rochelle salt produce electric charge when subjected to mechanical stress.
  - "Direct Piezoelectric Effect".
  - Discovered by Pierre and Jacques Curie in 1880.
- The materials also undergo mechanical strain when a voltage is applied across them.
  - "Converse / Reverse Piezoelectric Effect".
  - Predicted by Lippmann and verified by Curie brothers in 1880.
- "Piezo": Greek word Piezin, meaning to press or squeeze.



Force -> Voltage



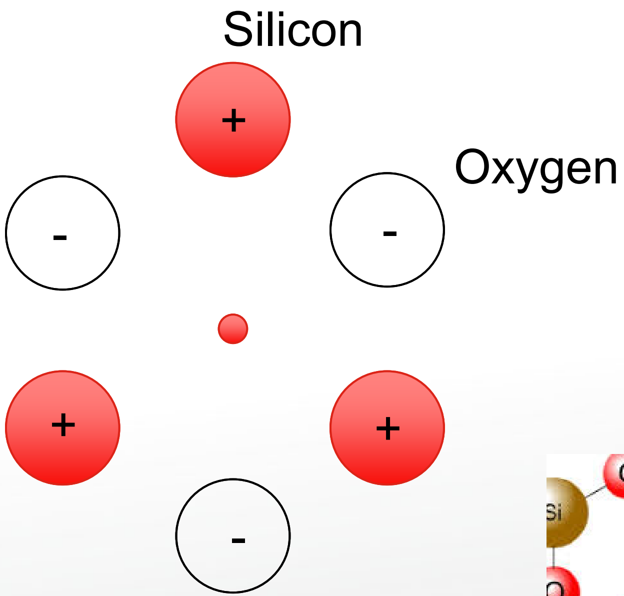
Voltage -> Strain

Piezoelectric Actuators

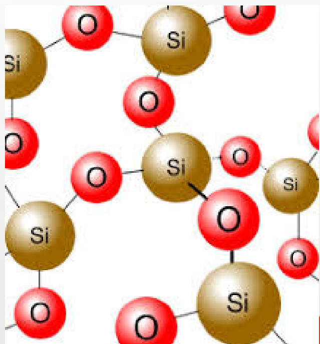
- By using the reverse piezoelectric effect, actuators can be created.
- High electric field corresponds to only tiny changes in the width of the crystal
  - Good precision can be achieved!
  - Piezo crystals are the most important tool for positioning objects with extreme accuracy. Examples:
    - Laser mirror alignment
    - Inkjet printer: Drive injection of ink from print heard
    - Active vibration control
    - XY stages for micro scanning used in infrared cameras

Model of the Piezoelectric Effect

- Two-dimensional model of a unit cell for a quartz crystal (SiO_2):
  - In equilibrium state, the center of gravity for positively charged ions coincide with center of gravity for negatively charged ions.



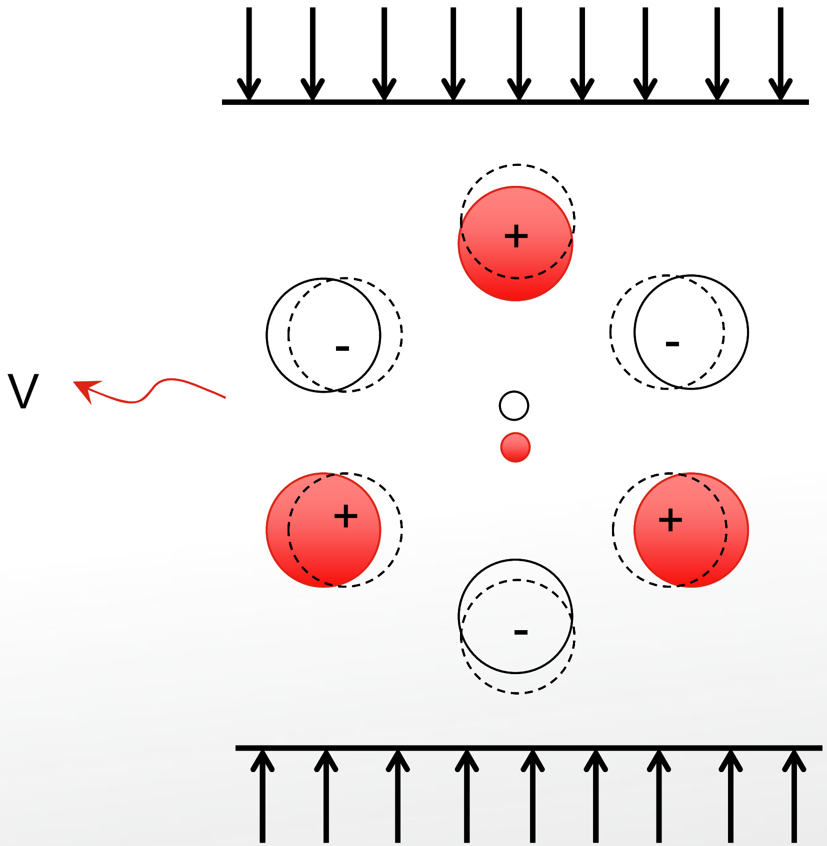
- (red dot) "Center of Gravity" for positively charged ions.
- (white dot) "Center of Gravity" for negatively charged ions.



https://ibchem.com/IB16/02.14.htm

Model of the Piezoelectric Effect

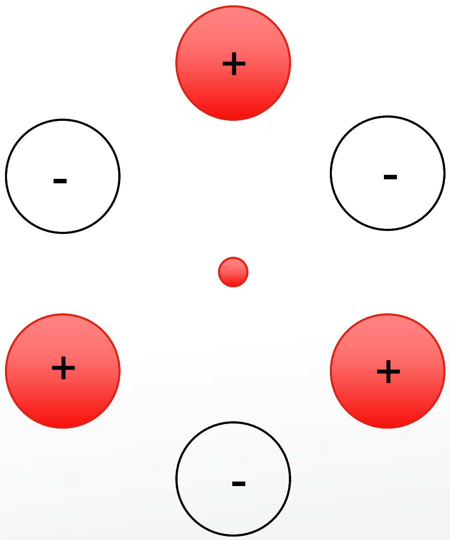
- Direct Piezoelectric Effect:



- Under mechanical stress, the centers of gravity for positive and negative ions become separated, creating an electric dipole.
- An electric potential develops along the axis of polarization.
- This can be measured across the surface of the crystal.

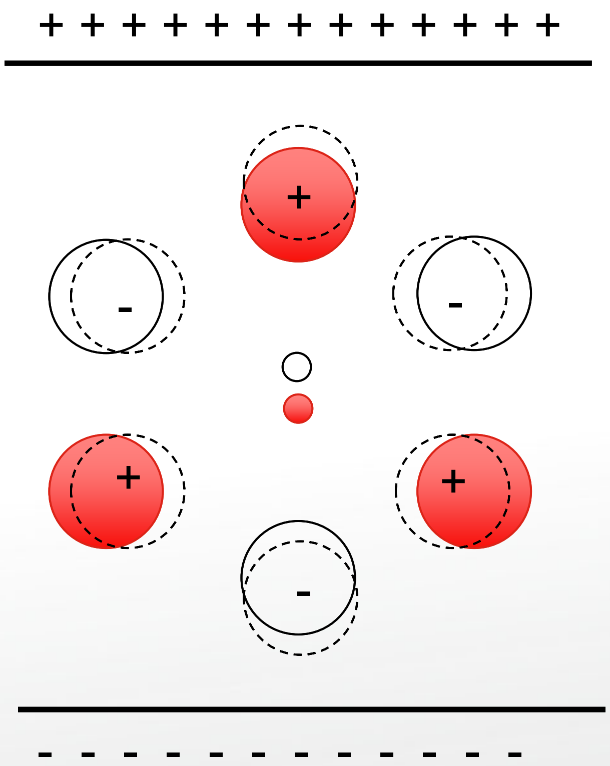
Model of the Piezoelectric Effect

- Reverse Piezoelectric Effect:



Model of the Piezoelectric Effect

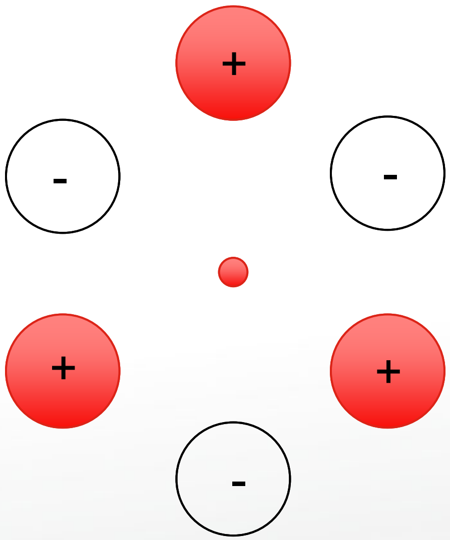
- Reverse Piezoelectric Effect:



- Two electrodes of opposite sign, one applied to the top and one to the bottom of the unit cell.
- The applied field causes corresponding ions to move in certain direction (attraction or repulsion).
- This induces deformation in the crystal lattice and mechanical strain is achieved.

Model of the Piezoelectric Effect

- Reverse Piezoelectric Effect:



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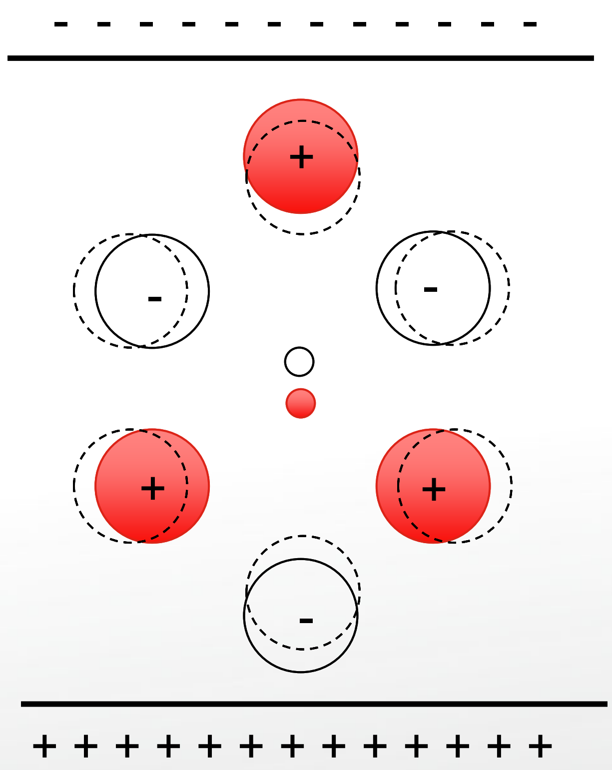
Model of the Piezoelectric Effect

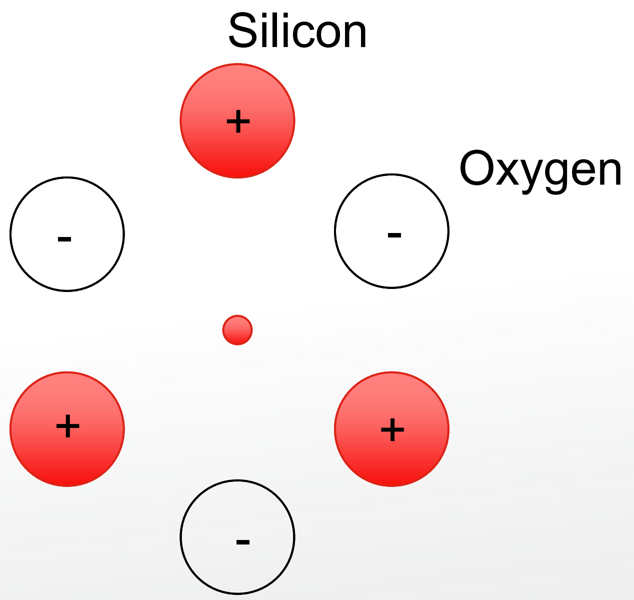
- Reverse Piezoelectric Effect:



- Two electrodes of opposite sign, one applied to the top and one to the bottom of the unit cell.
- The applied field causes corresponding ions to move in certain direction (attraction or repulsion).
- This induces deformation in the crystal lattice and mechanical strain is achieved.

Spontaneous Polarization

- Electric dipoles in the absence of applied stress or electric field.
- Quartz crystal (SiO_2) does not yield spontaneous polarization.
  - In equilibrium state, the center of gravity for positively charged ions coincide with center of gravity for negatively charged ions.



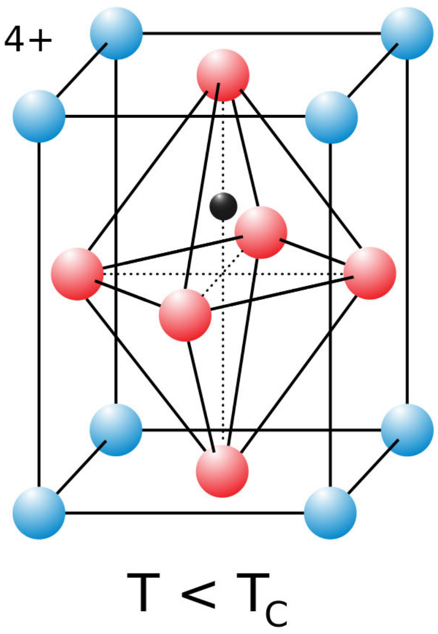
"Center of Gravity" for positively charged ions.

"Center of Gravity" for negatively charged ions.

Spontaneous Polarization

- Man-made Lead-Zirconate-Titanate (PZT) exhibits spontaneous polarization.
  - Due to arrangement of atoms within the unit cell at room temperature

At temperature lower than Curie temperature, the Zr^{4+} ion is biased towards one side of the unit cell.



PZT Crystal

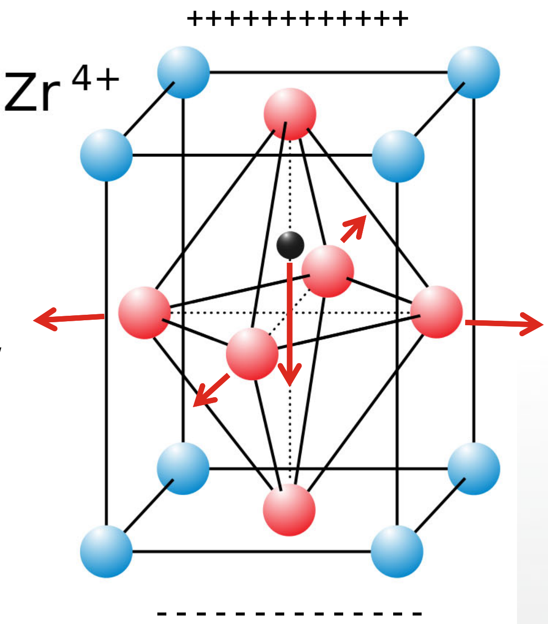
https://commons.wikimedia.org/wiki/File:Perovskite.svg

Spontaneous Polarization

- Also, by applying electric field across the unit cell, the moves Ti^{4+} / Zr^{4+} up or down, and induces deformation in the crystal lattice.

Pb^{2+} O^{2-} Ti^{4+}, Zr^{4+}

At temperature lower than Curie temperature, the Ti^{4+} / Zr^{4+} ion is biased towards one side of the unit cell.



PZT Crystal
https://commons.wikimedia.org/wiki/File:Perovskite.svg

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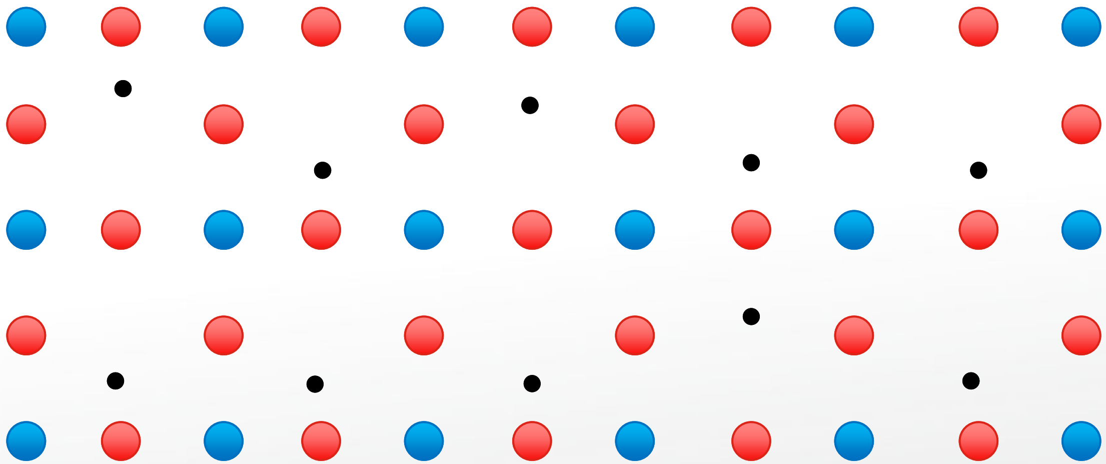
PZT Ceramics

- Widely used since 1960s.
- A high temperature heat treatment process gives the material its unique properties.
- Exhibit high efficiency in converting electrical energy to mechanical energy, and vice versa.
  - Large forces or displacement from relatively small applied voltages.

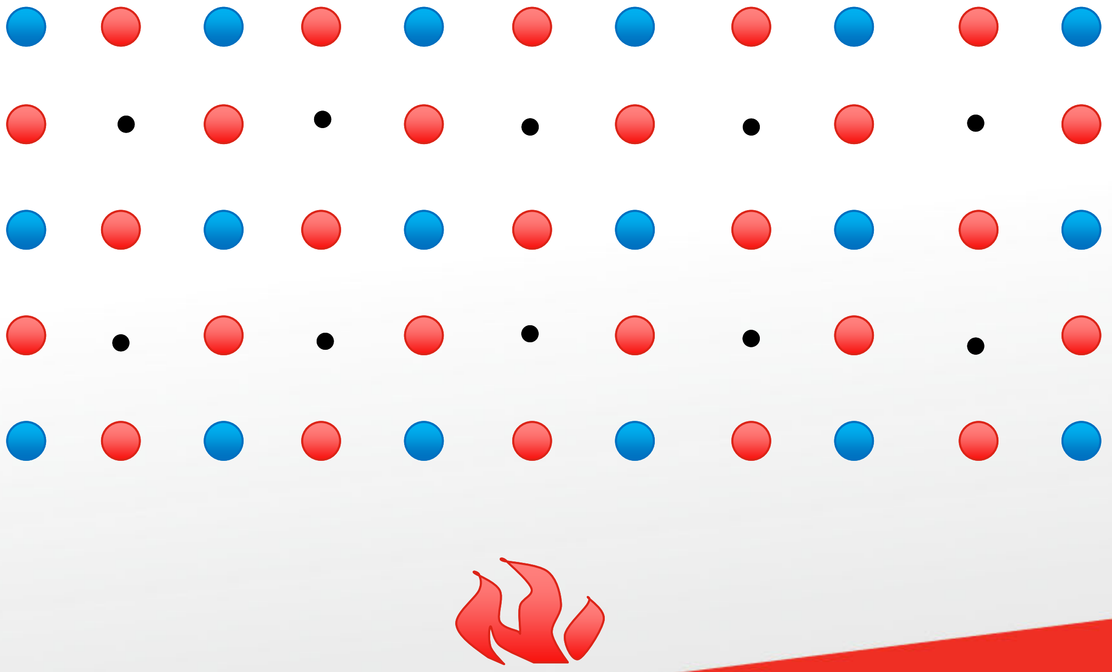
PZT Ceramics

- Initially (right after manufacturing), the piezoelectric ceramic consists of randomly oriented domains.
  - Material produces no net effect when mechanically stressed or when voltage is applied:



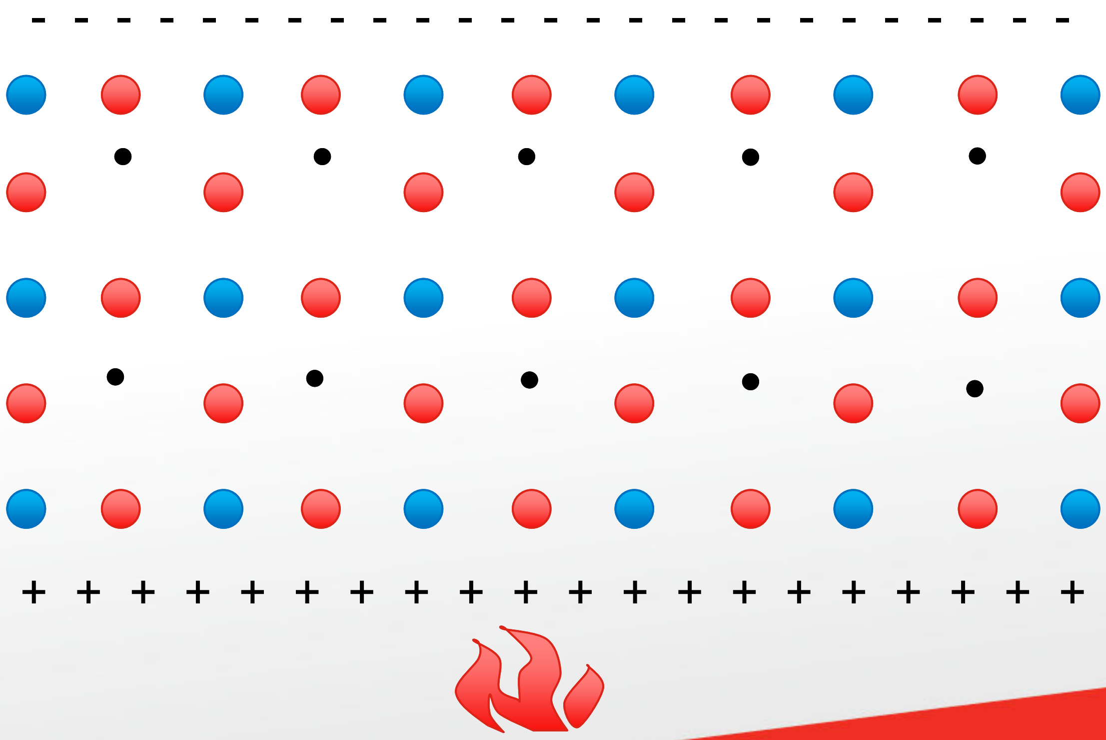
PZT Ceramics

- "Poling" process:
  1) Heat the material to temperature higher than Curie temperature
     - This will "unpole" the crystal



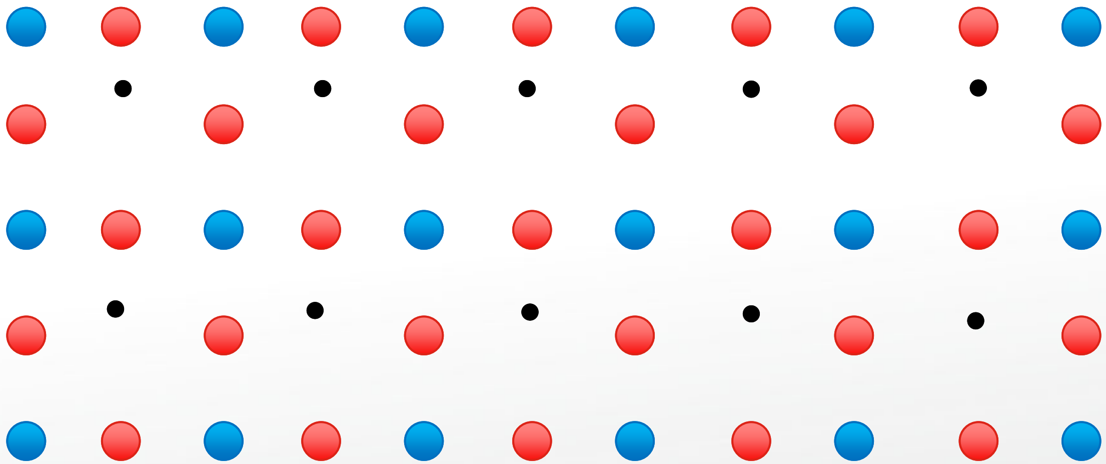
PZT Ceramics

- "Poling" process:
  2) Apply electric field to attract the Zr^{4+} / Ti^{4+} ions to one side



PZT Ceramics

- “Poling” process:
  3) Immediately cool down below Curie temperature to “freeze” the ions.
     - After poling, the material exhibits considerable piezoelectric effect.



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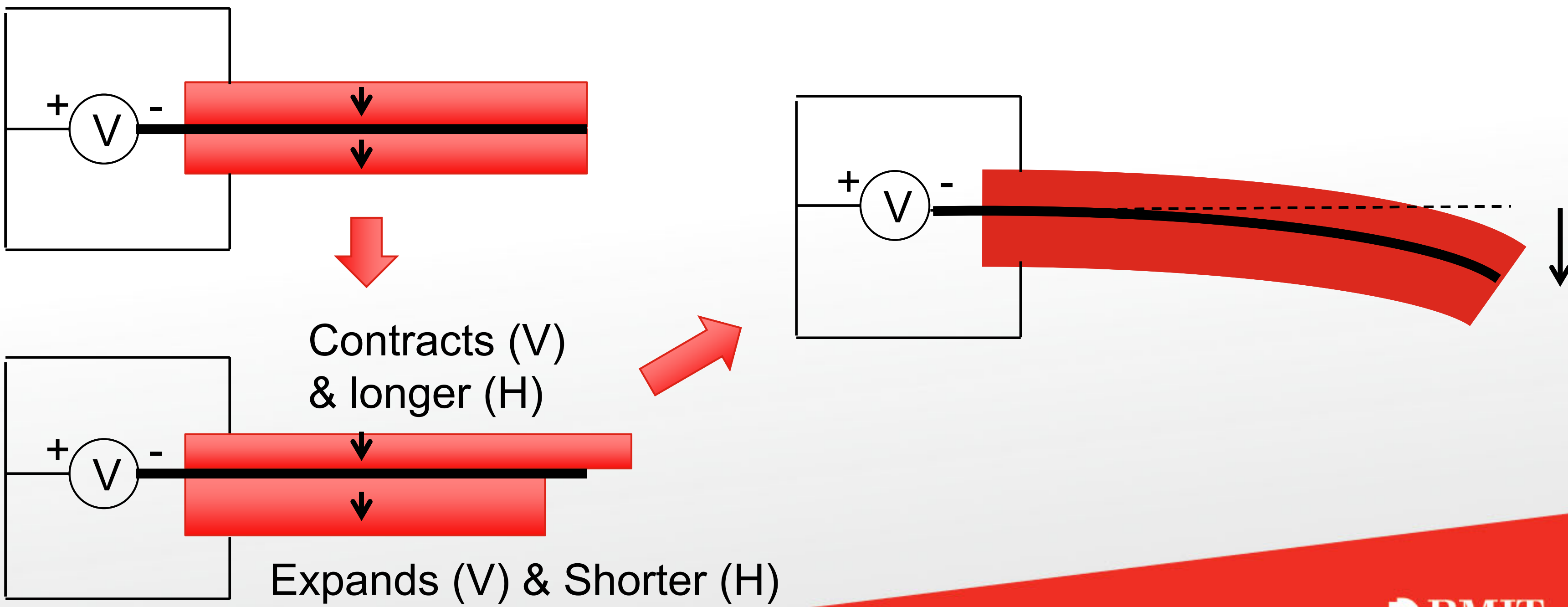
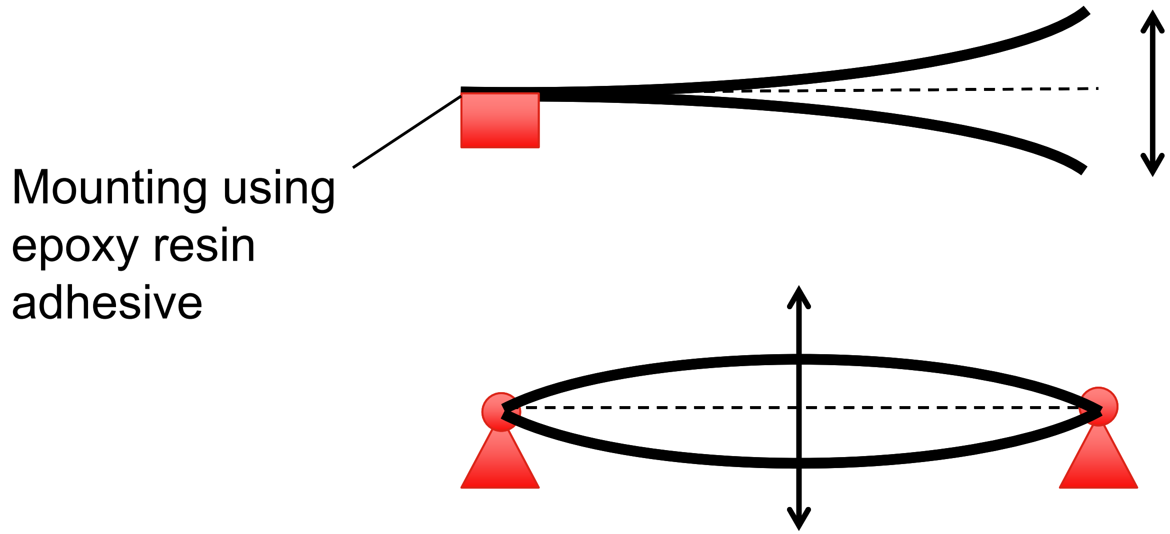
Unimorph / Bimorph

- Based on the basic deformation modes, different types of actuators can be developed.
- Unimorph: One piezoceramic element bonded to an elastic shim, e.g. aluminium, brass or steel.
- Bimorph: Two piezoceramic elements bonded together, but given different voltage polarity so that one contracts and one expands.



Unimorph / Bimorph

- Different configurations:



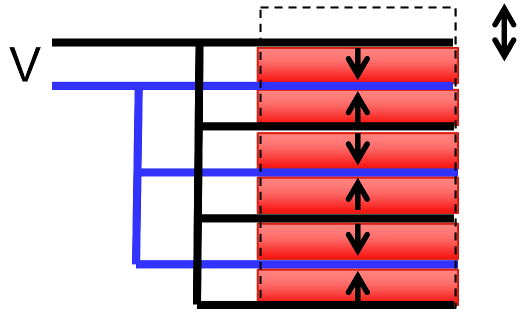
- Length (L) 18mm to 45mm
- Thickness (t) approximately 0.65mm
- Operating voltage (V) 0 to 60V
- Motion / Stroke up to several milimeters
- Blocking force 0.5N to 2N
- Response in ms

$$\Delta x = \frac{3 d_{31} L^2 V}{t^2}$$

(d_{31} = strain coefficient, normal to polarization. Typically about -0.1 to -0.3 nm/V)

Piezoelectric Stack Actuators

- Unimorph / Bimorph provides large stroke but low force.
- Piezoelectric stack actuators offer the reverse: High force but smaller stroke.
- Made by bonding thin layers of piezoelectric materials between electrodes:



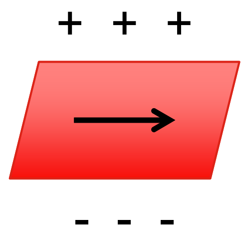
- Height up to 36mm
- Operating voltage (V) 0 to 120V
- Motion / Stroke up to 40um
- Blocking force up to 4000N
- Response in 10^{-6}s
  - High speed nanopositioning devices!

$$\Delta x = n d_{33} V$$

(d_{33} = strain coefficient, along polarization. Typically about 0.2 to 0.6 nm/V)

Shear Actuators

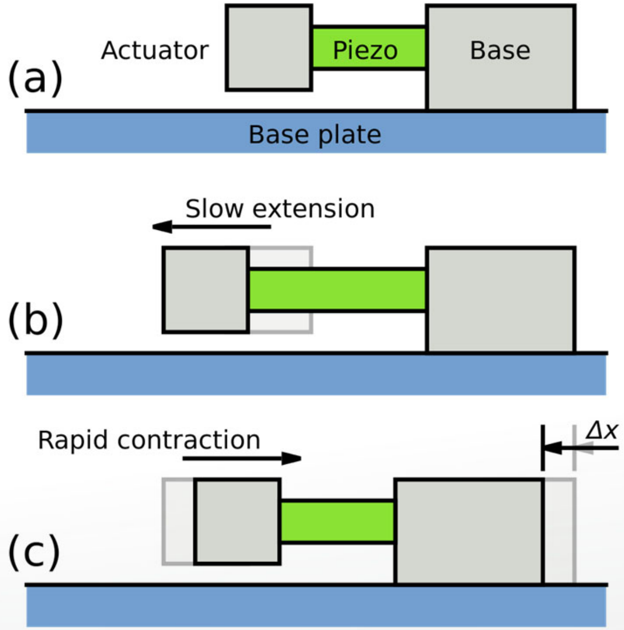
- Electric field is applied perpendicular to the polarization direction.



- Piezo actuators in stacked design can be configured for shear displacement.
- Combined with longitudinal actuators → multi-axis piezo actuators!
- Operating voltage -250V to 250V
- Force up to 300N
- Linear travel up to 10um

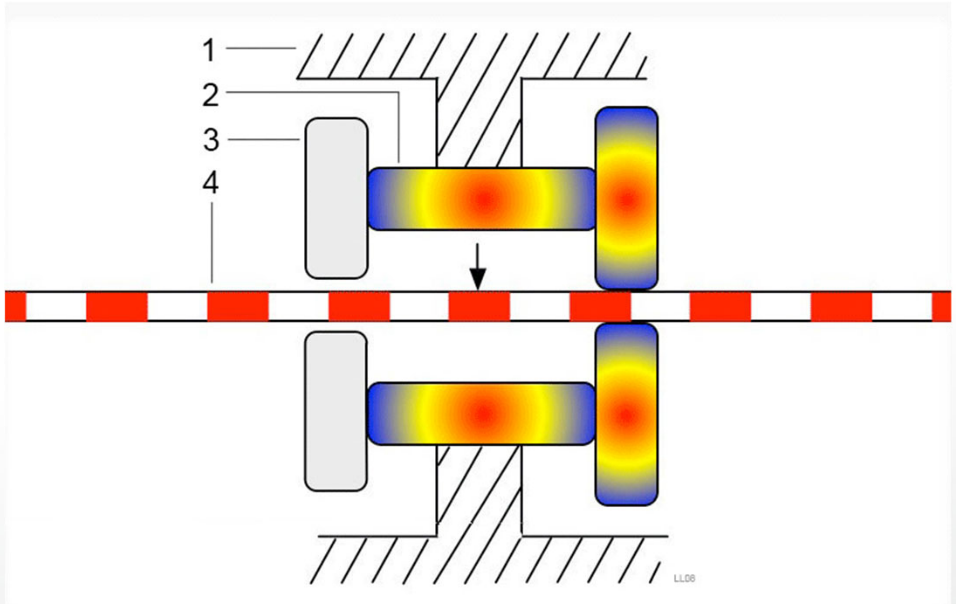
Piezoelectric Motor

- Piezo material produces ultrasonic vibrations (→ 10MHz) to produce motion.
  - Nanometer precision, linear speed up to 800mm/s.
  - Can operate under presence of strong magnetic field.



Slip-stick Actuator

https://commons.wikimedia.org/wiki/File:Slip-stick_actuator_operation.svg

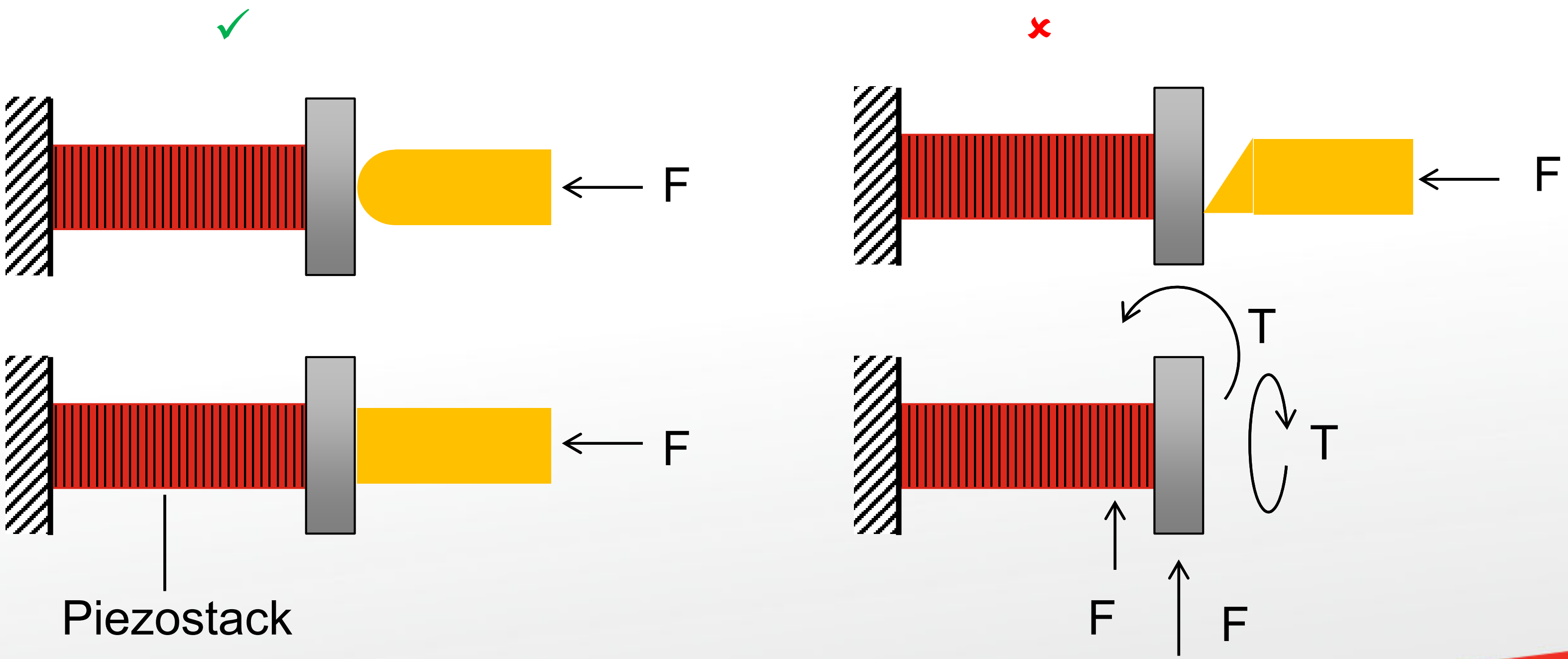


Piezo Inchworm

https://commons.wikimedia.org/wiki/File:Piezomotor_type_inchworm.gif

Application Considerations

- Mounting:
  - Piezoelectric materials are brittle.
  - Proper support and elimination of off-center loading are essential.
    - E.g. Lateral or bending forces must be avoided when possible.

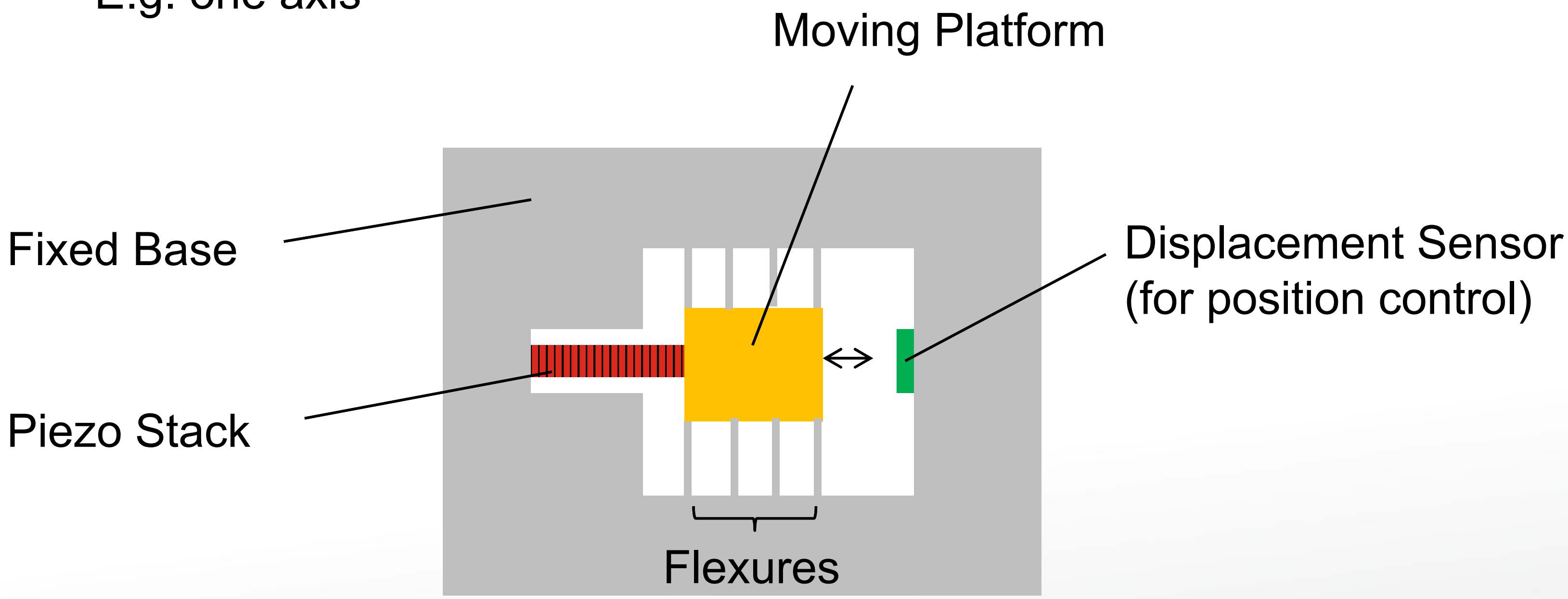


Application Considerations

- Mounting (Continued):
  - Recommended to use a very thin layer of glue to glue actuator to a substrate or other components.
    - Epoxy-type adhesives.
    - Pressure during curing process between 2 and 5 Mpa.
  - Operation in humid environment is not recommended.
    - This will increase chances of arcing between electrodes.
    - If unavoidable, surround the actuator with nonconductive coating.
  - High temperature (near Curie temperature) can depole the piezoelectric actuator.
    - MUST be avoided!

Piezo Positioning Stages

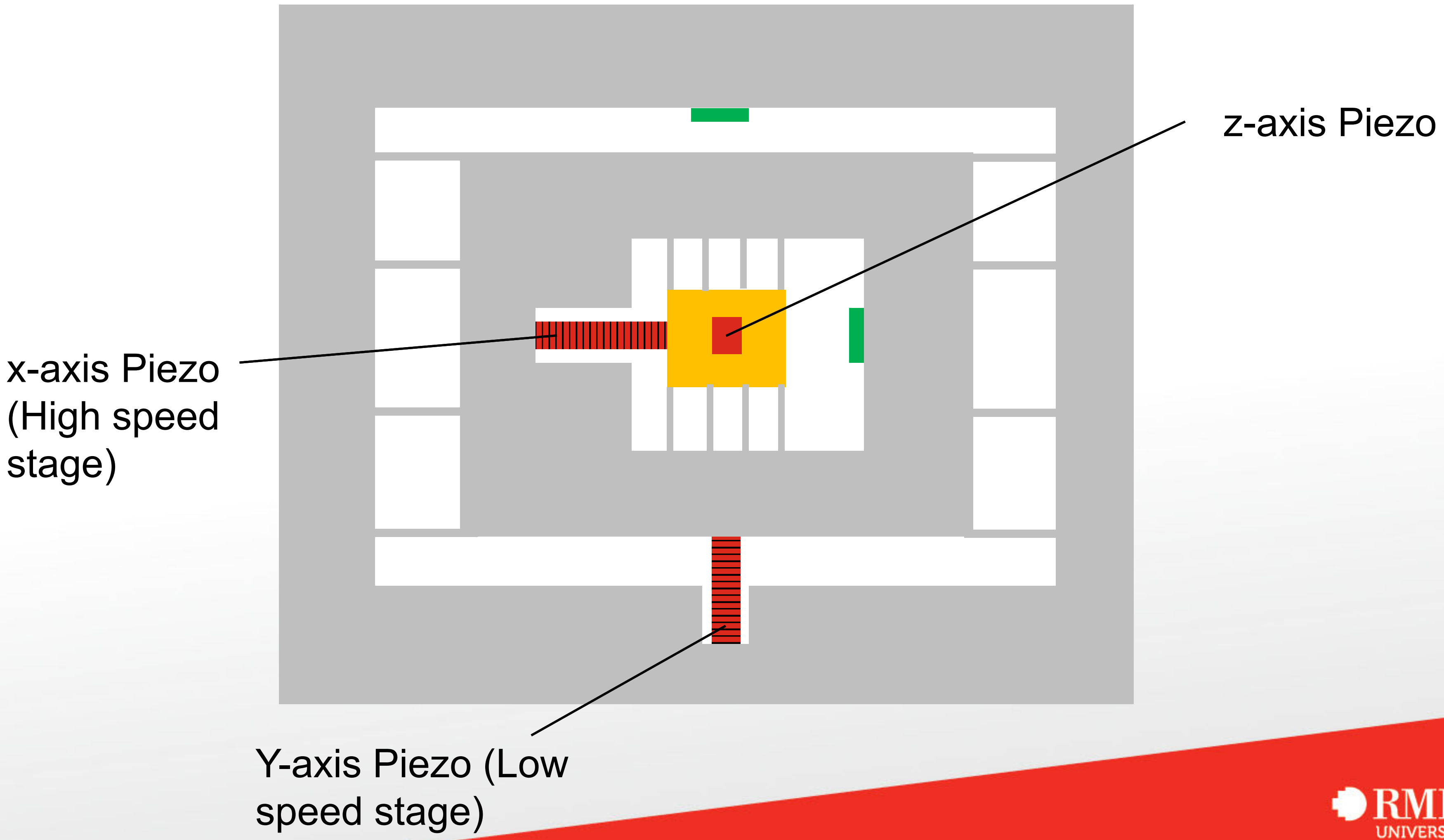
- Using Piezo actuators in positioning stages:
  - E.g. one axis



  - The flexures permits only lateral deflection.
  - Position control is needed to reduce error due to actuator nonlinearities, creep, vibration, and thermal drift.

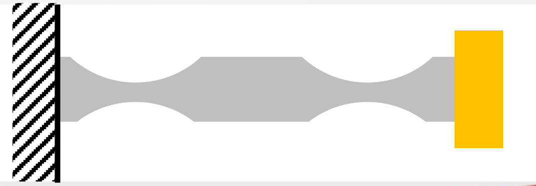
Piezo Positioning Stages

- Two / Three Axes: Serial-kinematic configuration



Piezo Positioning Stages

- The flexures needs to be placed so as to minimize the platform's tendency to rotate.
- Resonance:
  - Translation: $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$
  - Rotation: $f = \frac{1}{2\pi}\sqrt{\frac{k_\theta}{J}}$
  - Design flexure and stage such that $\frac{k_\theta}{J} > \frac{k}{m}$ so that rotational resonance is not felt earlier than translational.
- The vertical stiffness of the x- and y-stages is increased by:
  - Increasing the number of flexures
  - Utilizing shorter flexures
  - Using double-hinged flexure with rigid center, instead of rectangular.

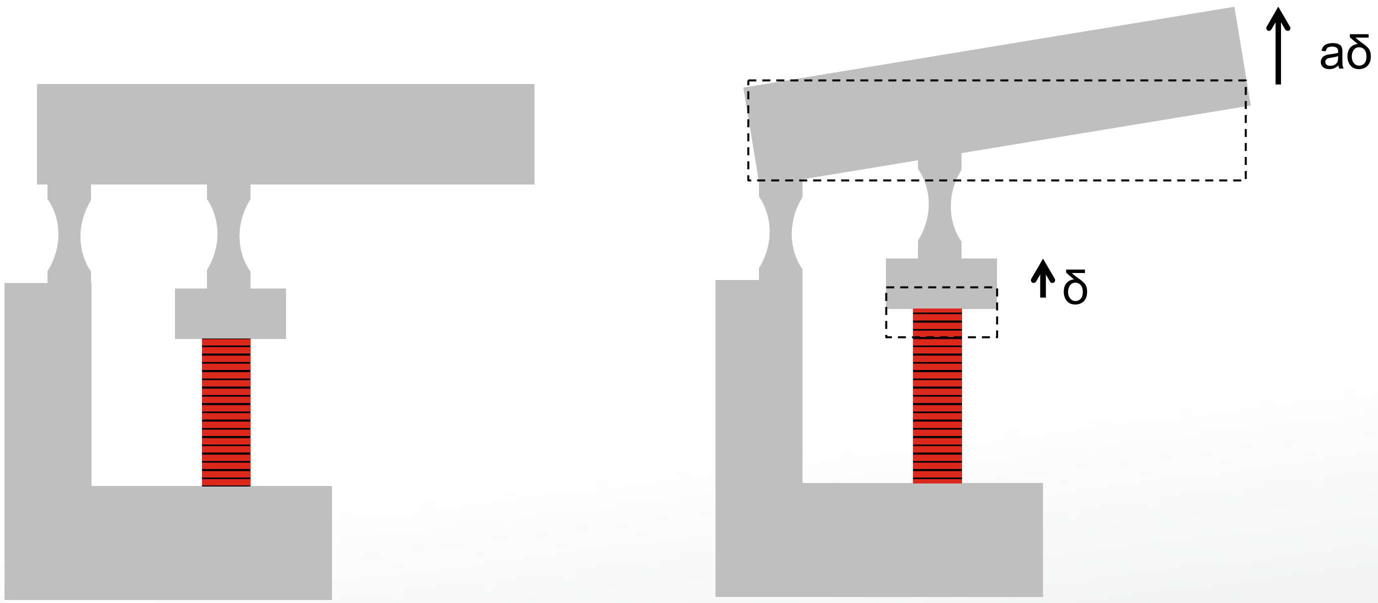


Piezo Positioning Stages

- Other than translational positioning stages, there are also:
  - Rotational positioners
    - Fiber alignment, beam steering, beam alignment, crystallography
  - Tilting positioners
    - Beam steering, beam alignment
    - Mirror is mounted onto the moving surface

Mechanical Amplifier

- Flexure-based mechanical amplifier provides a scaled output:



- Flexures are invaluable for nanopositioning: no friction, no need for lubrication, no hysteresis effects.

Contents

- Piezo-Actuators
  - The Piezoelectric Effect
  - PZT Ceramics
  - Applications
  - Issues
  - Modeling and Control
- Induction Motor
- Synchronous Motor
  - Mathematical Model
  - Field Oriented Control
- Actuators Suitable for Force Control

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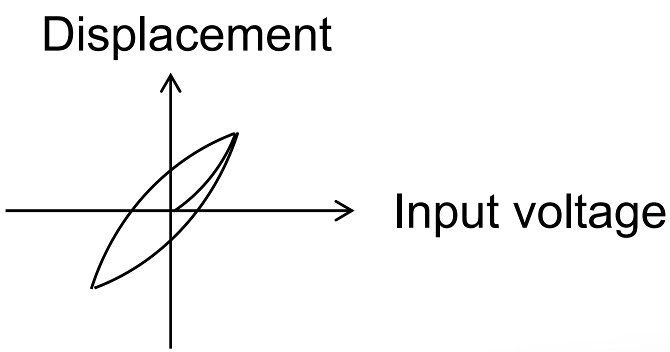
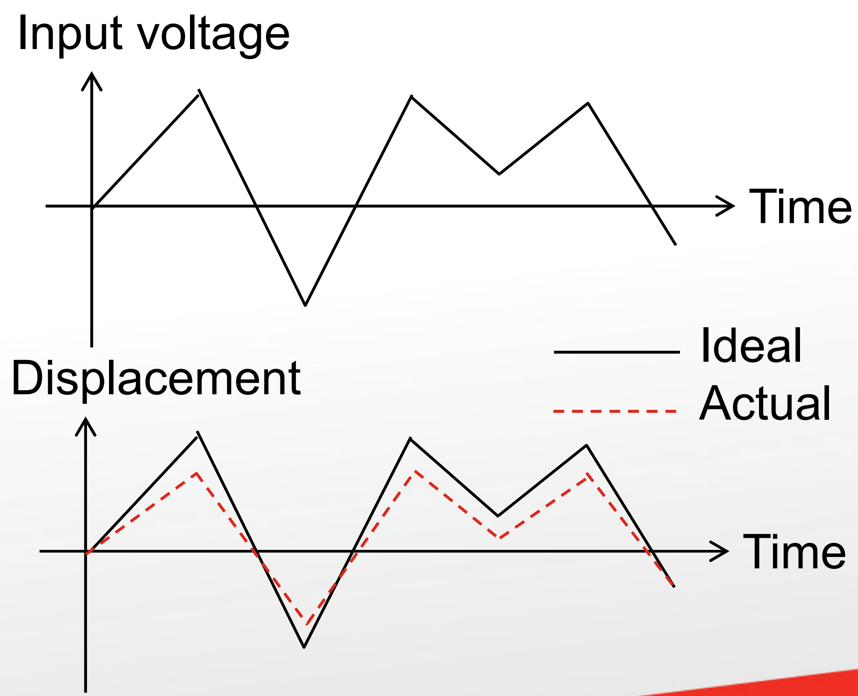
Issues with Piezoelectric Actuators

- So far, we have assumed that the piezo actuators expand and contract proportionally to the applied voltage.
- However, this assumption is not always true.
- Four significant sources of error which complicate the response:
  - Hysteresis
  - Creep
  - Temperature Dependence
  - Structural Dynamics

Issues with Piezoelectric Actuators

- Hysteresis:
  - Nonlinear behavior between the applied electric filed and the mechanical displacement of piezo actuator.
  - Significant over large-range displacement

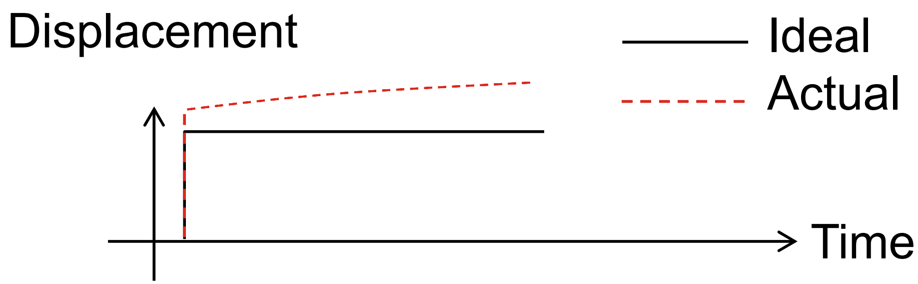




- Solutions:
  - Operating over short range (linear region) → limited range!
  - Use feedback / feedforward control

Issues with Piezoelectric Actuators

- Creep:
  - Low-frequency drift after step change:



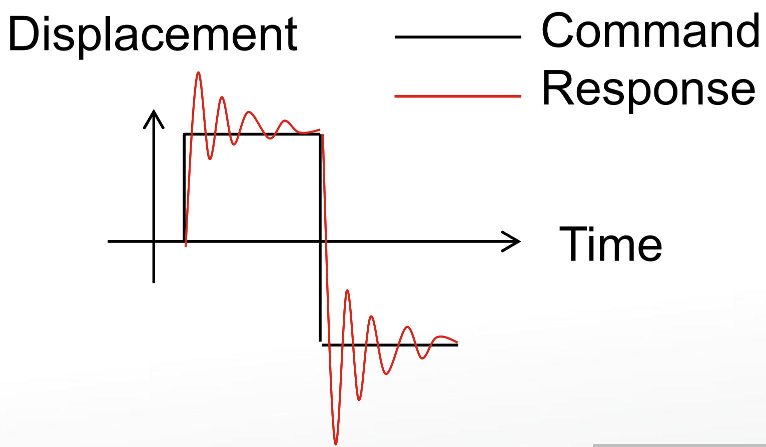
- Solutions:
  - Operate fast enough so that creep effect becomes negligible.
    - However, this limits the use of piezo positioners in slow and static applications.
  - Use feedback / feedforward control

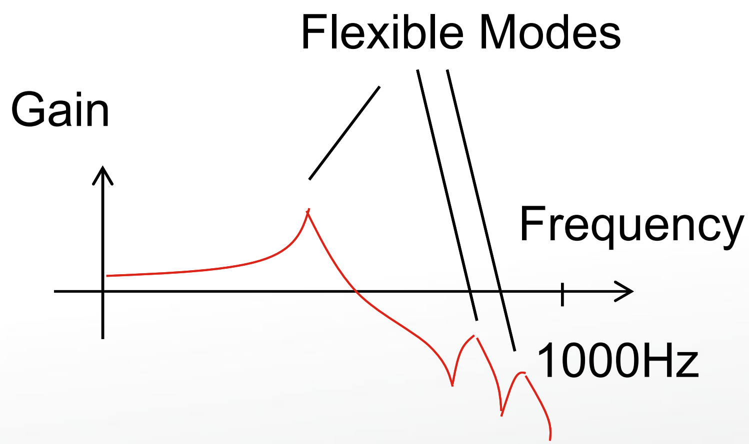
Issues with Piezoelectric Actuators

- Temperature Dependence:
  - The piezoelectric strain constant *d* varies widely with temperature.
  - E.g. when PZT is cooled down to 77degC or lower, the strain constant d_{33} reduces.
  - When driven with voltage, the response increases by e.g. 10% every 25degC.
  - Solution:
    - Use feedback / feedforward control

Issues with Piezoelectric Actuators

- Structural Dynamics, e.g. Structural Resonances
  - Command signals exciting the flexible modes of the structure
  - Limits the operating bandwidth of piezo-based positioning systems



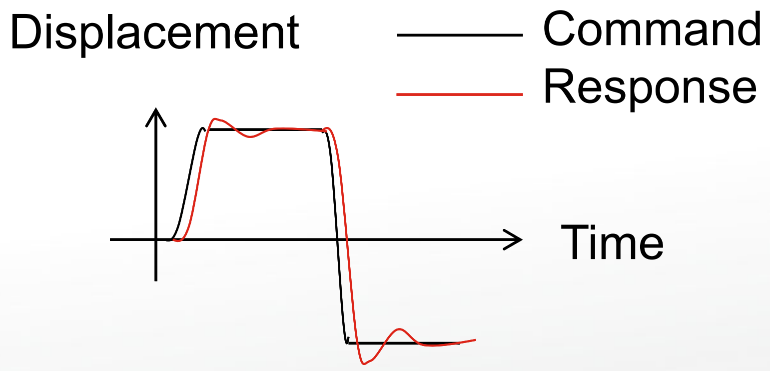


- Transfer function model:

$$G(s) = k\prod_{i=1}^{n}\frac{\omega_i^2}{s^2 + 2\xi_i\omega_i s + \omega_i^2}\prod_{j=1}^{m}\frac{s^2 + 2\xi_j\omega_j s + \omega_j^2}{\omega_j^2}$$

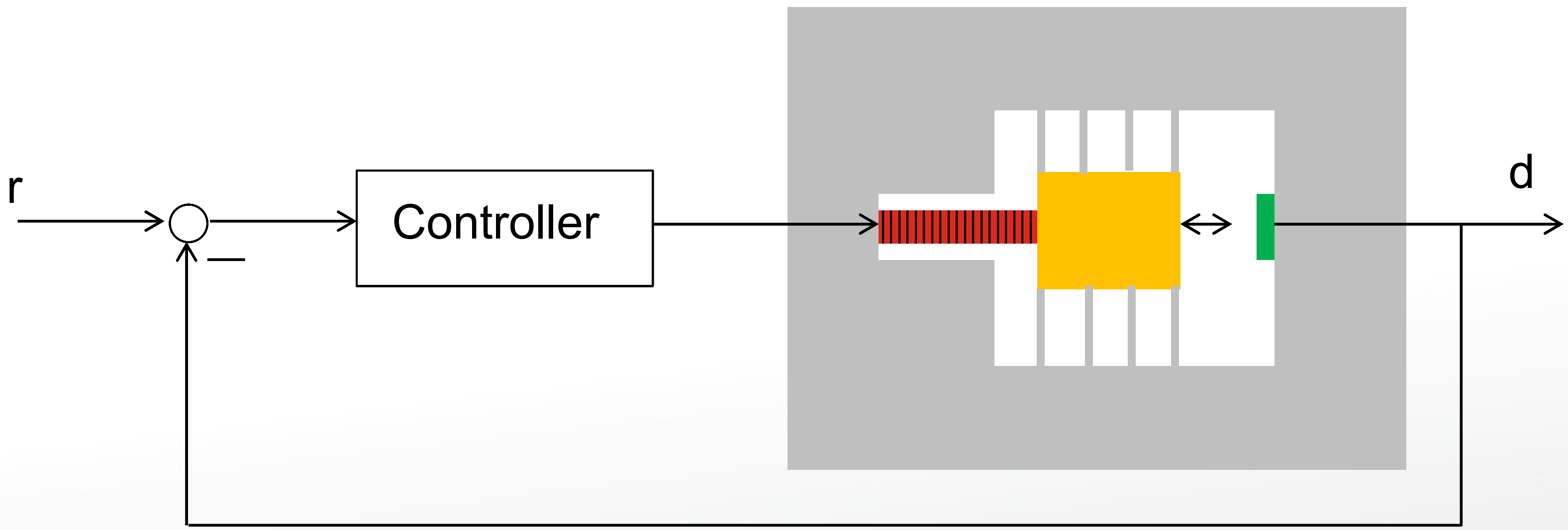
Issues with Piezoelectric Actuators

- Structural Dynamics, e.g. Structural Resonances (Continued)
  - Solutions:
    - Command shaping – Design input signals which are smoother and have negligible frequency components near the first resonant frequency.



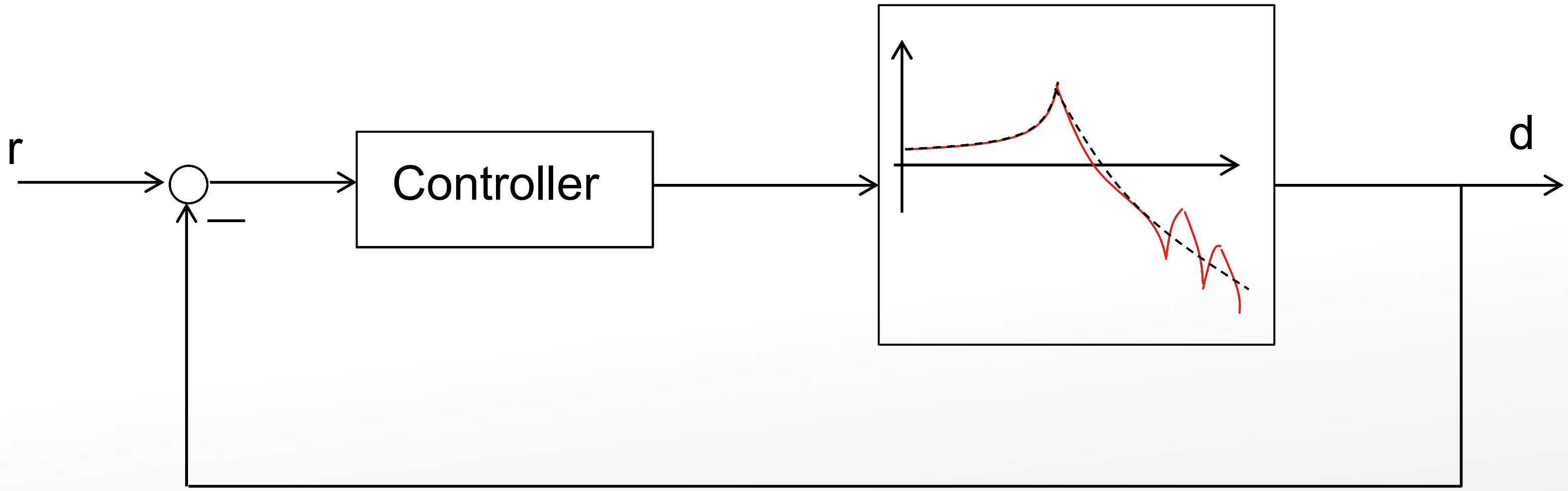
Issues with Piezoelectric Actuators

- Structural Dynamics, e.g. Structural Resonances (Continued)
  - Solutions:
    - Feedback Control



Issues with Piezoelectric Actuators

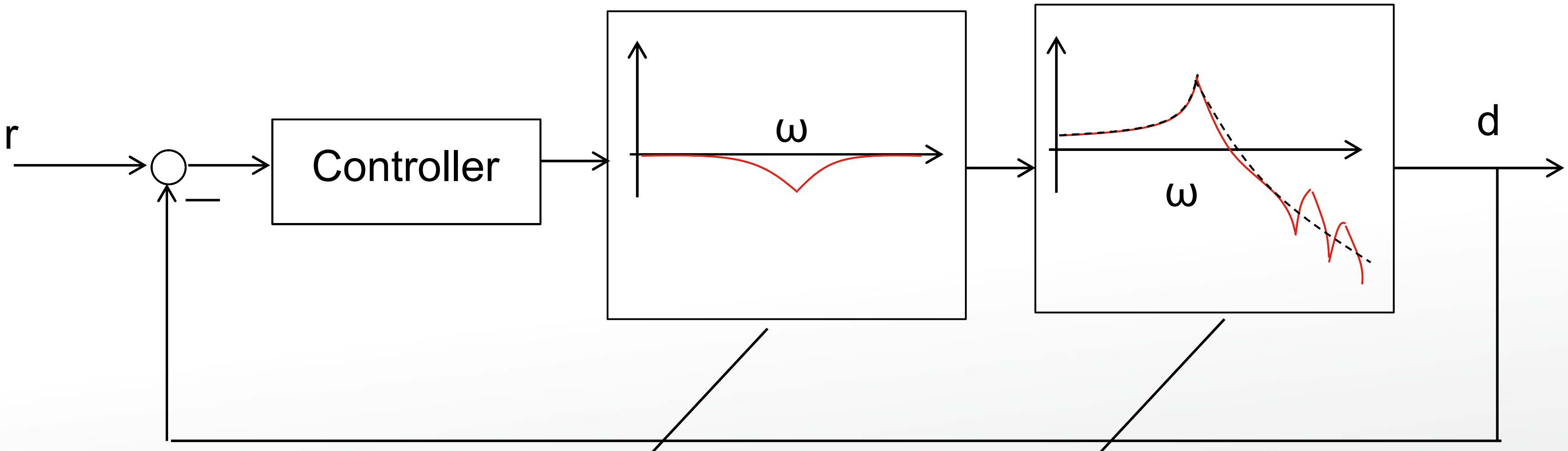
- Structural Dynamics, e.g. Structural Resonances (Continued)
  - Solutions:
    - Feedback Control



- Approximate the model by only one mode: $G(s) = \dfrac{\omega^2}{s^2 + 2\xi\omega s + \omega^2}$

Issues with Piezoelectric Actuators

- Structural Dynamics, e.g. Structural Resonances (Continued)
  - To reduce the effect of the resonance mode, cascade a “notch filter” with notch frequency ≈ ω before the actuator:

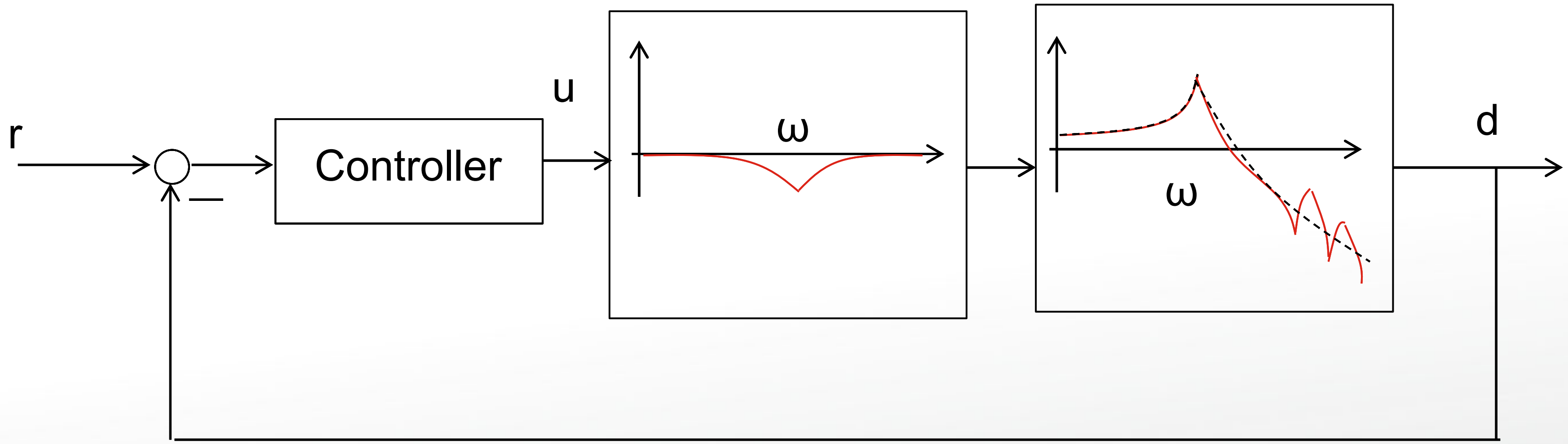


$$G_{Notch}(s) = \frac{s^2 + 2\xi\omega s + \omega^2}{s^2 + 2\xi_{\text{Large}}\omega s + \omega^2}$$

$$G(s) = \frac{\omega^2}{s^2 + 2\xi\omega s + \omega^2}$$

Issues with Piezoelectric Actuators

- Structural Dynamics, e.g. Structural Resonances (Continued)
  - The notch filter reduces the frequency content around ω in u, before passing through u to the actuator.

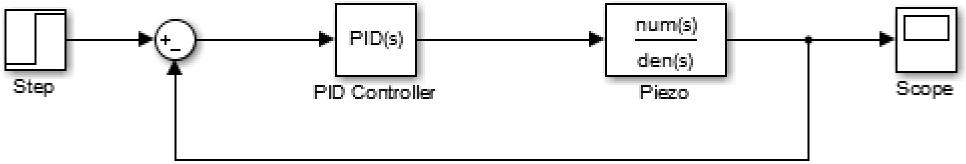


- Reduces excitation of the flexible mode.
- Easier to design / tune controller.

Contents

MATLAB Simulink Simulation

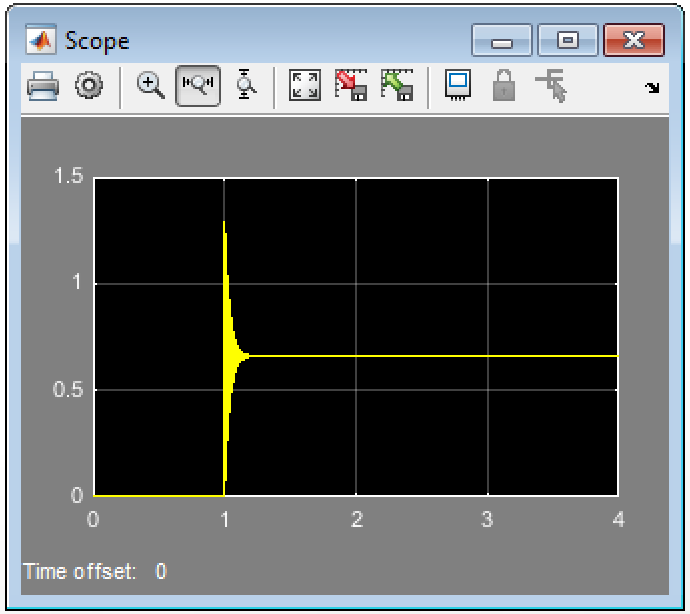
- We shall do some simulation to see the effect of notch filter.
- First, start MATLAB, then activate the Simulink Library.
- Create the following loop:



- Some settings:
  - PID Controller: P = 1, I = 0, D = 0
  - Piezo: $$G = \frac{2.025x10^7}{s^2 + 48.63s + 1.042x10^7}$$
  - Scope: History → Uncheck limit data points to last 5000
  - Simulation → Model Configuration Parameters → Solver type: Fixed-step // Solver: ode4 // Fixed Step Size: 1e-4

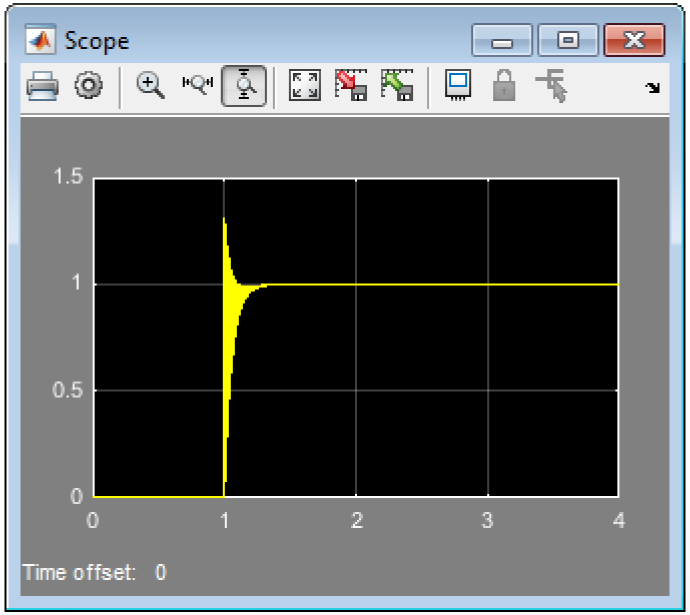
MATLAB Simulink Simulation

- Run the simulation and you would obtain the following response:
  - Highly oscillatory



MATLAB Simulink Simulation

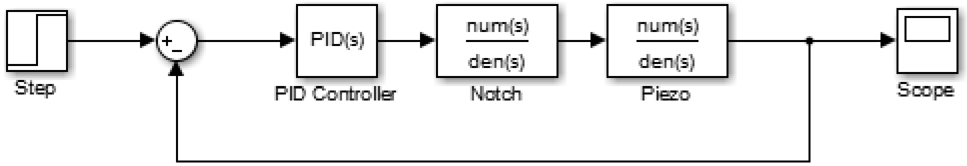
- Set I as 20 and re-run the simulation.



- Apparently, it is quite difficult to tune the controller to obtain good response.

MATLAB Simulink Simulation

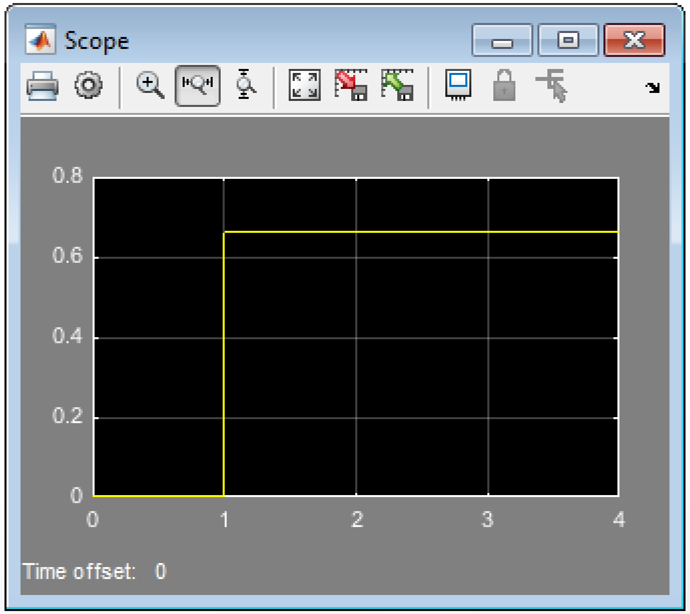
- Add in a notch filter between the PID controller and the Piezo model:

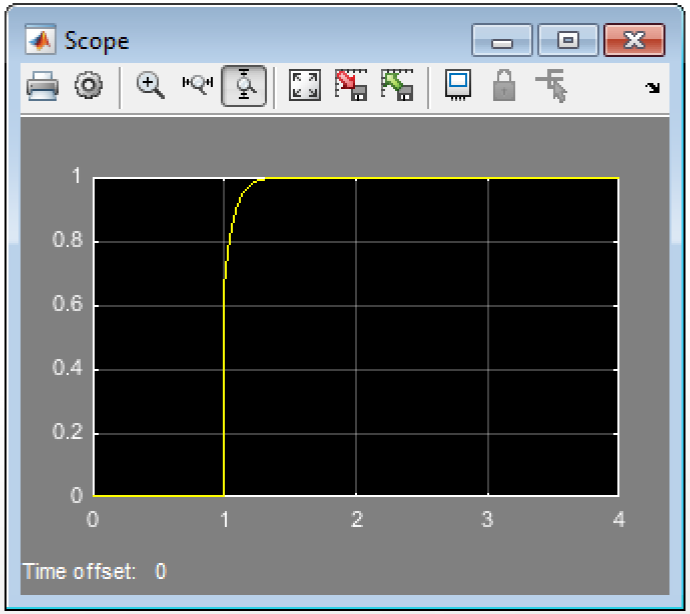


  - Some settings:
    - Notch Filter: $$G_{Notch} = \frac{s^2 + 48.63s + 1.042x10^7}{s^2 + 1x10^4 s + 1.042x10^7}$$

MATLAB Simulink Simulation

- Run the simulation again with different PID gains:
  - P = 1, I = 0 P = 1, I = 20





- The vibration is suppressed!

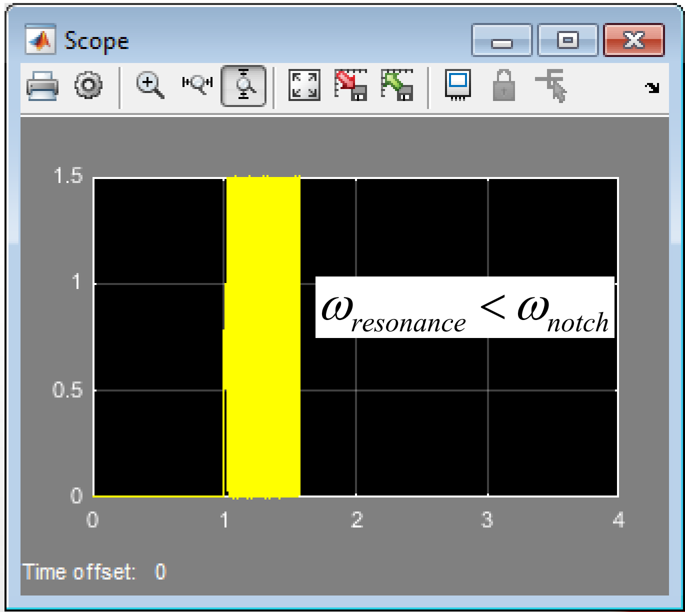
A Word of Caution

- We set the notch filter frequency to be the same as the resonance frequency of the piezo actuator.
- In practice, the resonance frequency of piezo actuator may shift, for e.g. due to load during service.
  - If resonance frequency drops below notch filter frequency → The closed loop can become unstable!
  - E.g. set Piezo as:

$$G = \frac{2.025x10^7}{s^2 + 48.63s + 0.9x10^7}$$

  - While notch remains as:

$$G_{Notch} = \frac{s^2 + 48.63s + 1.042x10^7}{s^2 + 1x10^4 s + 1.042x10^7}$$



A Word of Caution

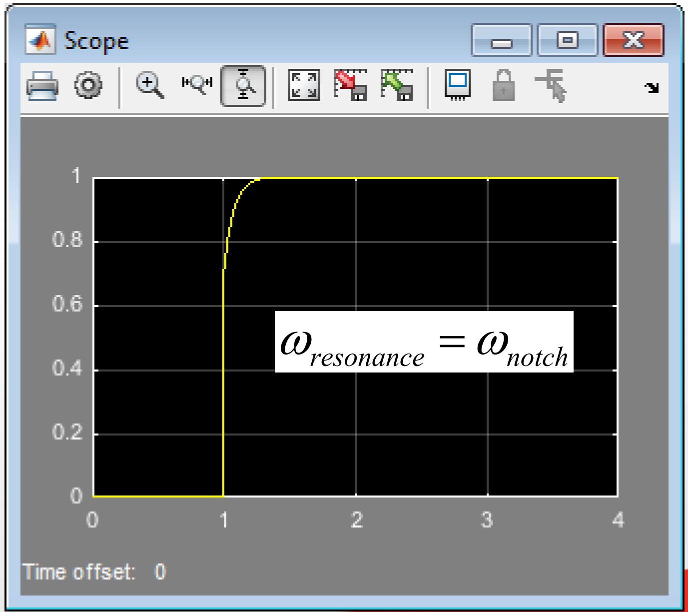
- Therefore, we must set the notch filter frequency to be the same as the lowest expected resonance frequency of the piezo actuator during service.

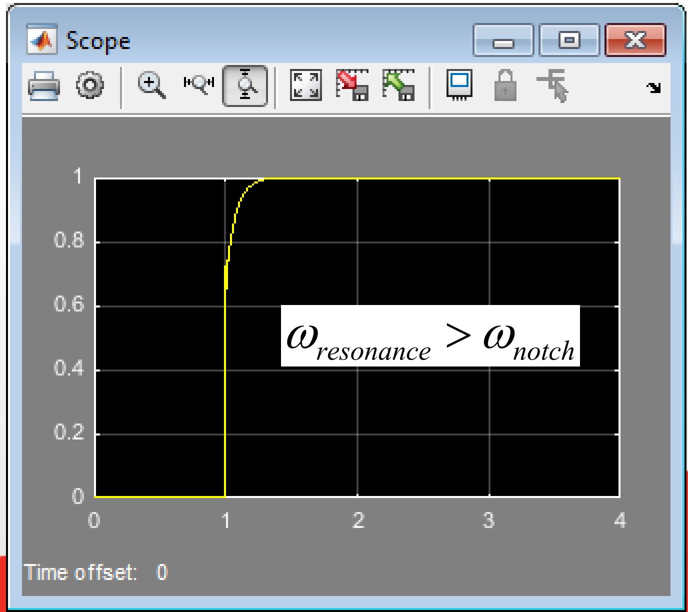
$$G = \frac{2.025x10^7}{s^2 + 48.63s + 0.9x10^7}$$

$$G = \frac{2.025x10^7}{s^2 + 48.63s + 1.024x10^7}$$

$$G_{Notch} = \frac{s^2 + 48.63s + 0.9x10^7}{s^2 + 1x10^4 s + 0.9x10^7}$$

$$G_{Notch} = \frac{s^2 + 48.63s + 0.9x10^7}{s^2 + 1x10^4 s + 0.9x10^7}$$





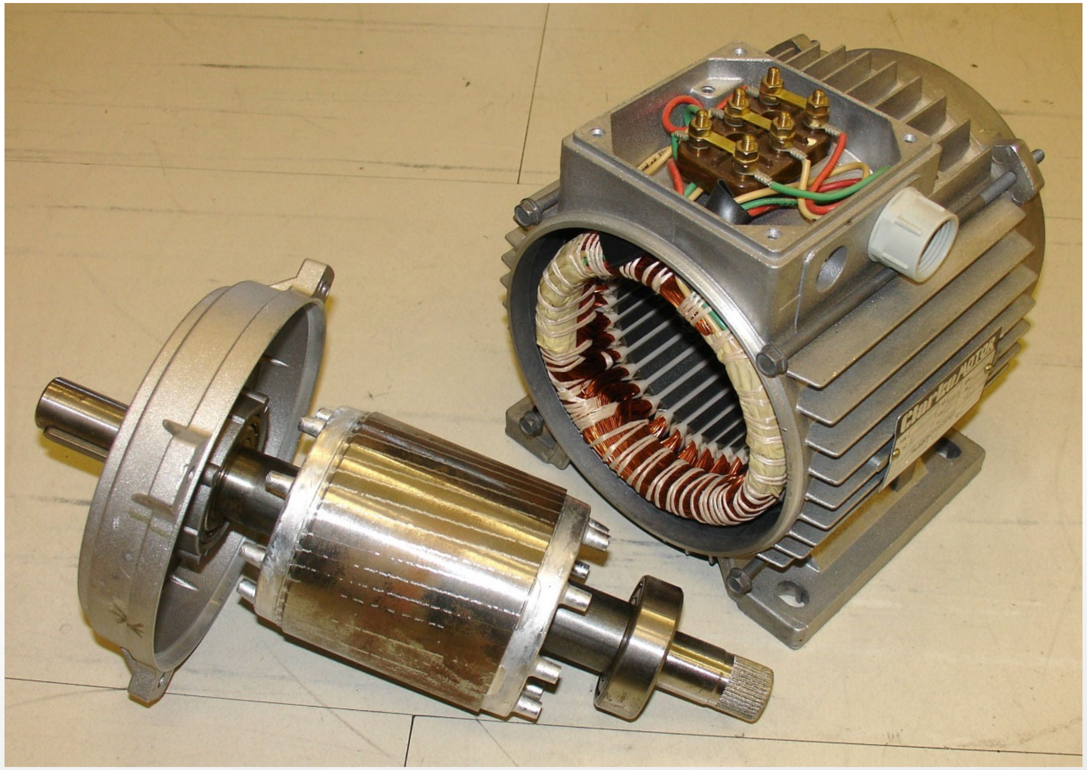
RMIT UNIVERSITY

Contents

RMIT UNIVERSITY

Induction Motor

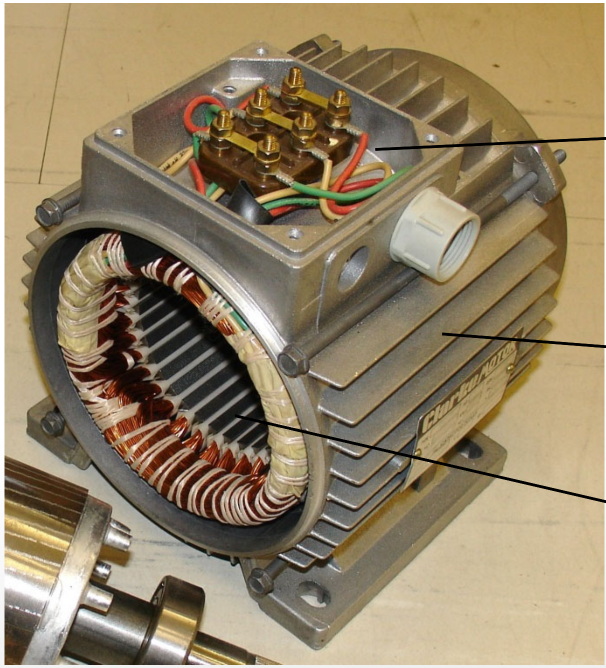
- Most commonly used machine.
- Cheaper, rugged and easier to maintain than other alternatives.



Stator & Rotor of Induction Motor
https://commons.wikimedia.org/wiki/File:Stator_and_rotor_by_Zureks.JPG

Stator

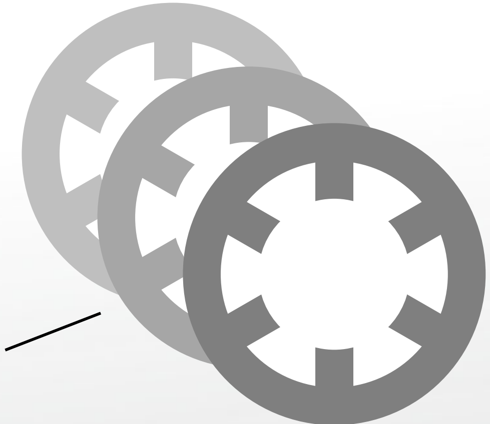
- Stacking thin slotted, highly permeable steel laminations, inside a steel or cast iron frame.
- 3-Phase windings pass through slots of stator.



3 Wires for 3 Separate Phases of Current

Frame

Slotted steel laminations



(Stacks)

Stator – Rotating Magnetic Field

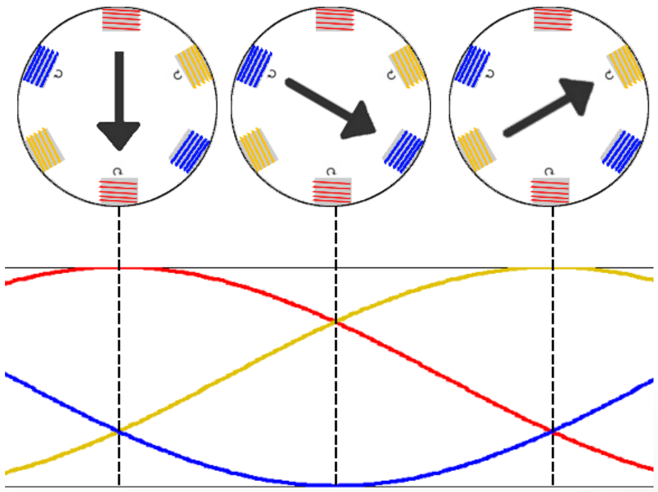
- When 3-Phase AC current passes through the windings, a rotating magnetic field is produced.

- The speed of rotation of the magnetic field is called synchronous speed, n_s.

- $$n_s = \frac{2f}{p}$$

  - f = motor supply frequency
  - p = number of magnetic poles (number of coils divide by 3).

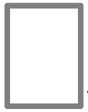
- E.g. 12 coils → 4 poles.
- F = 50Hz
- Then $n_s = \frac{2(50\text{Hz})}{4} = 25\text{Hz} = 1500\text{rpm}$



Rotating Field
https://en.wikipedia.org/wiki/Induction_motor#/media/File:Rotatingfield.png

Rotor – Induced Current

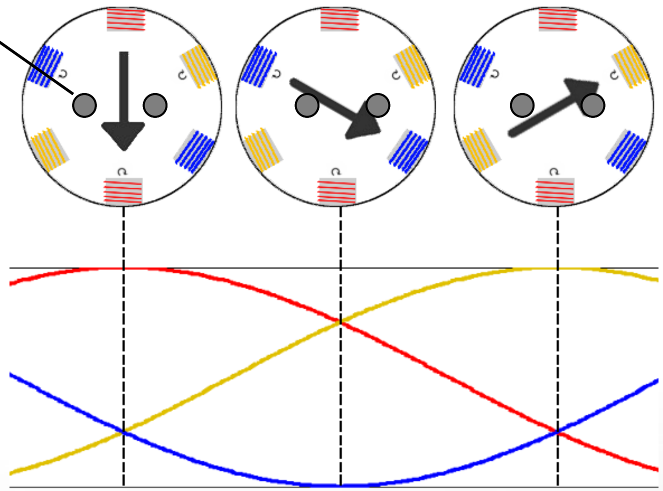
- Now, imagine we put a closed conductor inside the rotating magnetic field.



- Because the conductor experiences a fluctuating (rotating) magnetic field, an electromotive force (EMF) will be induced in the loop according to Farraday's Law.
  - "The EMF is given by the rate of change of magnetic flux".

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

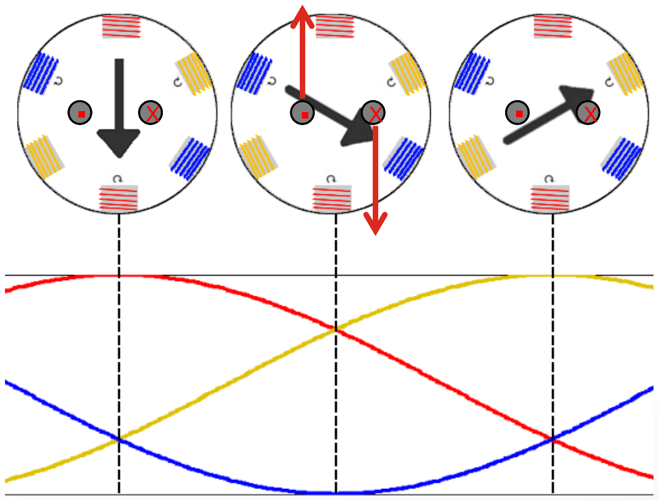
- This EMF produces a current through the loop.



Rotating Field
https://en.wikipedia.org/wiki/Induction_motor#/media/File:Rotatingfield.png

Rotor – Force and Rotation

- Finally, due to the current-carrying loop situated in a magnetic field, a magnetic force is produced in the loop according to Lenz's law.
- The loop will start rotating!
- But at what speed???
- <u>Assume</u> $n_{rotor} = n_s$
  - Then the rotating loop experiences a "constant" magnetic field.
  - No induced EMF, no current, and thus no force on the rotor / loop!
  - The rotor will slow down.
  - But as it slows down, it will experience a rotating magnetic field.
  - Current is induced and force will rise again → Rotor will speed up.



Rotating Field
https://en.wikipedia.org/wiki/Induction_motor#/media/File:Rotatingfield.png

Rotor – Force and Rotation

- As can be imagined, the rotor will never be able to catch up with the magnetic field.
- The difference between Ns and Nrotor is called the "Slip".

$$Slip = n_s - n_{rotor}$$

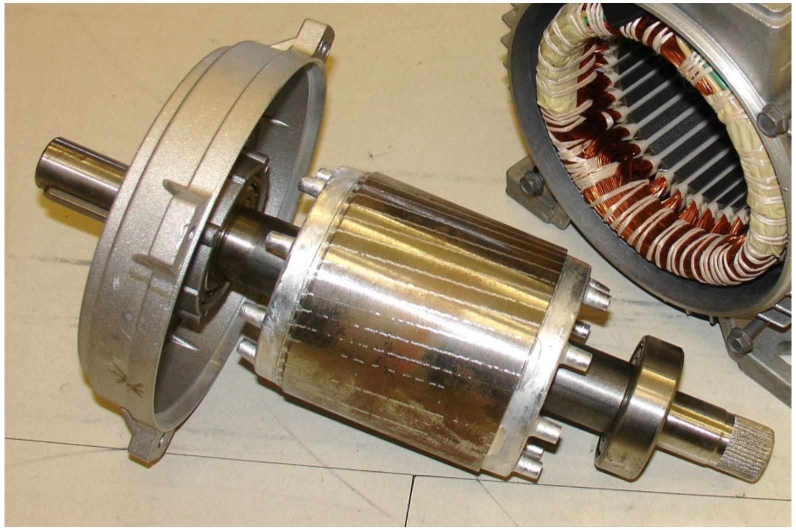
- Sometimes it is also given in ratio but it should be clear from context:

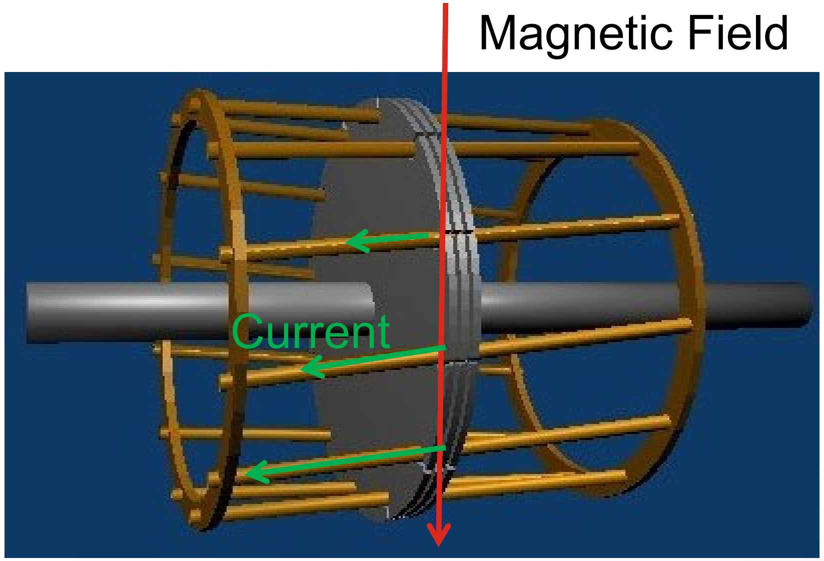
$$Slip = \frac{n_s - n_{rotor}}{n_s}$$

  - 0 when rotor at synchronous speed
  - 1 when rotor at rest
  - At full rated load, slip varies from less than 1% for large motors to more than 5% for small motors.

Rotor – Squirrel Cage

- Instead of simple loops, something similar to squirrel cage is often used as rotors in induction motors.



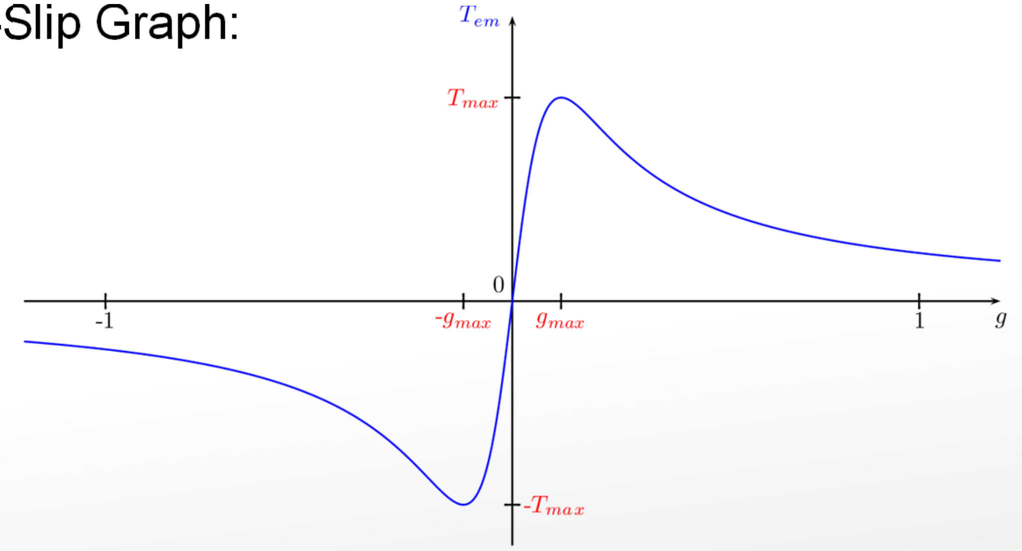


Squirrel Cage
https://commons.wikimedia.org/wiki/File:Squirrel_cage.jpg

- 3 phase AC current pass through stator windings produces a rotating magnetic field.
- Current will be induced in bars of the squirrel cage → Force

Induction Motors – Other Info

- The name "Induction Motors" refers to the fact that electricity is induced in the rotor by magnetic conduction, rather than direct electric current.
- It is also called "Asynchronous Motor" because it runs at a speed less than the synchronous speed n_s.
- Torque-Slip Graph:



Torque vs Slip
https://en.wikipedia.org/wiki/Induction_motor#/media/File:Couple_glissement_MAs.svg

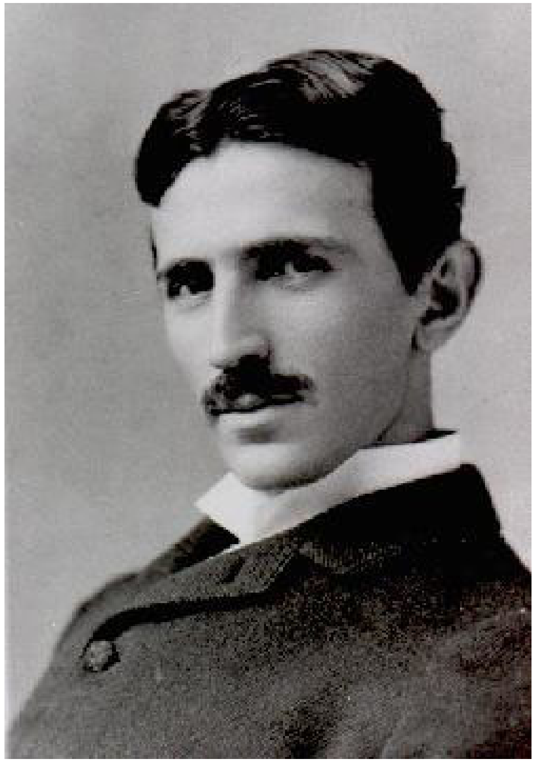
- A small slip induces large current in the rotor and produces large torque.

Induction Motors – Other Info

- Why are the rotors designed with skewed conductors?
  - Reduces magnetic hum, and thus the motor is quieter.
  - To prevent cogging phenomenon
    - If the rotor conductors are straight, there are chances of magnetic locking or strong coupling between rotor & stator.
    - With the bars skewed, the amount of the bar cutting the magnetic field line grows continuously and the next bar starts cutting the field lines as the first finishes.

Nikola Tesla

10 July 1856 – 7 January 1943



Nikola Tesla

(No Model.)

N. TESLA.

ALTERNATING MOTOR.

No. 555,190. Patented Feb. 25, 1896.

Fig. 1

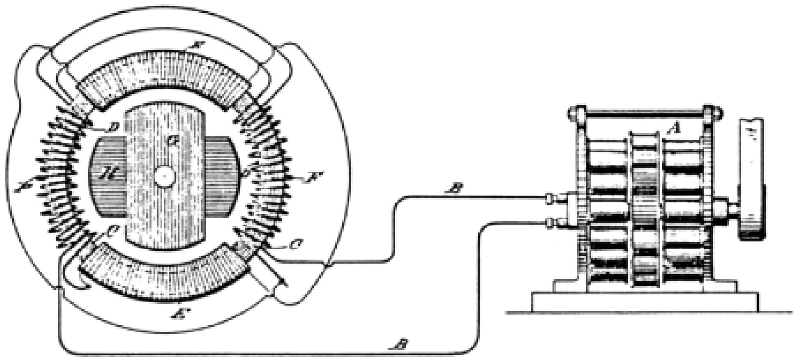
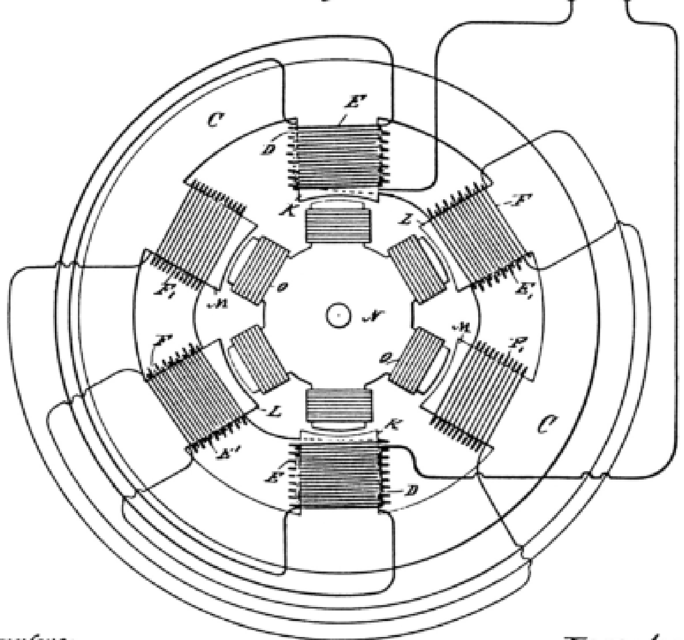


Fig. 2



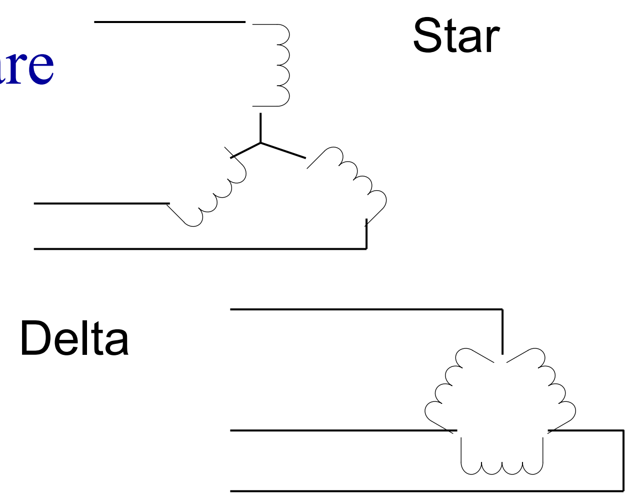
Witnesses:
Raphaël Netter
Robt. F. Gaylord

Inventor
Nikola Tesla

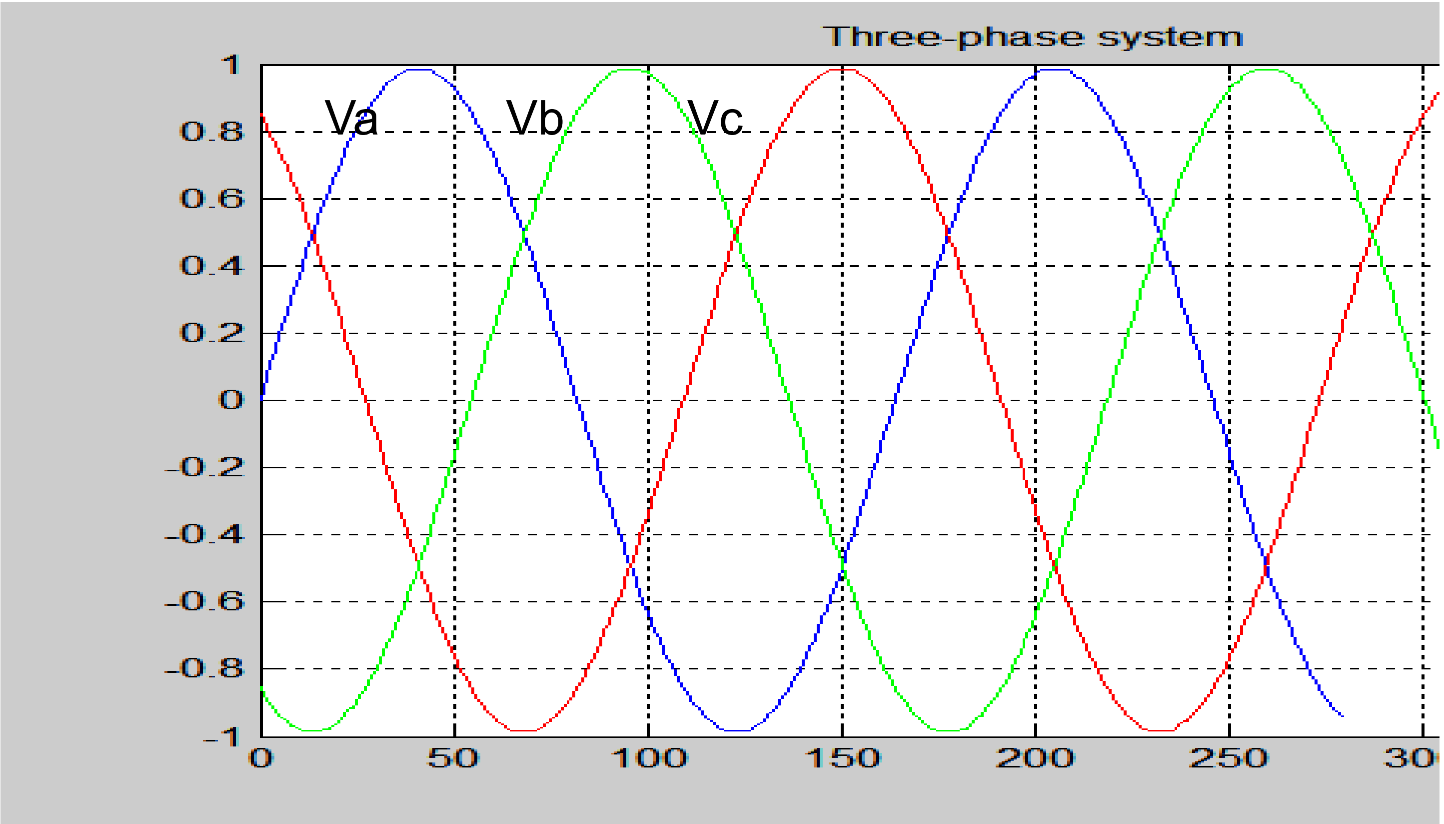
by
Duncan, Curtis & Page
Attorneys.

Tesla Induction Motor: Stator

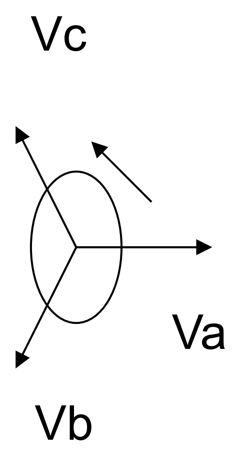
- AC windings are physically separated
- Angle between windings is $2\pi/3$ (120^0)
- Voltage range is up to 33kV
- The ends of three phase windings are connected in
  - Star, or
  - Delta configuration



Three-phase Power System



Phasor Diagram

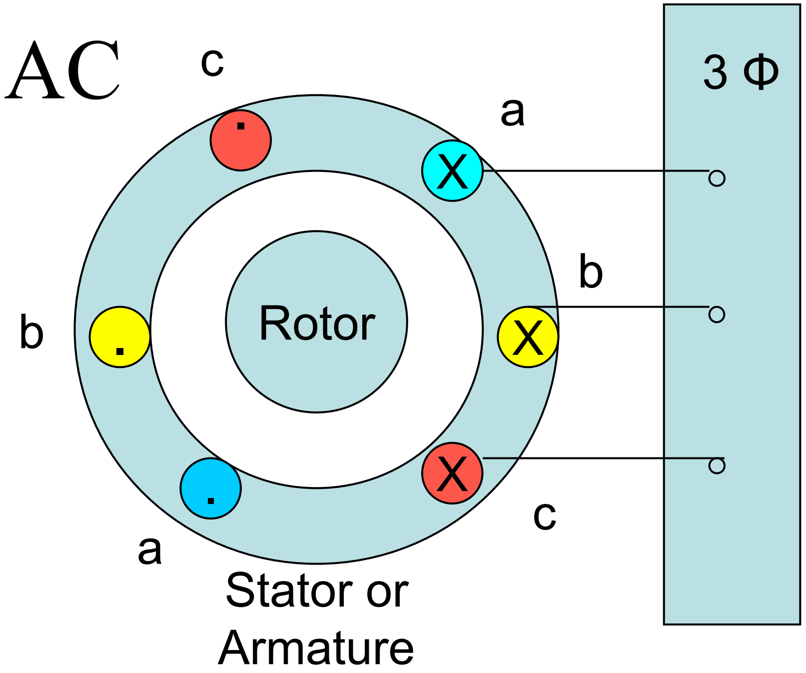


Three-phase Induction Motors

- Most widely used
- Nearly all motors above 3kW are three-phase induction motors
- Economical
- Long life
- Less maintenance

Stator

- Stator windings are star or delta connected
- They use three-phase AC
- ***=> Rotating Magnetic Field is Generated***



Rotating Magnetic Field

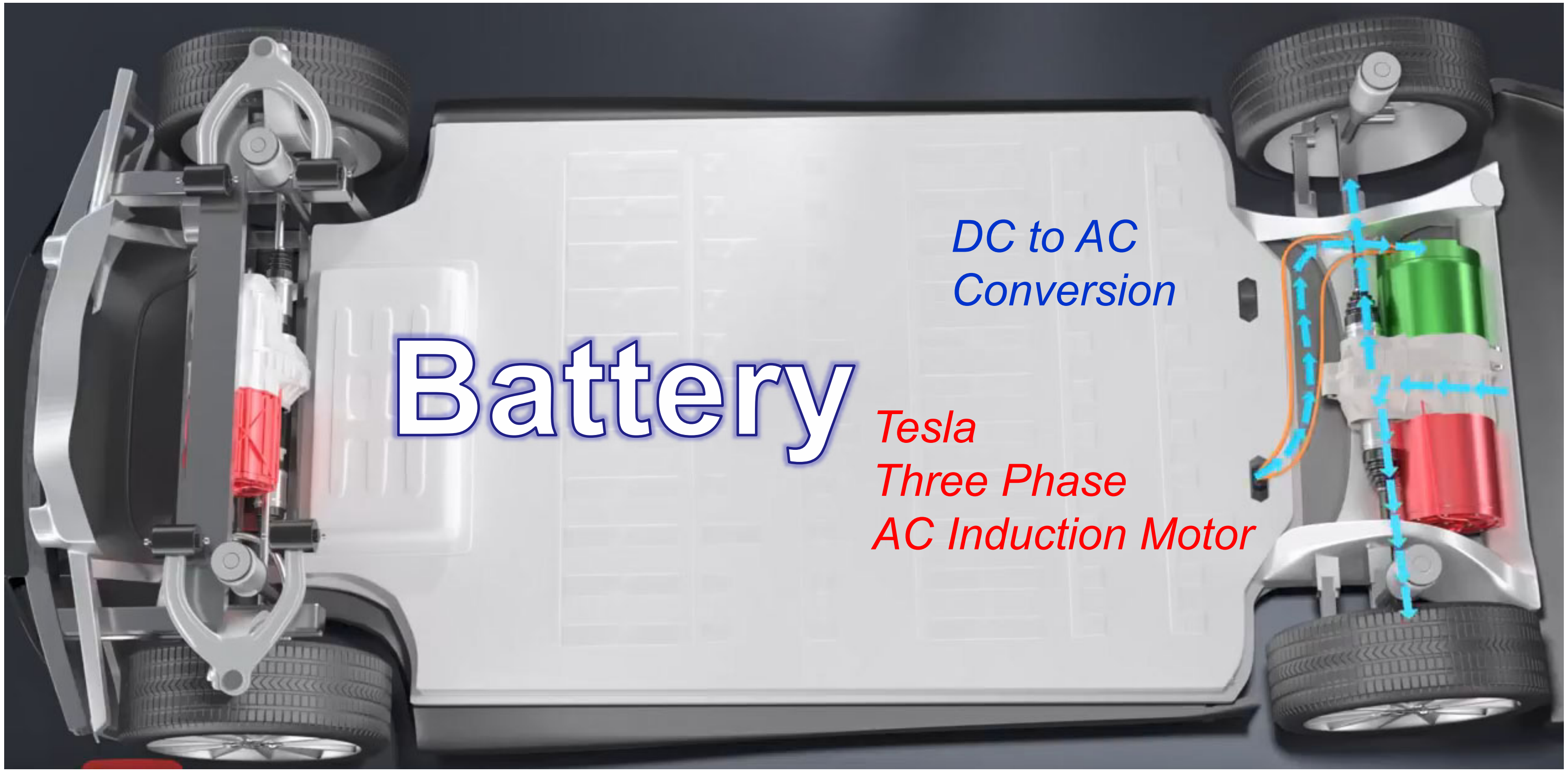
- Sinusoidal space distribution

- It is changing, rotating and so generates current in the rotor
- **Rotor windings are always short-circuited**

AC Motors

- https://www.youtube.com/watch?v=awrUxv7B-a8
- https://www.youtube.com/watch?v=AQqyGNOP_3o

TESLA Electrical Car



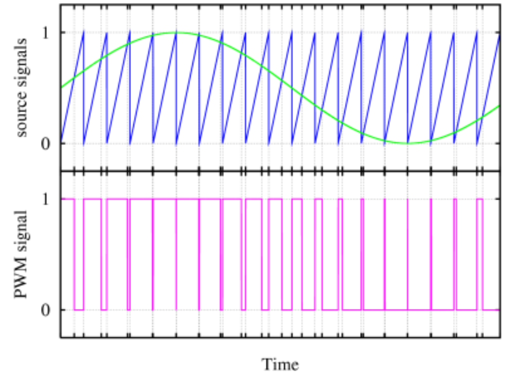
Induction Motors – Other Info

- Earlier we saw that the speed of induction motor is tied to the supply frequency: $$n_s = \frac{2f}{p}$$
- How can we control or vary the speed for different applications?
  - Use Variable Frequency Drive
    - A device which adjusts the frequency of supply before going into the motor.

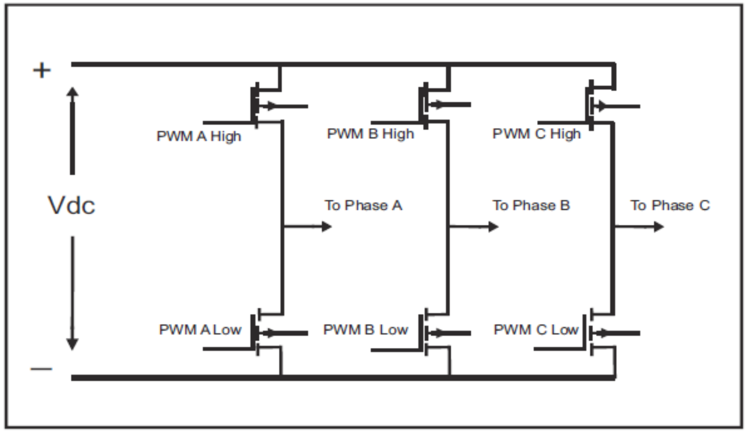
Variable Frequency Drive
https://commons.wikimedia.org/wiki/File:Small_VFD_2.jpg

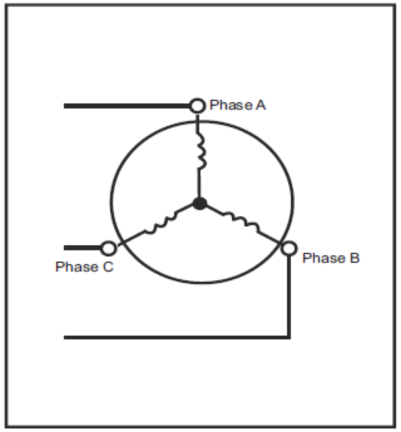
Induction Motors – Other Info

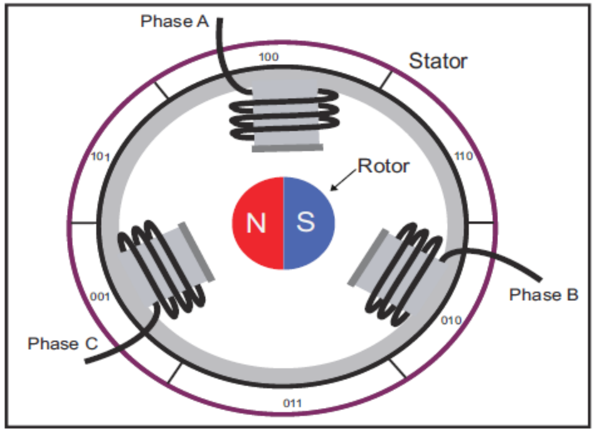
- The variable frequency device works on the principle of PWM, which you learnt last week.



PWM Generation
https://commons.wikimedia.org/wiki/File:Pwm.png







Microsemi
Field Oriented Control of Permanent Magnet Synchronous Motors User's Guide

Contents

- Piezo-Actuators
  - The Piezoelectric Effect
  - PZT Ceramics
  - Applications
  - Issues
  - Modeling and Control
- Induction Motor
- Synchronous Motor
  - Mathematical Model
  - Field Oriented Control
- Actuators Suitable for Force Control

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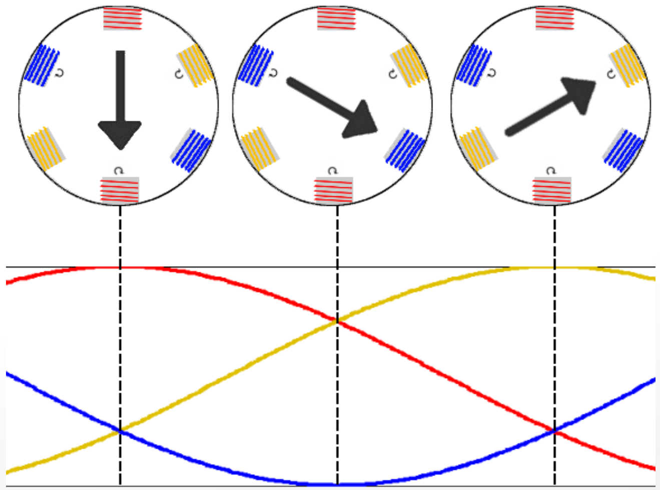
Synchronous Motor

- Can anyone guess the meaning of “Synchronous Motor”?

- Synchronous motors are capable of running at constant speed irrespective of load acting on them.
- High efficiency.
- Mainly used in high precision applications.

Synchronous Motor

- The constant speed is achieved by the interaction between a constant & a rotating magnetic field.
- The rotating magnetic field ("RMF") is created by a 3-phase AC supply on the stator field coil, similar to the induction motor:



Rotating Field
https://en.wikipedia.org/wiki/Induction_motor#/media/File:Rotatingfield.png

- Again, this RMF rotates at the synchronous speed n_s.

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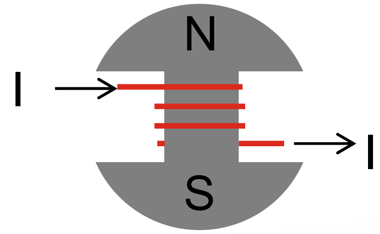
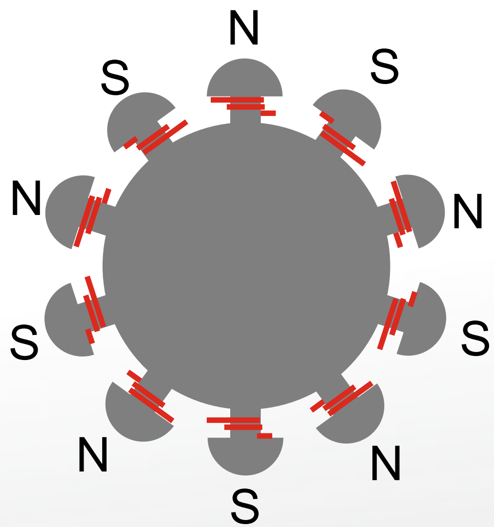
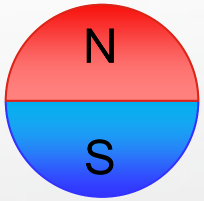
Synchronous Motor - Rotor

- The rotor of the synchronous motor produces a constant magnetic field. This can be either:
  - Electromagnet
    - Rotor is excited by a DC power supply
    - Acts like a permanent magnet



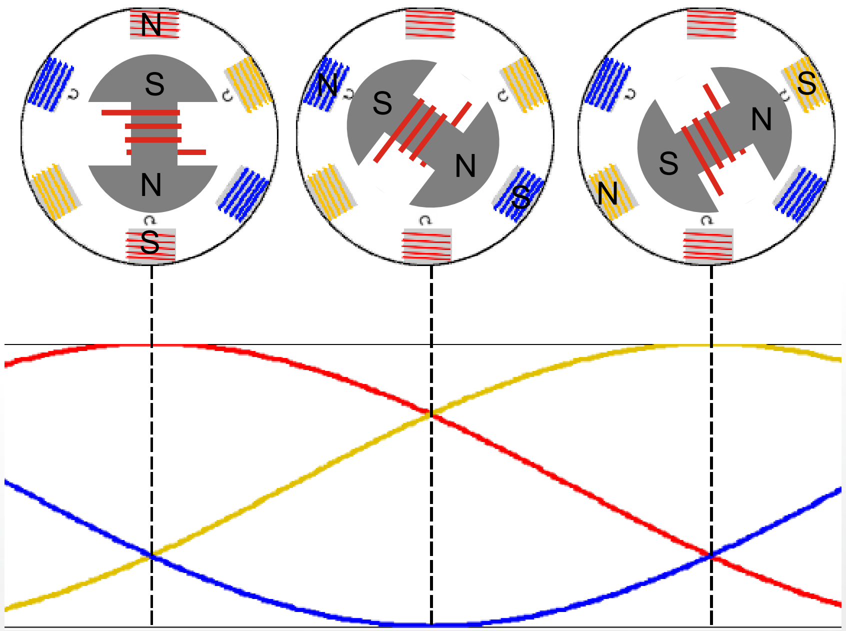


  - Permanent Magnet



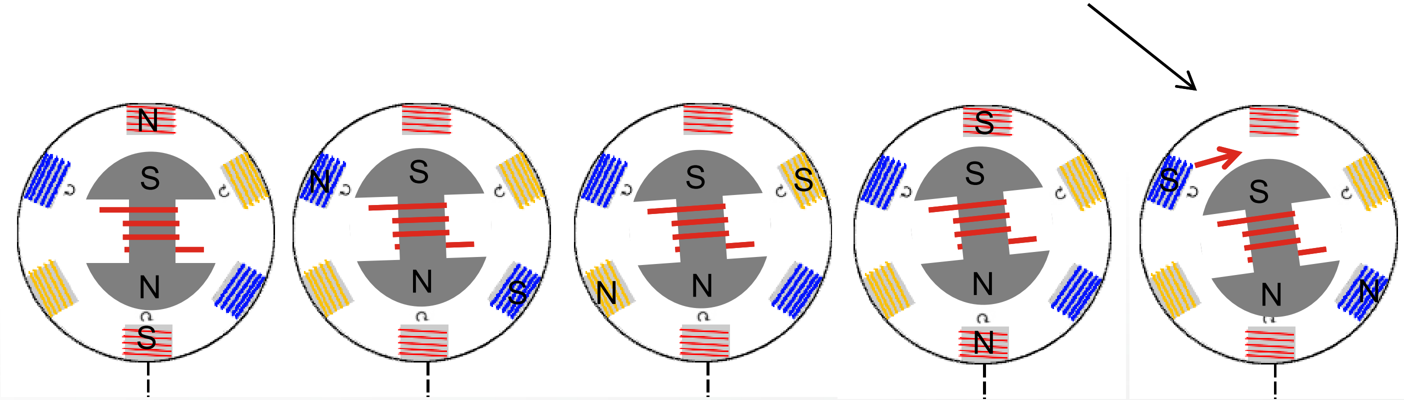
Synchronous Motor - Rotation

- Assume the rotor has an initial rotation in the same direction as RMF.
- The opposite poles of RMF and rotor will attract each other.
- They will get locked magnetically and thus the rotor rotates at same speed (n_s) as RMF.
- Thus "Synchronous Motor".



Synchronous Motor – Starting Up

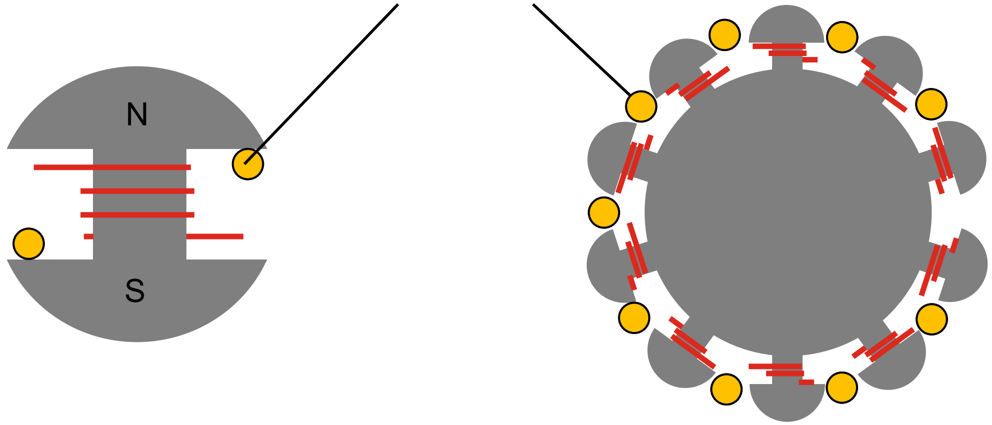
- However, if the rotor does not have an initial rotation, the following is going to happen:
  - Firstly, opposite poles will attract each other, and the rotor will start to turn.
  - However, due to inertia, it starts turning slowly.
  - After a short while, the original pole of the RMF is replaced by the opposite pole, so it gives the rotor a repulsive force:



  - As a net effect, the rotor won’t be able to start.
  - → Synchronous Motors are not inherently self-starting!

Synchronous Motor – Starting Up

- To make synchronous motor self start, we borrow idea from induction motor:
  - Fit a squirrel cage (also called "Damper Winding") through the pole tip.



  - During starting, the rotor coils are not energized.
  - The RMF induces electricity in the cage bar, and rotor starts rotating just like induction motor.
  - When rotor achieved its maximum speed, rotor field coil is energized → rotor poles locked with RMF poles and rotates at synchronous speed.
  - Relative motion between cage & RMF becomes zero → No current & force, therefore the cage would not affect the operation of Synchronous Motor.

Synchronous Motor – Other Info

- The squirrel cage in Synchronous Motor is also called “damper winding” because it damps oscillation in motor speed during operation.
- Constant speed irrespective of load <u>only if</u> load is within capability of motor.
  - If load is too high, the motor will slip out of synchronism and will come to rest.
- Out of synchronism can be caused by:
  - Motor overload
  - Low supply voltage
  - Low excitation voltage

Synchronous Motor

<table>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>

Higher efficiency (93% - 98%)
No conductor losses in rotor
Suited for high power at lower speeds
Power varies linearly with applied voltage
Higher power density (output power / physical size)
Because of higher magnetic flux compared to induction motor
Speed constant at any load
More accurate control of speed
Cooler, therefore longer bearing life and insulation life
Wider air gap, less vibration & more stable

</td><td>

Permanent Magnet Synchronous Motor subject to demagnetization when operated at high current or high temperature
Doubly excited (Stator by AC and Rotor by DC)
Starting torque is zero
Not self-starting
More expensive because it is more complicated to build
Hunting: When sudden or variable loads are applied, the motor hunts (swings / seek equilibrium)
When overloaded, the motor stops

</td></tr>
</table>

Induction Motor

Advantages	Disadvantages
• Simply excited (AC to stator only) • Best suited for high speed • 3-Phase IM has high starting torques • 3-Phase IM are self-starting • Rugged, sturdy & strong • Flexible, robust, operates in any environmental conditions • Simple, easy to manufacture and maintain • Safer in explosive application (no arcing, sparking or fire hazard) • Smoother operation • Cheaper	• High I^2R losses • Lower efficiency: • IM with squirrel cage have rotor losses of 20-35% of the total motor losses • Speed less than n_s • Speed is dependent on load • Cannot produce torque without slip

Contents

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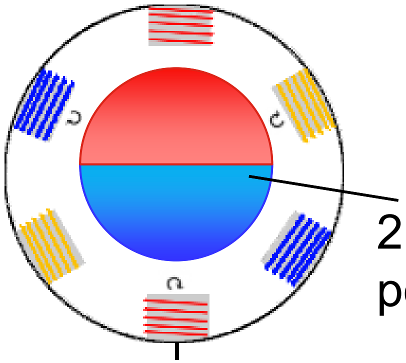
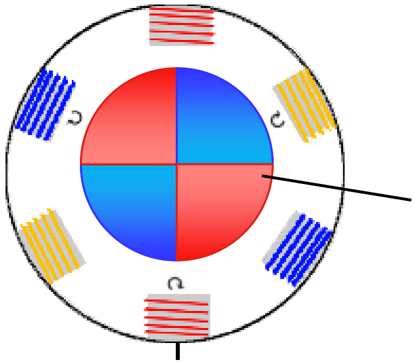
Mathematical Model

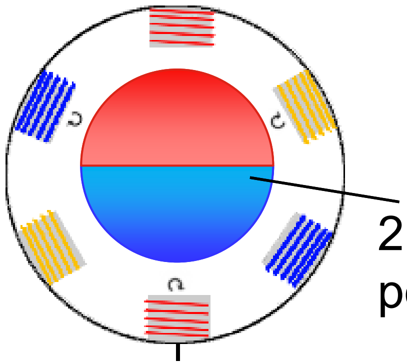
- We are going to focus on Permanent Magnet Synchronous Motor.

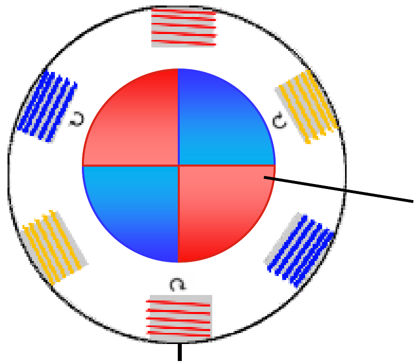




- We need to define the mechanical and electrical position.
  - Mechanical position (θ_m) is related to the rotation of rotor shaft.
    - When the rotor shaft turns 360 mechanical degrees, the rotor is back in the same position where it started.

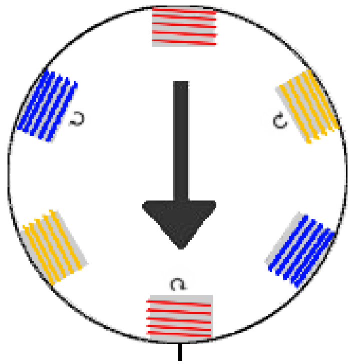
Mathematical Model





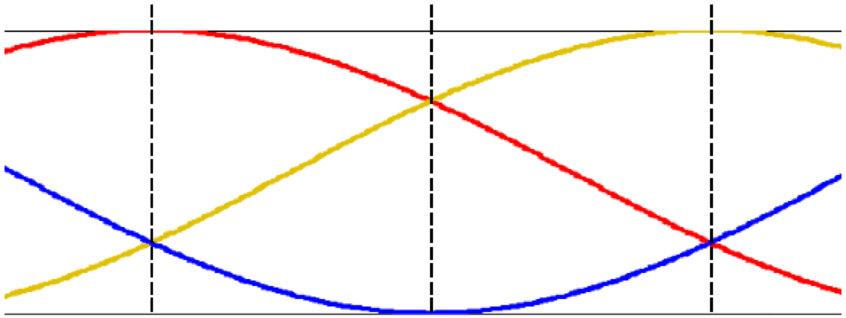
- Electrical position (θ_e) of the rotor is related to the rotation of the rotor magnetic field.
  - In the left figure, the rotor needs to move 360 mechanical degrees to obtain an identical magnetic configuration as when it started.
  - In the right figure, the rotor needs only to move 180 mechanical degrees to achieve the same.
  - Therefore: $\theta_e = \theta_m \times pp$ where pp is the number of pole pair.
  - Also, we have $\omega_e = \omega_m \times pp$ where ω is the speed.

Electrical Model



- To create the rotating stator flux, the commonly applied phase voltages present a phase shift of 120 electrical degrees from one to another:

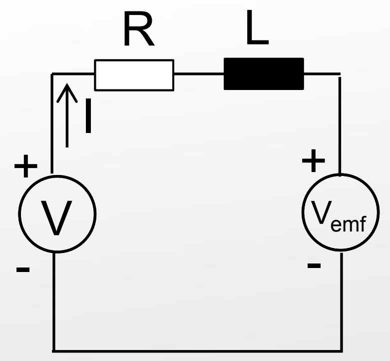
$$v_a = V\cos(\omega_e t)$$
$$v_b = V\cos\left(\omega_e t - \frac{2\pi}{3}\right)$$
$$v_c = V\cos\left(\omega_e t - \frac{4\pi}{3}\right)$$



- A one phase electrical equation can be written as:

$$v = Ri + L\frac{di}{dt} + \underbrace{\frac{d\Psi_m(\theta_e)}{dt}}_{\text{induced voltage}}$$

  - Where ψ_m corresponds to the amplitude of the natural magnetic flux of the permanent magnets.



Electrical Model

- Now, $$\frac{d\Psi_m(\theta_e)}{dt}=\frac{d\Psi_m(\theta_e)}{d\theta_e}\cdot\frac{d\theta_e}{dt}=\frac{d\Psi_m(\theta_e)}{d\theta_e}\cdot\omega_e$$

- Since $$\Psi_m(\theta_e)=\Psi_m\begin{bmatrix}\cos(\theta_e)\\ \cos\left(\theta_e-\frac{2\pi}{3}\right)\\ \cos\left(\theta_e-\frac{4\pi}{3}\right)\end{bmatrix}$$

- The induced voltage has the following form:

$$E=\begin{bmatrix}E_a(\theta_e)\\ E_b(\theta_e)\\ E_c(\theta_e)\end{bmatrix}=\omega_e\Psi_m\begin{bmatrix}-\sin(\theta_e)\\ -\sin\left(\theta_e-\frac{2\pi}{3}\right)\\ -\sin\left(\theta_e-\frac{4\pi}{3}\right)\end{bmatrix}=\omega_e\Psi_m[K(\theta_e)]$$

Mechanical Model

- From the electrical power delivered to the motor,
  - A part of it is transformed in Joule losses.
  - Another part is going to the energy stored in the magnetic field.
  - And the last part is transformed into mechanical energy (torque production).
- The torque in PMSM is expressed by:

$$T_e = pp \cdot [I_s]^T \cdot \Psi_m \cdot [K(\theta_e)]$$

- If we can control the current to be:

$$I_s = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} I_s \sin(\omega_e t) \\ I_s \sin\left(\omega_e t - \frac{2\pi}{3}\right) \\ I_s \sin\left(\omega_e t - \frac{4\pi}{3}\right) \end{bmatrix}$$

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Mechanical Model

- Then the torque is:

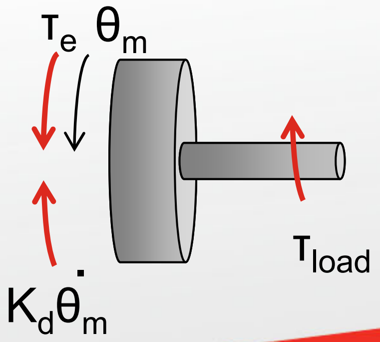
$$
\begin{aligned}
T_e &= pp \cdot \Psi_m \cdot \left(I_a \cdot K_a(\theta_e) + I_b \cdot K_b(\theta_e) + I_c \cdot K_c(\theta_e)\right) \\
&= pp \cdot \Psi_m \cdot I_s \left(\sin^2(\omega_e t) + \sin^2\left(\omega_e t - \frac{2\pi}{3}\right) + \sin^2\left(\omega_e t - \frac{4\pi}{3}\right)\right) \\
&= \frac{3}{2} pp \cdot \Psi_m \cdot I_s
\end{aligned}
$$

  - Which is a constant.

- Finally, the torque would drive the load, and the dynamic equation is given by:

$$J\ddot{\theta}_m = T_e - T_{load} - K_d \omega_m$$

  - Where Kd is the viscosity coefficient.



Contents

Current Control in Stator Windings

- Just now, we determined that if we can control the currents to be proper sine waves:

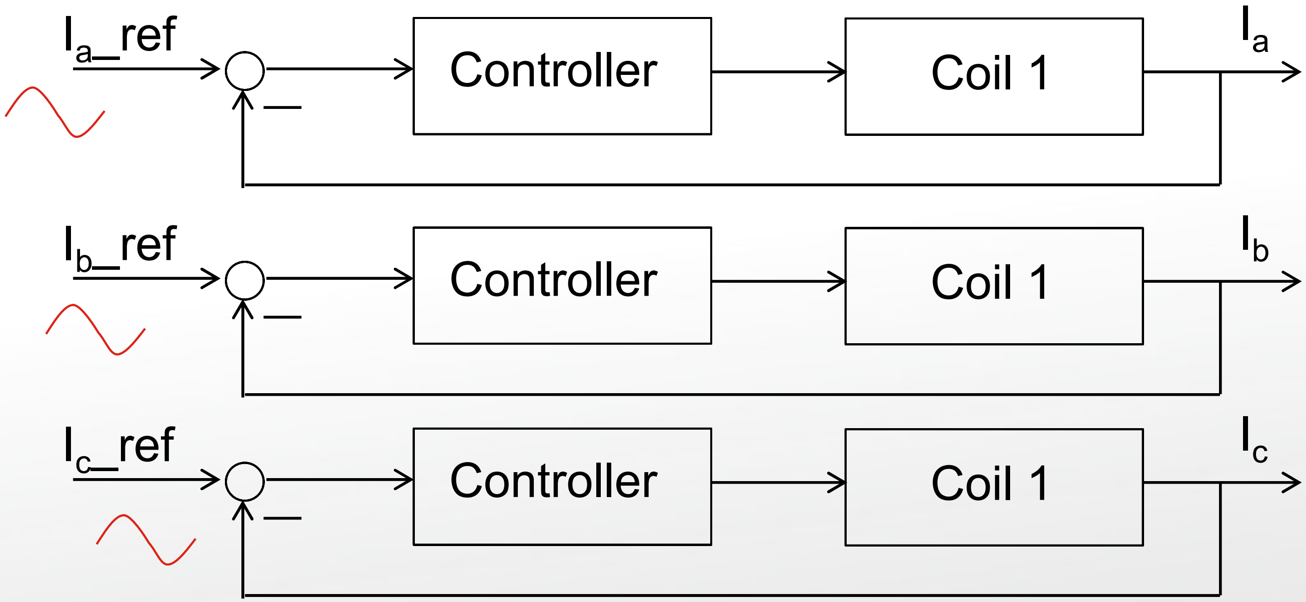
$$I_s = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} I_s \sin(\omega_e t) \\ I_s \sin\left(\omega_e t - \frac{2\pi}{3}\right) \\ I_s \sin\left(\omega_e t - \frac{4\pi}{3}\right) \end{bmatrix}$$

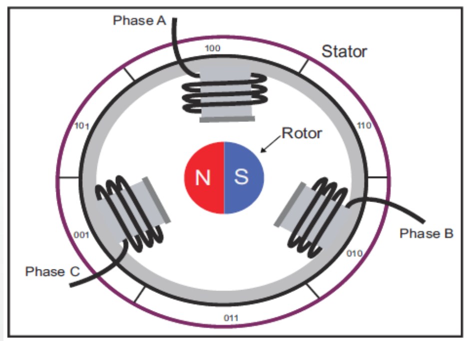
- Then the torque will be a constant:

$$\begin{aligned} T_e &= pp \cdot \Psi_m \cdot (I_a \cdot K_a(\theta_e) + I_b \cdot K_b(\theta_e) + I_c \cdot K_c(\theta_e)) \\ &= pp \cdot \Psi_m \cdot I_s \left(\sin^2(\omega_e t) + \sin^2\left(\omega_e t - \frac{2\pi}{3}\right) + \sin^2\left(\omega_e t - \frac{4\pi}{3}\right)\right) \\ &= \frac{3}{2} pp \cdot \Psi_m \cdot I_s \end{aligned}$$

Current Control in Stator Windings

- To make sure that the current is a nice sine wave, there is a need for current control:
  - The phase current is measured using current sensor (e.g. Shunt Resistors), and fed back to a controller (e.g. PI) for adjustments.
- Before the introduction of Field Oriented Control, the 3 phase currents are controlled separately.





Current Control in Stator Windings

- This method has the following drawbacks:
  - Great difficulty in controlling the currents with sinusoidal references.
  - The machine models are valid only in steady state. This causes the control to allow high peak voltage and current transients, which damages drive dynamic performance and power conversion efficiency.
  - No three phase system imbalance management.
    - No consideration of the phase interaction.

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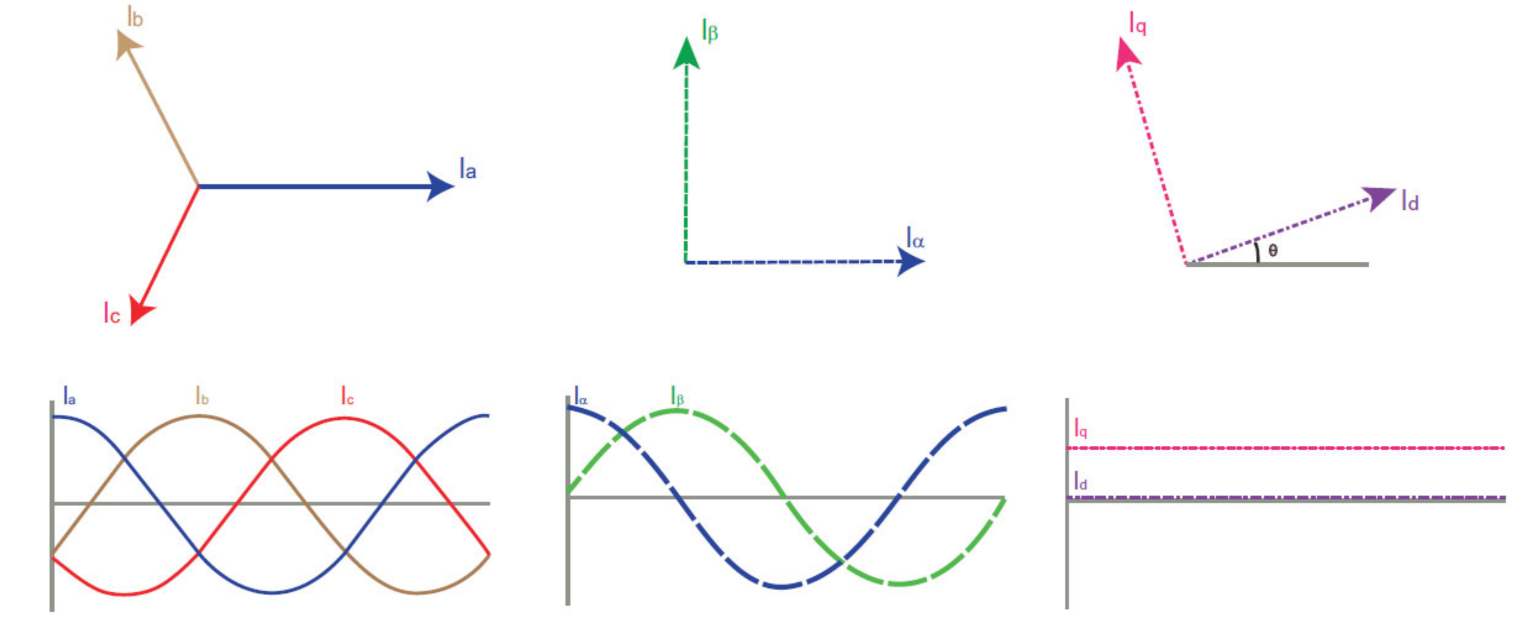
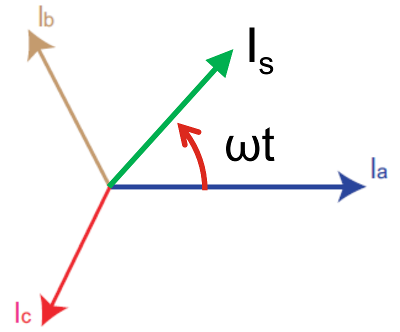
Field Oriented Control

- The Field Oriented Control (FOC) is basically a projection of the 3-phase sinusoidal system into a 2-phase time invariant system.
  - Coordinate transformation



What do I mean by that?

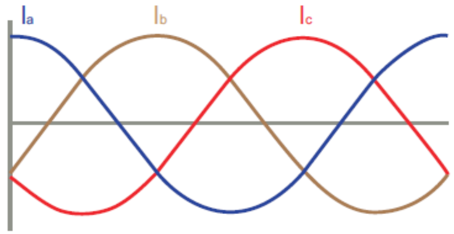
- Initially, we have 3 currents, I_a, I_b and I_c, which if added vectorially will give us a vector I_s. ("s" stands for stator).



$$I_a = I_s cos(\omega t)$$

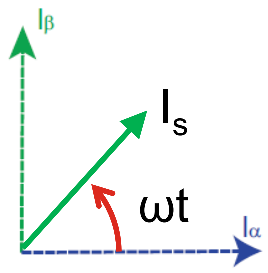
$$I_b = I_s cos(90 - \omega t + 30) \\ = I_s cos(120 - \omega t)$$

$$I_a + I_b + I_c = 0$$



What do I mean by that?

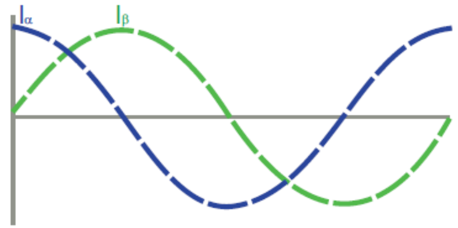
- Now, we want to project the current stator into a 2-axis coordinate system.



$$I_\alpha = I_s cos(\omega t) = I_a$$

$$I_\beta = I_s sin(\omega t)$$

However, this needs to be expressed in I_a and I_b as we have the measurements



- I_b was:

$$I_b = I_s cos(120 - \omega t) = I_s cos(120) cos(\omega t) + I_s sin(120) sin(\omega t)$$

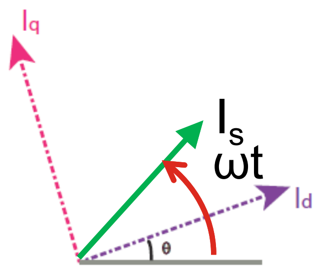
$$= -\frac{1}{2} I_s cos(\omega t) + \frac{\sqrt{3}}{2} I_s sin(\omega t) = -\frac{1}{2} I_a + \frac{\sqrt{3}}{2} I_\beta$$

- Thus:

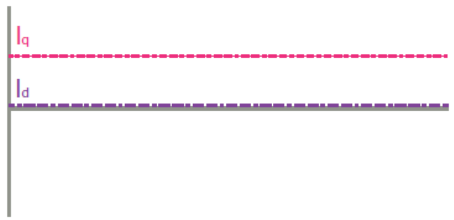
$$I_\beta = \frac{1}{\sqrt{3}} I_a + \frac{2}{\sqrt{3}} I_b$$

What do I mean by that?

- Finally, we project the vector into a rotating frame, which rotates at the same speed as the vector.



$$I_d = I_s\cos(\omega t - \theta)$$
$$= I_s cos(\omega t)cos(\theta) + I_s sin(\omega t)sin(\theta)$$
$$= I_\alpha cos(\theta) + I_\beta sin(\theta)$$



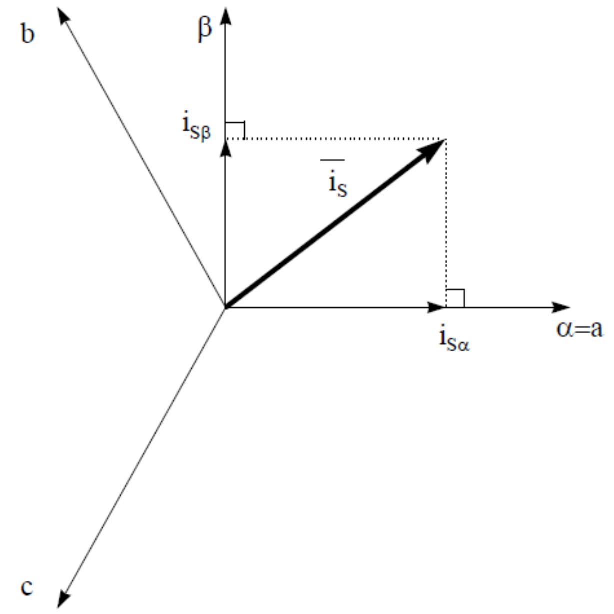
$$I_q = I_s\sin(\omega t - \theta)$$
$$= I_s sin(\omega t)cos(\theta) - I_s cos(\omega t)sin(\theta)$$
$$= I_\beta cos(\theta) - I_\alpha sin(\theta)$$

Field Oriented Control

- In summary, there are two steps to transform the 3-phase sinusoidal currents to 2-phase constant currents:
  - Clarke Transformation
    - From (a,b,c) to (α,β)
    - Assume a = α, then:

$$i_\alpha = i_a$$

$$i_\beta = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b$$



Texas Instruments

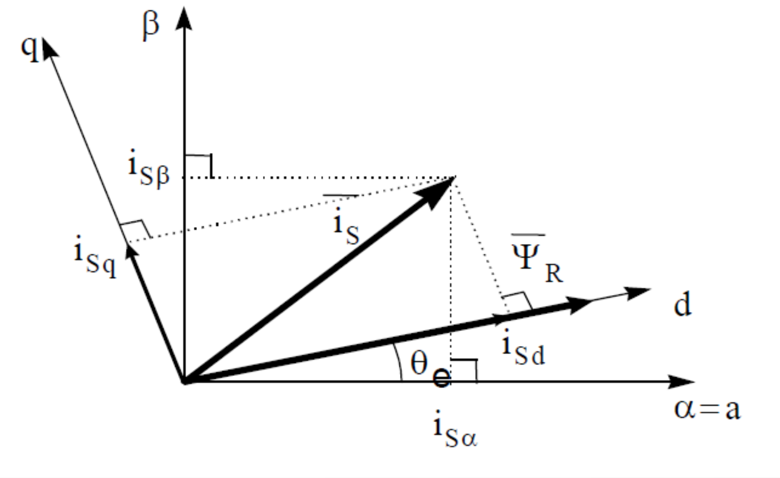
Application Report
SPRA588

Implementation of a Speed Field Oriented Control of 3-phase PMSM Motor using TMS320F240

Erwan Simon *Digital Control Systems*

Field Oriented Control

- Park Transformation
  - From (α,β) to (d,q)
  - We attach the (d,q) frame together with the rotating rotor, where d-axis is aligned with the rotor flux:

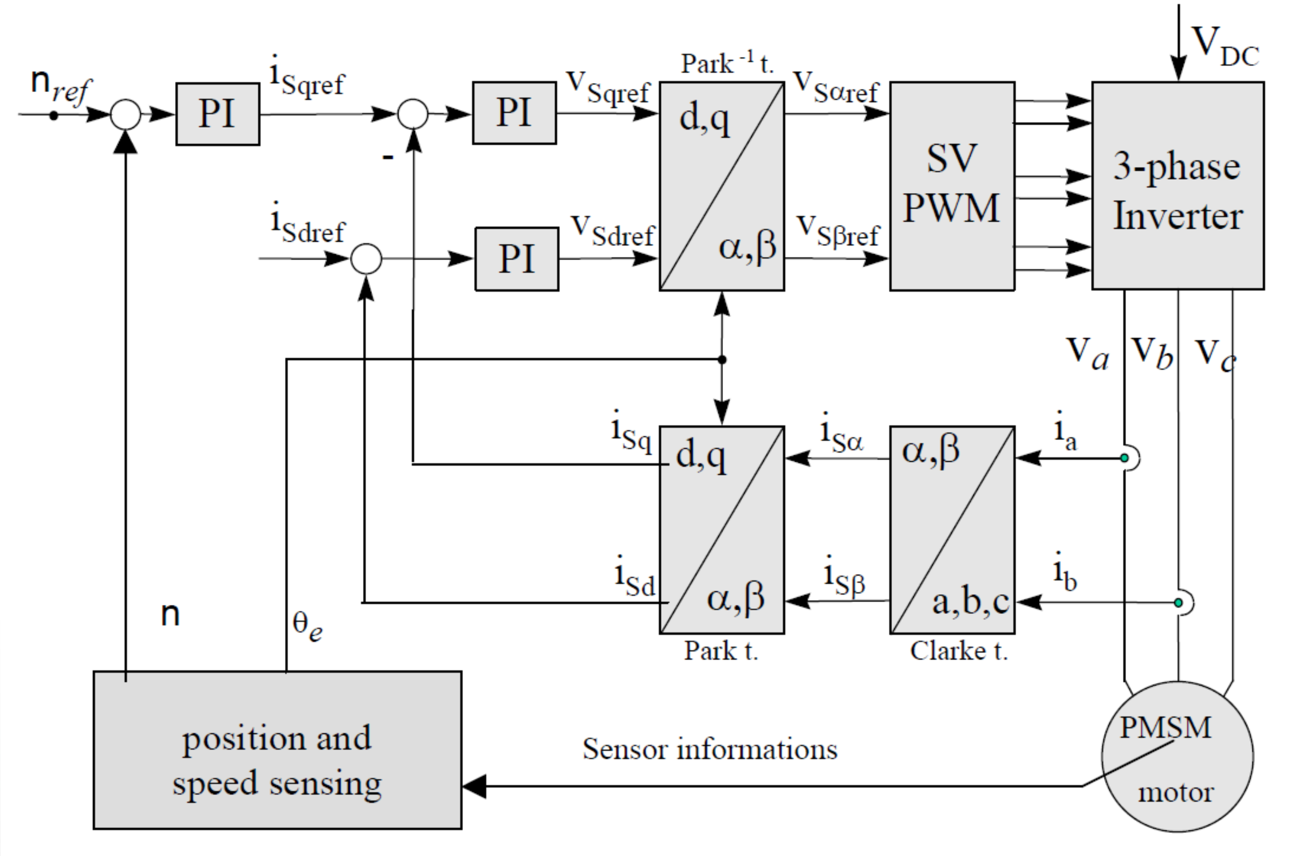


$$i_d = i_\alpha \cos(\theta) + i_\beta \sin(\theta)$$
$$i_q = -i_\alpha \sin(\theta) + i_\beta \cos(\theta)$$

  - Because the (d,q) frame rotates together with the vector i_s, we obtain constant values for i_d and i_q.

Field Oriented Control

- The basic scheme of the FOC is shown in the following diagram:



Field Oriented Control

- Because i_d and i_q are constants, it is easy to give them each a constant reference i_{dref} and i_{qref} and control them using PI controllers.
- The PI controllers provide the voltage in the (d,q) frame, and this needs to be transformed back to the (α,β) frame.
  - Inverse Park Transformation:

$$v_\alpha = v_d \cos(\theta) - v_q \sin(\theta)$$
$$v_\beta = v_d \sin(\theta) + v_q \cos(\theta)$$

- To transform from (α,β) frame back to (a,b,c) frame, the modern method is called "Space Vector Modulation". But let's use the more primitive way here which is:
  - Inverse Clark transformation:

$$v_a = v_\alpha$$
$$v_b = \frac{\left(-v_\alpha + \sqrt{3} v_\beta\right)}{2}$$
$$v_b = \frac{\left(-v_\alpha - \sqrt{3} v_\beta\right)}{2}$$

Field Oriented Control

- As mentioned, we can give constant values for i_{dref} and i_{qref}, but what should their values be?
- Let's look at the (d,q) frame again. In this frame, the expression of the torque is given by:

$$T_e = \frac{3}{2} pp\left(\psi_d \cdot i_q - i_d \cdot \psi_q\right)$$

- To optimize the torque, the appropriate strategy is to set i_{dref} to 0.
- The torque is now given by:

$$T_e \propto \psi_d i_q$$

  - So you can set i_{qref} to any value suitable for your torque.

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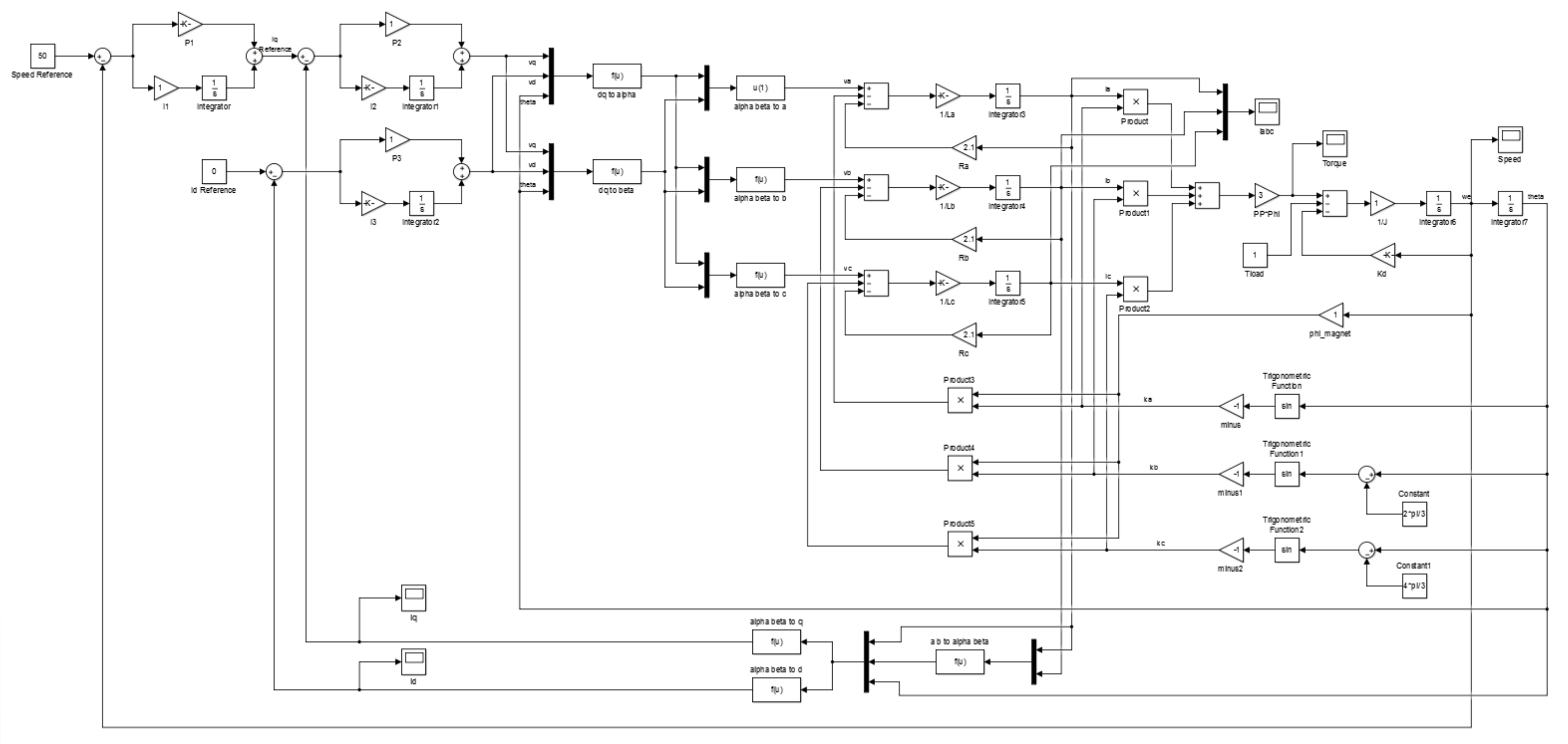
Simulink Example

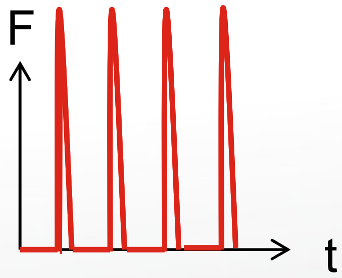
- Please see FOC file which is uploaded in Canvas

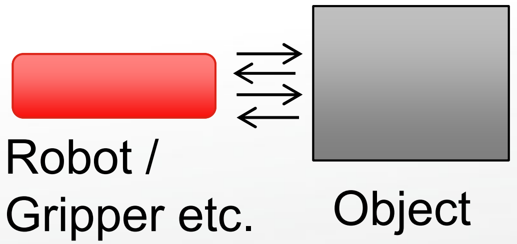


Contents

Actuators Suitable for Force Control

- The traditional premise for good robot design is "Stiffer the better".
  - Allows high bandwidth and precise position control.
- However, the stiffness makes force control difficult.
  - Damage the workpiece.
  - Instability when come into contact with hard surfaces.
    - Chattering effect: Keeps contacting and losing contact

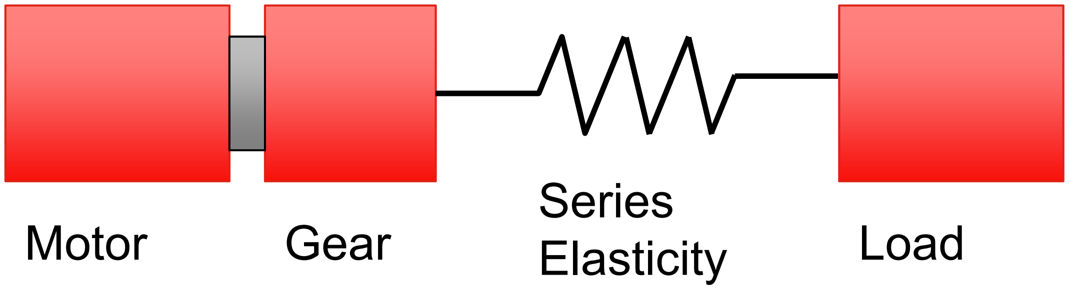




- Interestingly, researchers have solved this problem by wrapping compliant coverings around the robot end-point to reduce stiffness.
  - "Stiffness isn't everything!"

Series Elastic Actuators

- There are some proper designs of actuators which reduce the overall stiffness.
- E.g. Placing an elastic element into the actuator:



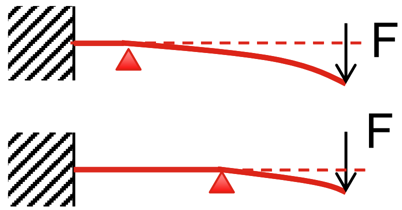
- Advantages:
  - Force control is easier.
  - The effects of friction, backlash, and torque ripple are reduced.
  - The series elasticity also acts as low pass filter, protecting the gear from shock loads.

Series Elastic Actuators

- Applications:
  - Prosthetic Limbs
    - http://biomech.media.mit.edu/portfolio_page/cvsea/
  - Biped robots
    - https://www.youtube.com/watch?v=PZCSkHyjLGQ
  - For safety purposes: the actuators are "flexible" thus can stop if hits human.
    - Important for modern "Robot co-worker" concept in manufacturing.
    - https://www.youtube.com/watch?v=JvIGINLAd_c

Variable Impedance Actuators

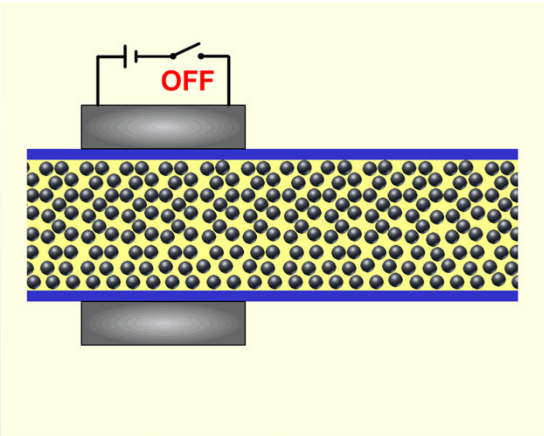
- The Series Elastic Actuator uses a fixed spring.
- Researchers later came up with ideas of variable stiffness and variable damping, which are called “Variable Impedance Actuators”.
- Variable Stiffness:
  - A simple example:
    - Stiffness varies due to change in pivot point
    - Same force, different displacement



  - Usually needs two motors
    - First motor to do the usual actuation.
    - Second motor to tune the stiffness, in the above example the motor is used to move the pivot point.
  - Many other designs, a hot research topic → Search for papers if interested.

Variable Impedance Actuators

- Variable Damping:
  - Dampers reduces oscillations and makes force control easier to achieve.
  - E.g. 1: Magnetorheological (MR) damper
    - Filled with MR fluid, which is controlled by an electromagnet.
    - The damping characteristics can be continuously controlled by varying the power of the electromagnet.
    - More details: When subject to magnetic field, the MR fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid.

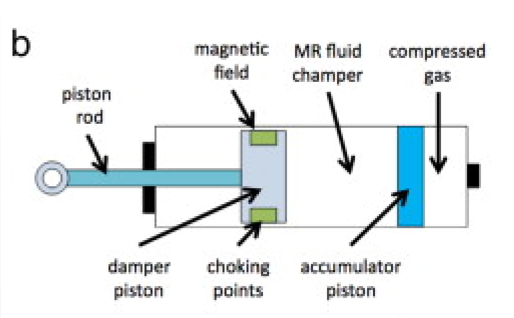


MR Fluid

https://en.wikipedia.org/wiki/Magnetorheological_fluid#/media/File:MRF-Effekt-static-crop.png

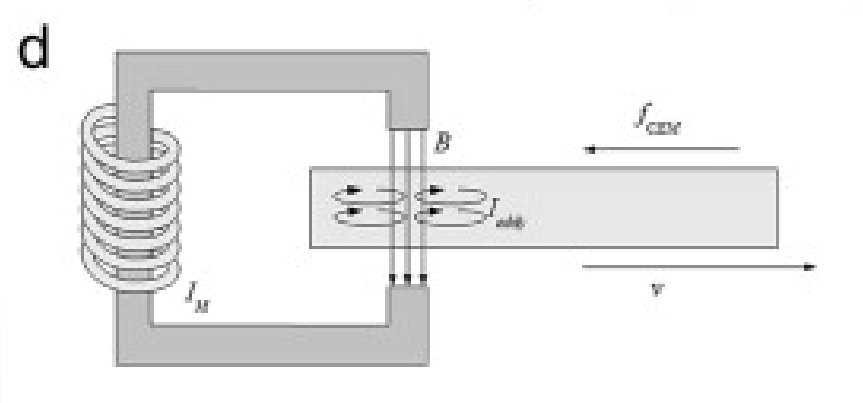
MR Damper

http://www.sciencedirect.com/science/article/pii/S0921889013001188



Variable Impedance Actuators

- E.g. 2: Eddy Current damper
  - Magnetic devices composed of a conductive material moving through a magnetic field.
  - Eddy currents are induced and create a damping force that is proportional to the relative velocity between material and magnetic field.



Eddy Current Damper
http://www.sciencedirect.com/science/article/pii/S0921889013001188

Pneumatic Muscles

- Contractile or extensional devices operated by pressurized air filling a pneumatic bladder.

Pneumatic Muscles
https://commons.wikimedia.org/wiki/File:Sam_animation-real-muscle.gif

- Usually grouped in pairs, one agonist and one antagonist → One muscle contracts, the other relaxes.
- Good for force control / delicate contact operations:
  - They are inherently compliant.
  - When a force is exerted onto the actuator, it gives in without increasing the force in actuation.
- Applications: Robotics, walking etc.
  - https://www.youtube.com/watch?v=ApR1rHkH_uE

Tesla Master Of Lightning

- https://www.youtube.com/watch?v=dxV4_61VEHY

Tesla's Columbus Egg

- https://www.youtube.com/watch?v=Ec4u4BfS4tE
- https://www.youtube.com/watch?v=iJpRHWoQTPU
- https://en.wikipedia.org/wiki/Tesla%27s_Egg_of_Columbus

Thank you!

Time to assemble gripper until 9.30pm

Any questions?

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