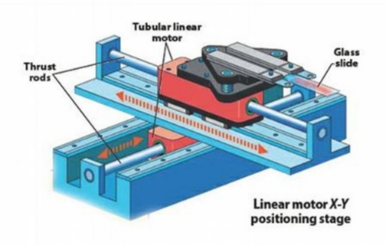
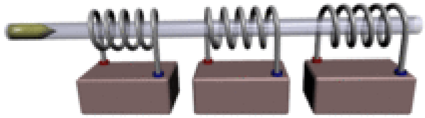
Fuel injector
Source: Bosch-presse.de



Positioning systems
Source: Machine Design



Rail gun
Source: commons.wikimedia.org

JR–Maglev MLX01
Source: Wikipedia.org

Linear actuators: A very diverse landscape

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Electrical Manufacturing & Coil Winding Expo

eMOTORS Consulting, LLC

May 13, 2015

Introduction

- Most electric machines rotate, but a lot of things move linearly
- In principle, electro-mechanical actuation works whether for linear or rotary motion
- Why then do we see mostly rotating machines? Where is there space for linear actuators?
- A lot of diversity in goal, purpose, and design
  - But always application oriented

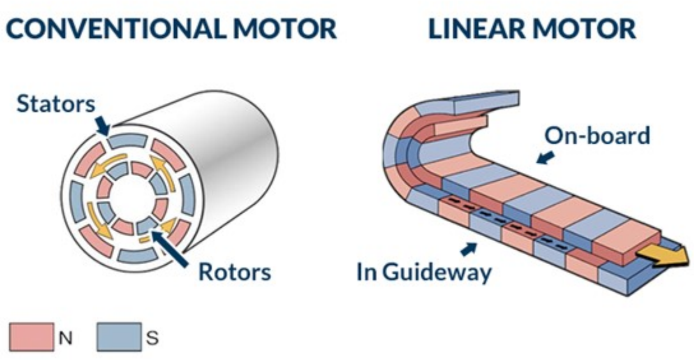
Source: Teslamotors.com

Linear actuation:
Types of electromagnetic force

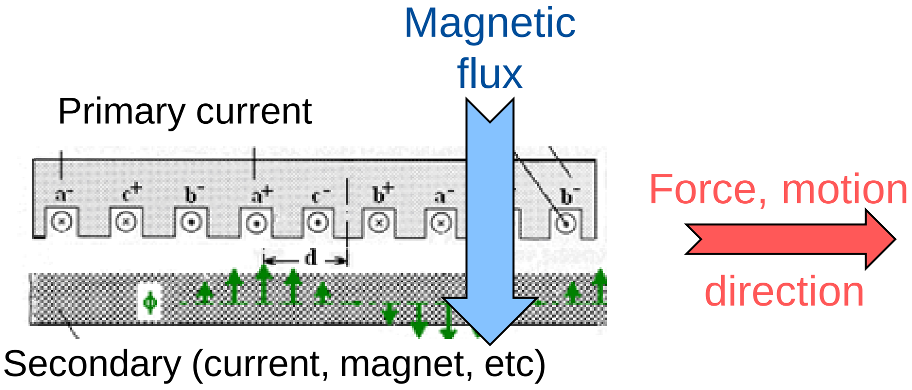
- Sliding
- Attraction
- Repulsion
- Other

Sliding force (as in rotating machines)

- Airgap length constant during travel
- Typical force pattern in a rotating machine



Source: northeastmaglev.com/the-train



Magnetic flux

Primary current

Force, motion direction

Secondary (current, magnet, etc)

Source: www.tanonyvtar.hu

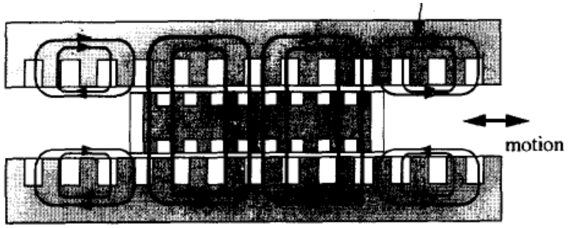
- Same machine types: Induction, PM, reluctance, stepper, etc
- Travel is limited only by size of machine

Linear motor with sliding force: Which is best?

- Induction, PM, reluctance, stepper, etc
  - Same pros and cons as for rotating machines
  - PM more efficient, reluctance has force ripple, etc

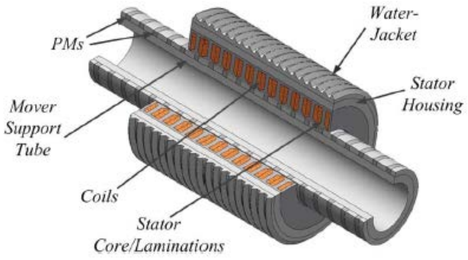
- Construction is different
  - Larger airgaps typical, because of attractive forces (normal to gap) and machine length
  - Attractive stator/translator:
    - Forces cancel out in a rotating machine (if balanced)
    - Dual stators or tubular construction provides similar cancellation in linear machines

Double-sided motor



Source: Jansen, et. al, IEEE T. IA 1995

Tubular motor

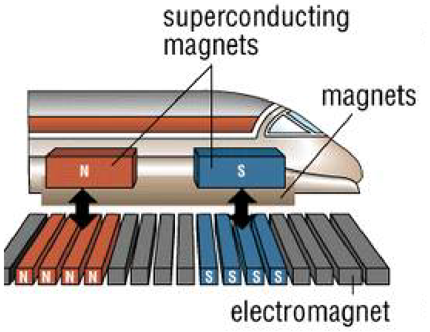


Source: Gerada, et. al, IEEE T. IA 2014

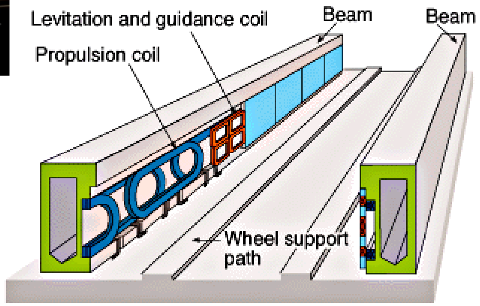
Sliding force: Long travel

- Induction favored because of simple secondary (as simple as an aluminum rail)
- PM favored because of large airgap capability

- Japan’s SCMaglev uses coils in the track, and superconducting magnets on board
  - Clocked at 603 km/h (375 mph) on April 21, 2015

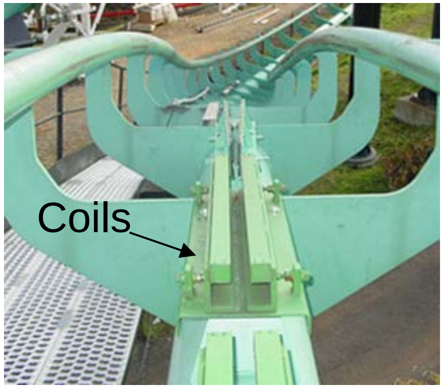


Source: thehigherlearning.com



Source: science.howstuffworks.com

- Roller coasters use induction or PM

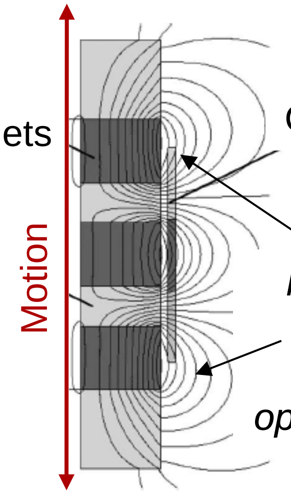


Source: kumbak.nl

Source: coastergallery.com

End effects

- Linear motor have ends (leading and trailing) which require special consideration
  - Can create drag
- In fact, machine needs two designs:
  - One for center of machine, one for edges
  - Affects both motor geometry and control (when and how to turn currents on or off)
    - With sinusoidal control, control must use different machine parameters near edge



Magnets

Coils

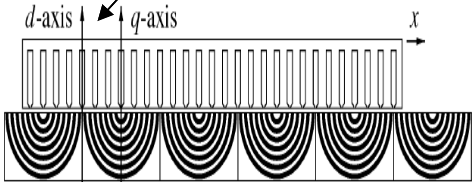
Motion

Magnetic flux at coil edges creates opposing forces

Source: Li and Pillay, IEEE T. IA 2011

Meaning of d- and q-axes near the edge?

d- and q-axes

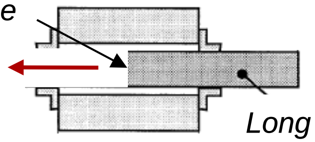


SynchRel motor

Source:
Stumberger, et. al, IEEE T. IA 2003

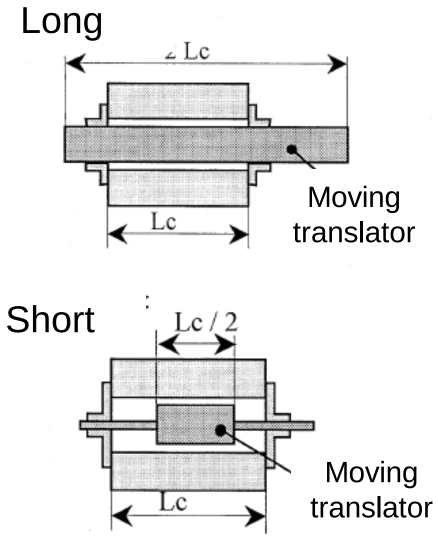
Translator: Short or long?

- Acceleration important → Short translator
- Most force from given input → Long translator
- Short travel → Focus on leading edge, neglect trailing edge



- Efficiency important → Avoid currents on after moving translator is gone
- Accurate positioning → Avoid detent forces and local equilibriums due to forces on edges

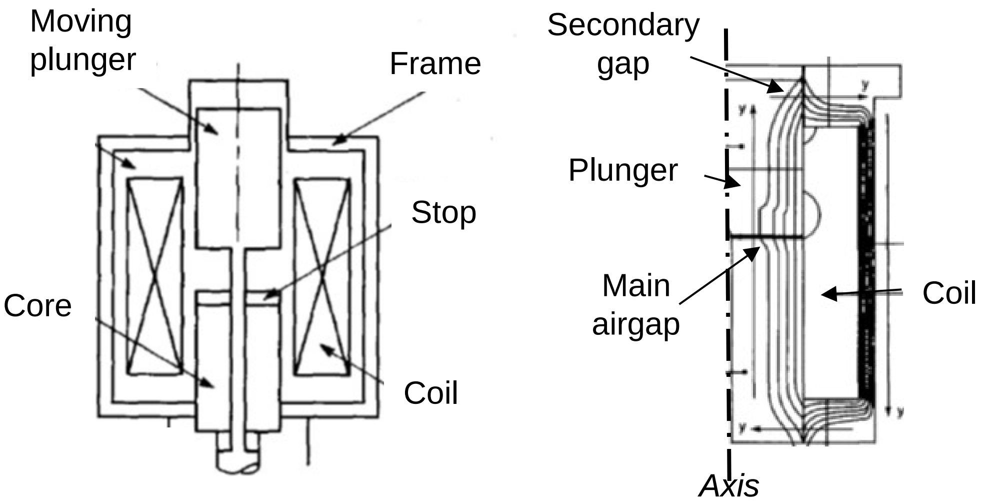
Translator length



Source: Bianchi, et. al, IEEE T. IA 2003

Attraction force (solenoids)

- Steel plunger attracted to stationary pole when surrounding coil is excited
  - Return achieved with spring
  - Holding with smaller, DC current
- Common for motion around 1 to a few mm
- Control valves for hydraulics, fuel injectors



Source: Lequesne, IEEE T. IA 1990

Fuel injector (Bosch)

Source: bosch-presse.de

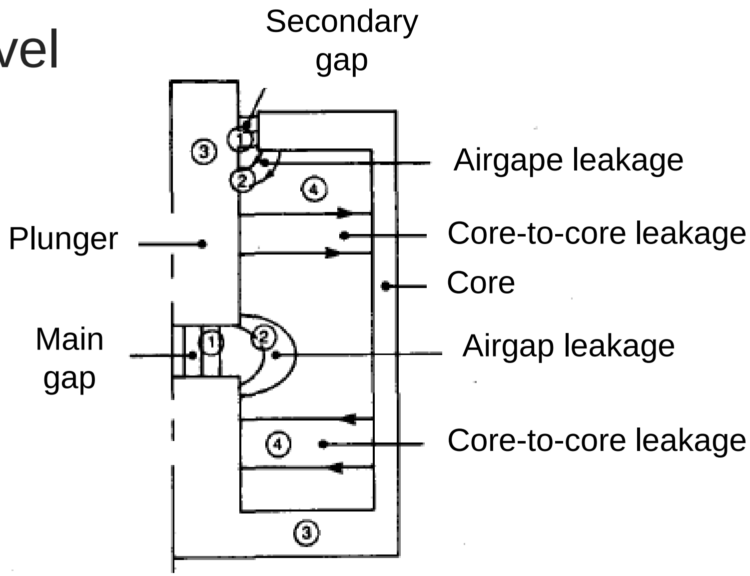
Attraction force

- Principle is based on reluctance variation
- Force tends to reduce airgap length, increasing inductance
- Travel is limited to airgap length
- Force is strongest when airgap is small
  - Force weakest at the beginning of motion (unfortunately)
- Application to small travels
- Eddy currents issue for fast travel
  - Solid core

$$F = \frac{1}{2\mu_0} \quad B^2 S$$

$$F = \frac{1}{2\mu_0 a}$$

$$B = \mu_0 \frac{NI}{(g + d)}$$


Secondary gap

Airgape leakage

Plunger

Core-to-core leakage

Core

Main gap

Airgap leakage

Core-to-core leakage

Source: Lequesne, IEEE T. IA 1990

Attraction force: Constant force versus distance

- Force pattern can be tailored to be constant over distance
  - Balancing magnetic and spring fore makes for simple positioning mechanism
  - Obtained with conical plunger
  - Used for fluid flow control

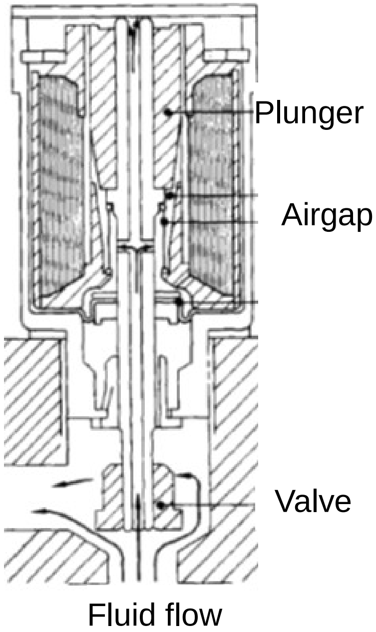
<u>At equilibrium</u>:

$$F_{mag} = F_{spring}$$

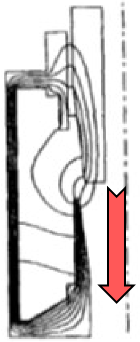
$$F_{mag} = \alpha\, I \;=\; k\, x$$

$$x = \frac{\alpha}{k}\, I$$

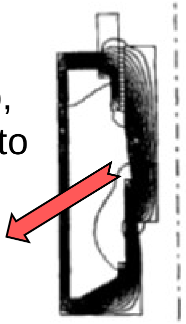
position x proportional to current I

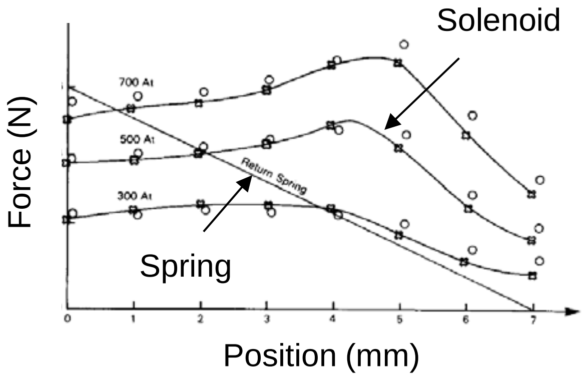


At large airgap, Flux is normal to plunger lower surface



At small airgap, Flux is normal to side of plunger

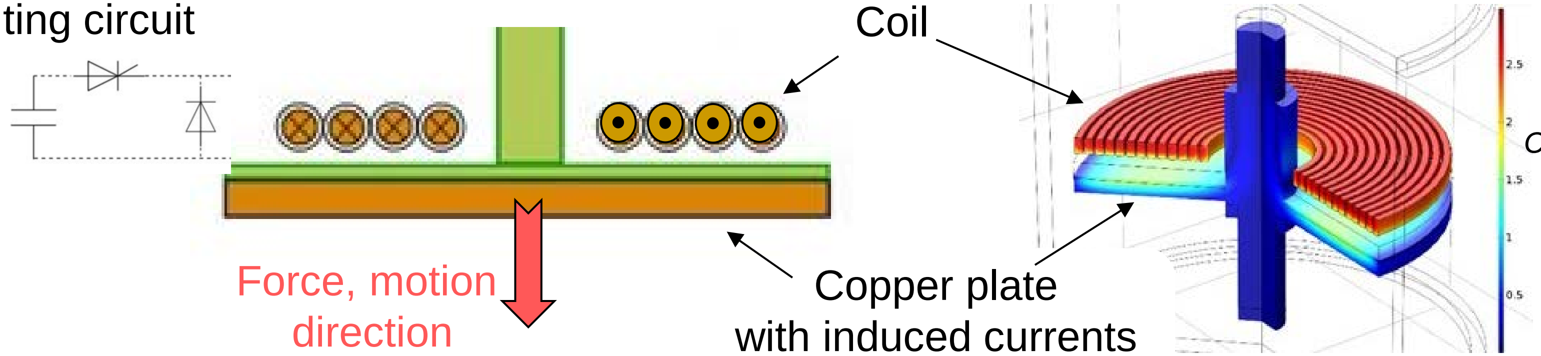




Source: Lequesne, IEEE T. IA 1988

Repulsion force

- Coil under excitation induces current in a conductive plate, repels it
    - Alternatively, two coils can be excited and repel each other
- Used for fast actuation
    - Also for suspension (bearingless motors, suspended trains)
- Force has limited range, but travel can go farther (ballistic motion)



Exciting circuit

Coil

Force, motion direction

Copper plate with induced currents

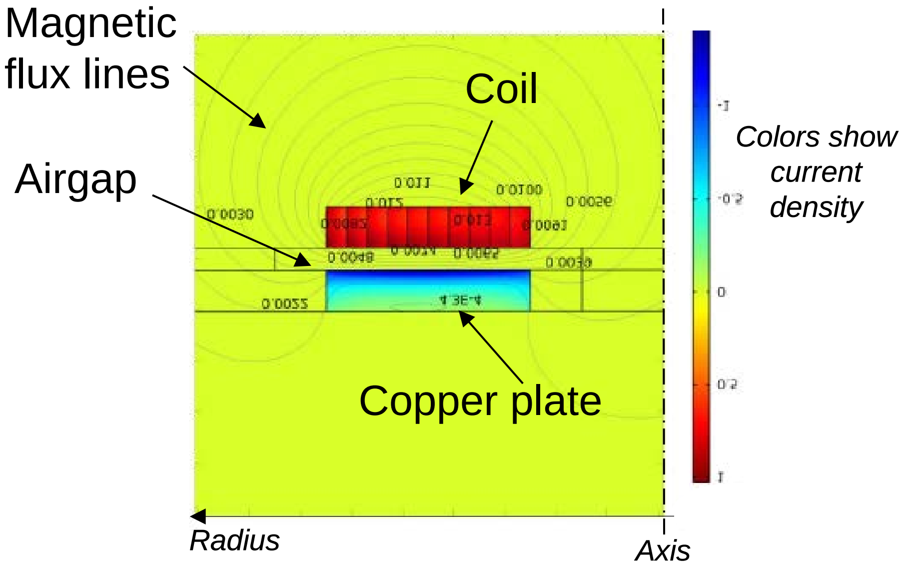
Colors show current density

Source: C. Peng, et. al., NCSU, unpublished

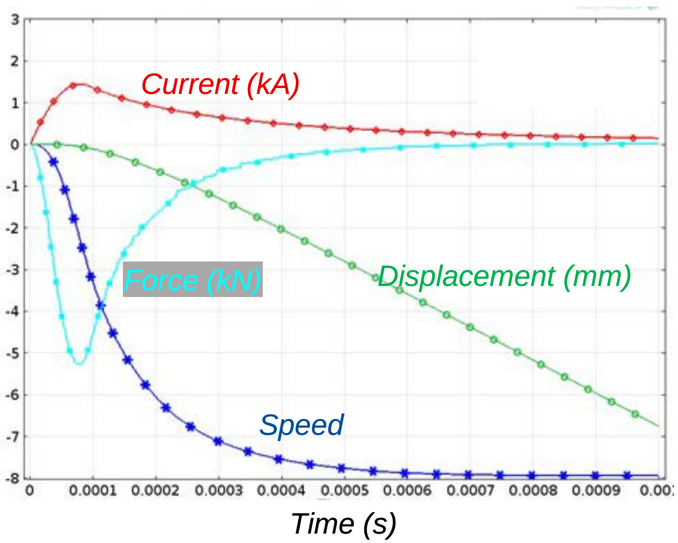
Repulsion force principle

- Magnetic field trapped in small airgap between excitation coil and plate
  - Motion corresponds to varying inductance
- Force strongest when airgap is small
  - Force strongest at beginning of motion (☺) but cannot be sustained over long travel

$$F_{mag} = i_{coil} \cdot i_{plate} \cdot \frac{\partial M}{\partial z}$$



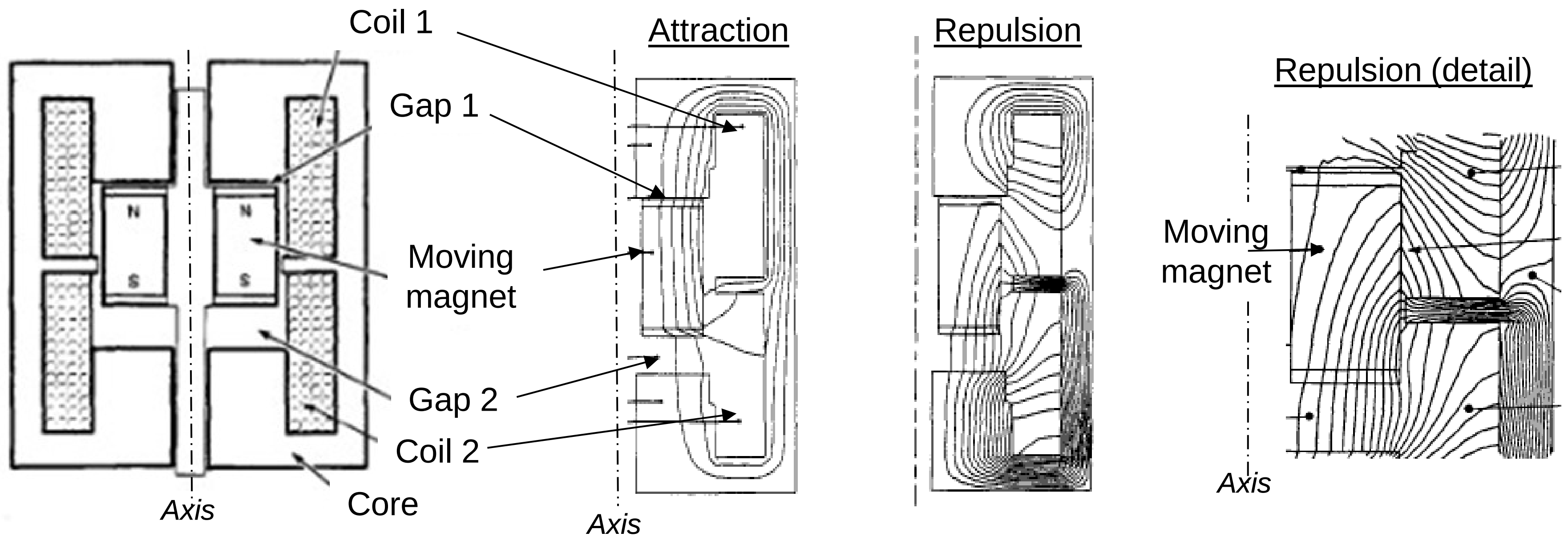
Source: Bissal, et. al., IEEE T. Magn, 2012



Source: C. Peng, et. al., NCSU, unpublished

Force with permanent magnets

- Can be attractive or repulsive, depending on coil current
- Advantages:
  - Two stable positions, without springs or current; No energy needed outside of motion
  - Repulsion feasible without inducing current, with force highest at beginning of motion
  - Fast travel over larger gaps (10 mm / ½ inch)

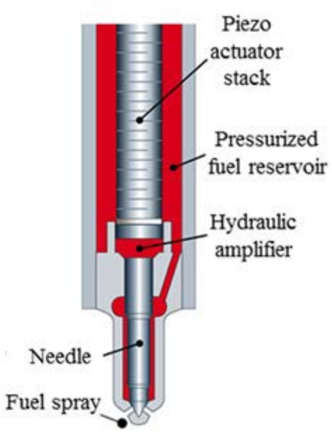


Source: Lequesne, IEEE T. IA 1990

Other actuation types: Piezoelectric, ultrasonic

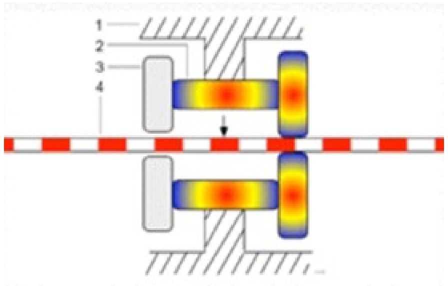
- Some materials (ceramics) expand when subjected to voltage
- Motion is very small, but force is very high, time constant is small, and force is very repeatable (nanometers at MHz)
- Ultrasonic motors use similar principles but enhance them with resonance (travelling wave)
- Applications:
  - Nano, precision positioning
  - Precision metering (fuel injectors): Motion from a stack of piezo disks is hydraulically amplified

Fuel injector (Delphi)



Source: MTZ Motortechnische Zeitschrift, 2008

Positioning mechanism

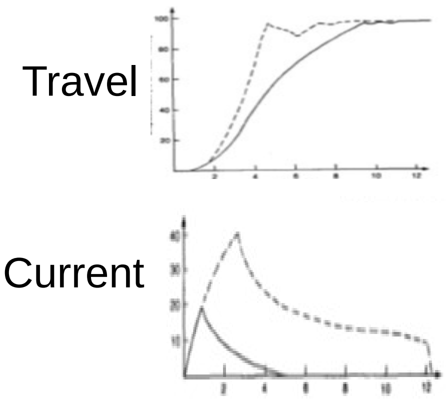


Source: Wikipedia.org

Travel length

- When is travel length “short”?
  - Travel time similar to electrical on time (mm / ms)
- Examples:
  - Solenoids: Travel time typically just a bit longer than current pulse
  - Oscillating actuator: Electrical frequency = Mechanical resonant frequency leads to best efficiency (Chen, et. al., 2009)

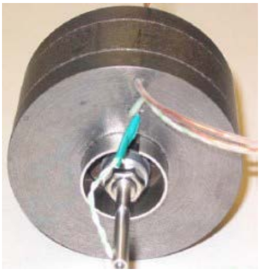
<u>Solenoid</u>

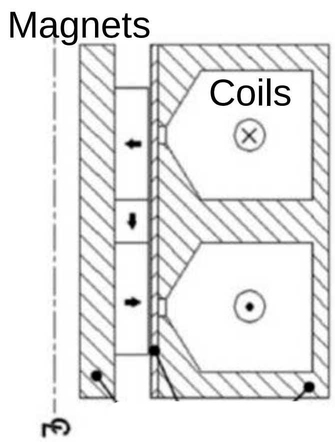


Current on-time similar to travel time

Source: Lequesne, IEEE T. IA 1990

<u>Oscillating PM actuator</u>

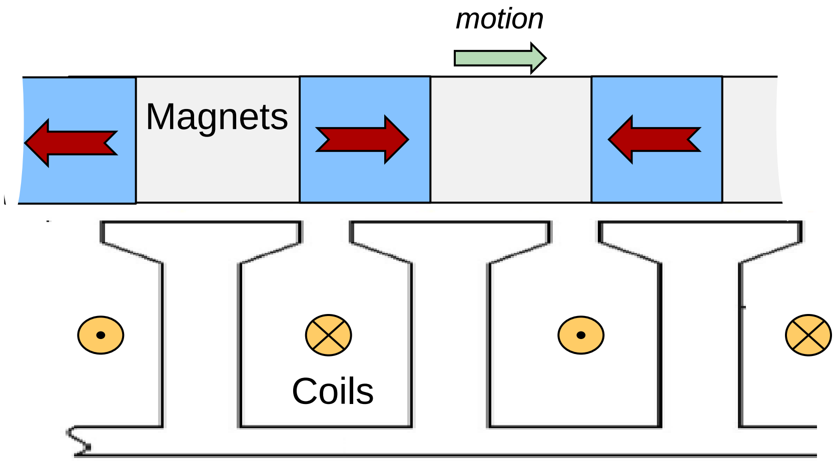




Source: Chen, et. al., IEEE T. IA 2009

Travel length: Transition from short to medium

- Transition from short to medium length:
    - When to go from single excitation to commutation, or multi-stage?
- At some point as magnets move in front of coils, need to reverse polarity
    - Reversing polarity complicate controls: Switching circuitry, position sensor
- Strong design incentive to keep system unipolar, with no commutation
    - Larger, fewer poles
    - Limit reached when slot size becomes too large for coil heat dissipation

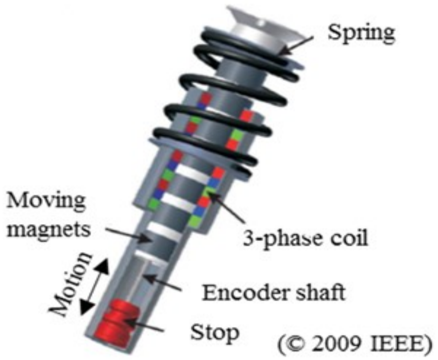


Linear versus rotating + gear, how to choose?

- Example: Automotive suspension is a linear motion
  - Electrified suspension makes for active damping control
- Approach: Design with a rotating motor and ideal gear
  - Determine appropriate motor diameter and number of rotations
  - If total rotation is similar to linear displacement, or:

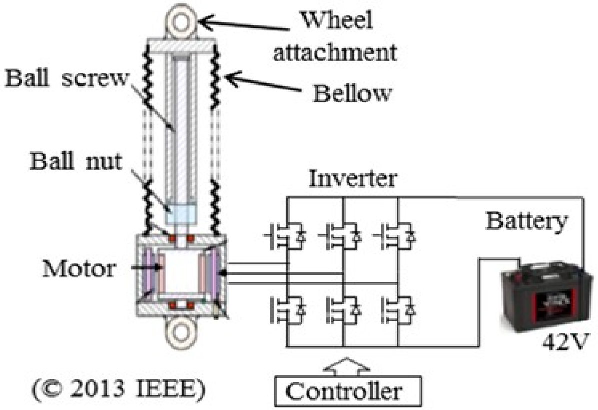
    Number of turns x π Diameter < 3 to 5 x Displacement → Linear
  - Equivalent to rotating system: Assume a gear, if best gear ratio is close to 1, no gear
- This, plus availability of rotating motors, rotating + gear more common

Linear motor (Eindhoven Un.)



Source: Gysen, et. al., IEEE T. IA 2009

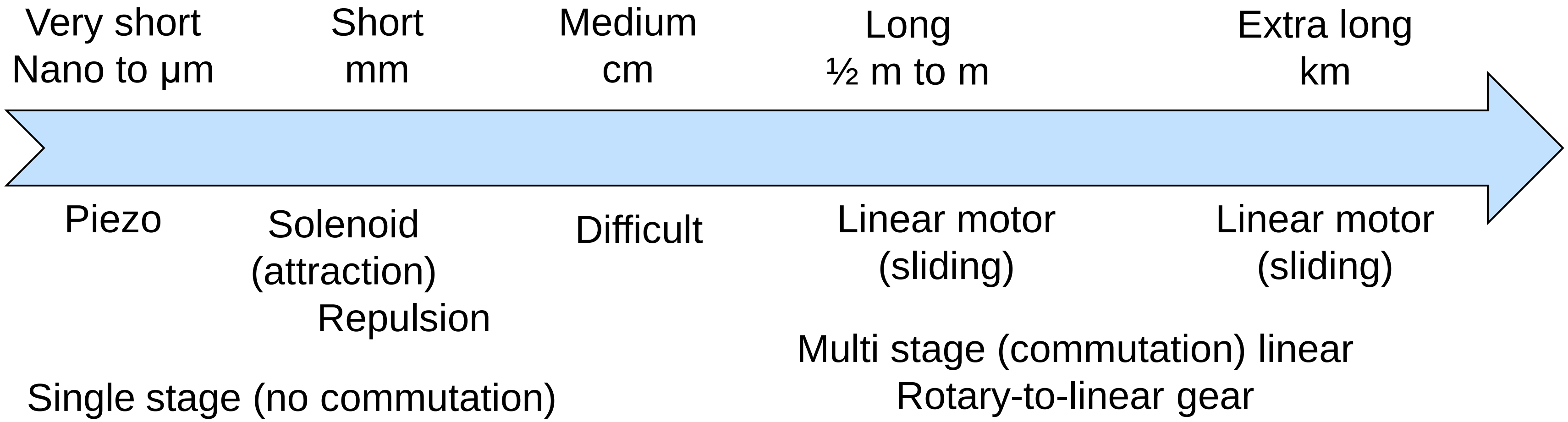
Rotating motor with ballnut/ballscrew (GM)



Source: Hao & Namuduri, IEEE T. IA 2013

Travel length: Best approach?

- Very short (nano- to micro-m): Piezo very attractive, although actuator is large and requires higher voltage
- Short (mm): Many options; Solenoids are inexpensive and very effective at lower end of range; repulsion actuators become effective at higher end of range
- Medium: (cm and more): Most challenging, as using commutation adds cost and complexity
- Long: Linear motor or rotary-to-linear system



Very short
Nano to μm

Short
mm

Medium
cm

Long
½ m to m

Extra long
km

Piezo

Solenoid
(attraction)
Repulsion

Difficult

Linear motor
(sliding)

Linear motor
(sliding)

Multi stage (commutation) linear
Rotary-to-linear gear

Single stage (no commutation)

Conclusions (1)

- Even for linear motion, a rotating motor + gear often preferred:
  - Linear motion means motor length is commensurate with travel
  - Linear motor is a motor with “1:1” gear ratio, often not optimum
  - Therefore, except for solenoids (mm range), linear motors are application driven, niche designs

- Many linear motor applications are dominated by transients
  - Acceleration, not force, must be optimized
  - Need to match electrical and mechanical transients

- Travel length:
  - Most challenging displacement is in the cm / dm range, when transitioning from single pulse to commutation excitation

Conclusions (2)

- Construction:
  - Need for careful study of mechanical forces between mover and primary
    - Except for tubular motors where such forces cancel out
  - Larger airgaps are common

- End effects require special attention or separate design
  - Topology and controls to minimize end effects

NASA Considering Rail Gun Launch System to the Stars

Source: N. Atkinson, universetoday.com and nasa.gov, 2010

But, the sky is the limit!

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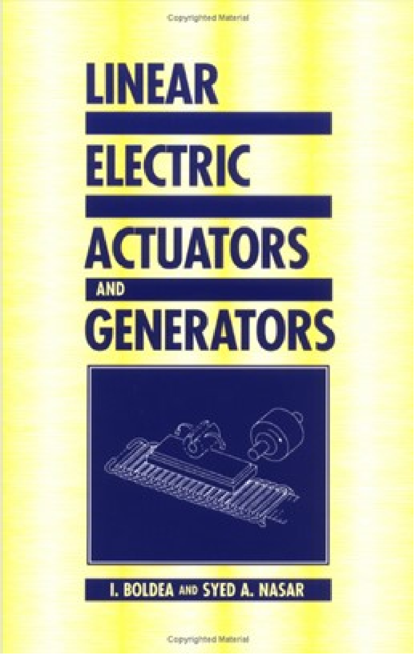

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