Linear actuators: A very diverse landscape

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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

- 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

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

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

- Roller coasters use induction or PM

Source: thehigherlearning.com
Source: science.howstuffworks.com
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

Source: Li and Pillay, IEEE T. IA 2011

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

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

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

\[ F = \frac{1}{2\mu_0} B^2 S \]

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

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

\[ F_{mag} = F_{spring} \]
\[ F_{mag} = \alpha I = kx \]
\[ x = \frac{\alpha}{k} I \]

At equilibrium:

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)

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

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

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
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)

Solenoid

Travel

Current

Current on-time similar to travel time

Source: Lequesne, IEEE T. IA 1990

Oscillating PM actuator

Magnets

Coils

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:
    \[ \text{Number of turns} \times \pi \times \text{Diameter} < 3 \text{ to } 5 \times \text{Displacement} \rightarrow \text{Linear} \]
  - 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.)**

**Rotating motor with ballnut/ballscrew (GM)**

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

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
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!
Bibliography


Bibliography (cont’d)

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