Lecture 8
Motors, Actuators, and Power Drives

Forrest Brewer
Motors, Actuators, Servos

- Actuators are the means for embedded systems to modify the physical world
  - Macroscopic Currents and power levels
  - Thermal Management
  - Power Efficiency (often vs. Performance)

- Motor Types
  - DC Brush/Brushless
  - AC (shaded pole and induction)
  - Stepper Motors
  - Servo (variety of DC motor)
  - Peisio-electric (Kynar, Canon ultra-sonic)
  - Magnetic Solenoid
  - Electro-static (MEMS)
DC Motor Model

• Torque (force) ~ Current
• Max Current = V/R
• Max RPM = V/B_{emf}

B_{emf} = L \, \text{d}l/\text{d}t

In general:
Torque \sim (V - B_{emf})/R
speed vs. torque, fixed voltage

Linear mechanical power \( P_m = F \cdot v \)

Rotational version of \( P_m = \tau \cdot \omega \)

\[ \frac{V}{k_e} \]

max speed

\[ \text{speed } \omega \]

power output

\[ \text{speed vs. torque} \]

\[ \frac{k_m V}{R} \]

stall torque

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Controlling speed with voltage

- The back emf depends only on the motor speed. \( e = k_e \omega \)
- The motor’s torque depends only on the current, \( I \). \( \tau = k_\tau I \)

\[
\begin{array}{|c|}
\hline
I_{\text{stall}} = \frac{V}{R} \\
\text{current when motor is stalled} \\
\text{speed} = 0 \\
\text{torque} = \text{max} \\
\hline
\end{array}
\]

- Consider this circuit’s \( V \): \( V = IR + e \)
  
  How is \( V \) related to \( \omega \) ?

\[
V = \frac{\tau R}{k_\tau} + k_e \omega
\]

Speed is proportional to voltage.

\[
\omega = -\frac{R}{k_\tau k_e} \tau + \frac{V}{k_e}
\]

Jizhong Xiao
Electrostatic MEMS Actuation

- Electrostatic Drives (MEMS)
  - Basic equations
  - Rotation Drive
  - Comb Drive
Electrostatic Actuator Analysis

- Consider the capacitance of the two figures:
  - To good approximation, the capacitance is double in the second figure: \( C_1 = \frac{C_2}{2} \)

- Imagine that the charge is fixed in the top figure: \( Q = C_1V_1 = C_2V_2 \)

- The stored energy is not the same!

\[
E_1 = \frac{1}{2}C_1V_1^2 = \frac{1}{2}(E_2 = \frac{1}{2}C_2V_2^2)
\]

- The difference must be the work done by the motion of the plate:

\[
\Delta E = \int Fdx \Rightarrow F = \frac{dE}{dx} \propto V^2
\]
Electrostatic Actuators

Consider parallel plate 1 & 2
Force of attraction (along y direction)

\[ F_p = \left( \frac{1}{2} \varepsilon V^2 \right) (A/g^2) \]

1nN@15V
dimensionless

Consider plate 2 inserted between plate 1 and 3
(Popularly known as a COMB DRIVE)

Force of attraction (along x direction)

\[ F_c = \left( \frac{1}{2} \varepsilon V^2 \right) (2t/g) \]
Constant with x-directional translation
Paschen Curve

Breakdown voltage

$\approx 200 \text{V}$

$E_{bd} \approx 100 \text{MV/m}$

$\approx 2 \text{um} @ 1 \text{atm}$

Distance * pressure
(meter * atm)
Side Drive Motors

Side view of SDM          Top view of SDM

First polysilicon motors were made at UCB (Fan, Tai, Muller), MIT, ATT
Typical starting voltages were >100V, operating >50V
A Rotary Electrostatic Micromotor 1×8 Optical Switch
A Rotary Electrostatic Micromotor 1×8 Optical Switch

A. Yasseen, J. Mitchell, T. Streit, D. A. Smith, and M. Mehregany
Microfabrication Laboratory
Dept. of Electrical Engineering and Applied Physics
Case Western Reserve University
Cleveland, Ohio 44106

Fig. 3 SEM photo of an assembled microswitch with vertical 200 μm-tall reflective mirror plate.

Micro Electro Mechanical Systems
Jan., 1998 Heidelberg, Germany

Fig. 4 Insertion loss and crosstalk measurements for multi-mode optics at 850 μm.
Comb Drives

Tang/Nguyen/Howe

Sandia cascaded comb drive (High force)

Close-up
Layout of electrostatic-comb drive

Folded beams (movable comb suspension)

Tang, Nguyen, Howe, MEMS89
Parallel-Plate Electrostatic Actuator Pull-in

Electrostatic instability

\[ F = \frac{\varepsilon_0 V^2}{2(s_0 - x)^2} = kx \Rightarrow \]

\[ V = \frac{\sqrt{2kx}}{\varepsilon_0} (s_0 - x) \]

\[ \frac{\partial V}{\partial x} = 0 \Rightarrow x_{\text{snap}} = \frac{s_0}{3} \]

\[ V_{\text{snap}} = \sqrt{\frac{8ks_0^3}{27 A\varepsilon_0}} \]
Electrostatic spring

\[ F = \frac{\varepsilon_0 V^2}{2(s_0 - x)^2} \approx \frac{\varepsilon_0 V^2}{2(s_0 - x_0)^2} \left( 1 + 2 \frac{x - x_0}{s_0 - x_0} \right) \]

\[ F = m\ddot{x} + kx \approx \frac{\varepsilon_0 V^2}{2(s_0 - x_0)^2} \left( 1 + 2 \frac{x - x_0}{s_0 - x_0} \right) \]

\[ m\ddot{x} + \left( k - \frac{\varepsilon_0 V^2}{(s_0 - x_0)^3} \right) x = \frac{\varepsilon_0 V^2}{2(s_0 - x_0)^2} \left( 1 - \frac{2x_0}{s_0 - x_0} \right) \]

- Adjustable stiffness (sensitivity) and resonance frequency
Stepper Motors

- Overview
- Operation – full and half step
- Drive Characteristics
VR Stepper Motor
Actual Motor Construction
Multi-pole Rotation, Full-Step

A = S
B = OFF

M. G. Morrow, P.E.
Multi-pole Rotation, Full Step

ROTOR

STATOR

A = OFF
B = S

M. G. Morrow, P.E.
Multi-pole Rotation, Full Step

A = N
B = OFF

M. G. Morrow, P.E.
Multi-pole Rotation, Full Step

M. G. Morrow, P.E.
Multi-pole Rotation, Full Step

A = S
B = OFF
“Full-Step” Stepping

Step 1

Step 2

Step 3

Step 4
“Full-Step, 2-on” Stepping

Step 1

Step 2

Step 3

Step 4
Half-stepping

Step 1

Step 2

Step 3

Step 4

Step 5

Step 6

Step 7

Step 8

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Unipolar motor

Unipolar Step | Q1 | Q2 | Q3 | Q4
---|---|---|---|---
1 | ON | OFF | ON | OFF
2 | OFF | ON | ON | OFF
3 | OFF | ON | OFF | ON
4 | ON | OFF | OFF | ON
1 | ON | OFF | ON | OFF

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Bipolar motor

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Torque v.s. Angular Displacement

Holding torque

Static torque

One step angle

Displacement $\theta$ from an equilibrium position
Stepping Dynamics

![Graph showing the dynamics of stepping motion with labels for forward and reverse directions.]
Load Affects the Step Dynamics

Motor PH266-01
No-Load
X axis: A 0.5 ms/div.
B 20 ms/div.
Y axis: 0.9°/div.

Motor PH266-01
Inertia Load 0.82 oz-in² (150 g-cm²)
X axis: A 0.5 ms/div.
B 20 ms/div.
Y axis: 0.9°/div.

Motor PH266-01
Inertia Load 0.82 oz-in² (150 g-cm²)
Friction Load 6.95 lbz-in (4.9 N-cm)
X axis: A 0.5 ms/div.
B 20 ms/div.
Y axis: 0.9°/div.
Drive Affects the Step Dynamics

Fig. 2.55. Difference in single-step response between the single-phase (a) and two-phase (b) excitation.
Stepper Motor Performance Curves

- Holding torque
- Maximum starting torque
- Pull-out torque
- Pull-in range
- Maximum starting frequency
- Unstartable range
- Unrotatable range
- Stepping rate (Hz)
- Maximum slewing frequency
Current Dynamics

- At High Frequency
- At Low Frequency

Graph showing the current dynamics over time.
Drive Circuits

- Inductive Loads
- AC Motor Drive (Triac)
- H-bridge
- Snubbing and L/nR Stepper Drive
- PWM
- Micro-Stepping
Inductive Load Drive Circuits

- **BJTs**
  - \( V_{\text{CEsat}} \approx 0.4 \text{V} \)
  - \( P_D = I_C \times V_{CE} \)

- **MOSFETs**
  - \( V_{DS} = I_D \times R_{DSon} \)
  - \( P_D = I_D \times V_{DS} \)

M. G. Morrow, P.E.
Switching Characteristics

\[ V_{\text{IN}} \rightarrow \text{Transistor} \rightarrow V_C \]

\[ +5V \rightarrow V_C \]

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Switching Characteristics

\[ V_{IN} \rightarrow V_C \rightarrow +5V \]

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AC Motor Drive
H-bridge

- An H-bridge consists of two high-side switches (Q1,Q3) and two low-side switches (Q2,Q4)
- BJTs or FETs

<table>
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<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
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H-Bridge/Inductor operation

\[ V = IR \rightarrow V = V+ \]

\[ V = IR \rightarrow V = 0 \ (V = -IR) \]
L/nR Drive

Diagram:
- External resistor $R_e$
- Winding resistance $R_w$
- Winding inductance $L$
- Diode $D_s$
- Source $E$
Current Rise in Detail

Motor Coil

L1
Resistance = R = 10Ω
10mH

I=0, $\frac{dl}{dt} = 2000\text{A/S}$

Motor Coil

L1
Resistance = R = 10Ω
10mH

I=0.33A, $\frac{dl}{dt} = 1000\text{A/S}$

Motor Coil

L1
Resistance = R = 10Ω
10mH

I=0.5A, $\frac{dl}{dt} = 0\text{A/S}$
Performance Improvement with L/nR Drive
Pulse-Width Modulation

- Pulse-width ratio = \( t_{\text{on}} / t_{\text{period}} \)
- Never in “linear mode”
  - Uses motor inductance to smooth out current
  - Saves power!
  - Noise from \( T_{\text{period}} \)
Pulse-Code Modulated Signal

- Some devices are controlled by the length of a pulse-code signal.
  - Position servo-motors, for example.
Back EMF Motor Sensing

- Motor torque is proportional to current.
- Generator voltage is proportional to velocity.
- The same physical device can be either a motor or a generator.
- Alternate Drive and Sense (note issue of Coils versus Induction)

Drive as a motor  Sense as a generator

20ms

Benjamin Kuipers
Back EMF Motor Control

Motor Winding  Measurement Gap  PWM Signal

Induction Dumping Spike  Stable Back-EMF Region

© Acroname Inc.
Microstepping

- Use partial Drive to achieve fractional steps
- Stepper is good approximation to Sine/Cosine Drive
  - $2\pi$ cycle is 1 full step!
- Usually PWM to reduce power loss
  - Fractional voltage drop in driver electronics
Microstepping Block Diagram

- Easy to synthesize the PWM from Microcontroller
  - Lookup table + interpolation
  - $\pi/2$ phase lag = table index offset
- Need to monitor winding current:
  - Winding L,R
  - Motor Back EMF
- PWM Frequency tradeoff
  - Low Freq: resonance (singing)
  - High Freq: Winding Inductance and switching loss
PWM Issues

● Noise/Fundamental Period
  – Low Freq: Singing of motor and resonance
  – High Freq: Switching Loss

● Can we do better?
  – Not unless we add more transitions! (Switching Loss)

● If we bite bullet and use MOS drives can switch in 2-50nS…

● Then can choose code to optimize quantitization noise vs. switching efficiency
  – Modulated White Noise
  – Sigma-Delta D/A

● Requires higher performance Controller
Motors and Actuators -- Software

- Embedded motor control is huge, growing application area
  - Need drive(sample) rates high enough to support quiet, efficient operation
  - Rates roughly inversely proportional to motor physical size
  - Stepper Motors are usually micro-stepped to avoid ‘humming’ and step bounce
    - Typical: 1kHz rate, 50kHz micro-step; slow HP motors 300Hz-1kHz
- Upshot- 1 channel “fast” or micro-stepped motor is substantial fraction of 8-bit processor throughput and latency
  - Common to run up to 3 “slow” motors from single uP
  - Common trend to control motor via single, cheap uP
  - Control multiple via commands send to control uPs