Solenoids and DC Motors

• What they are

• How they work

• Snubbing

• Why you have to
Solenoids

Cheap & Simple

Diagram showing a solenoid with labeled parts:
- Back Stop
- Coil
- Housing
- Mounting Mechanism
- Plunger

CMPE 118 – Intro. to Mechatronics
Common Solenoid Types

- **Pull Type**
  - Open frame
  - Cheap ($0.50)

- **Push Type**
  - Rotary
Solenoid Characteristics

Typical Pull Force Versus Stroke

These force curves do not account for return spring.

The typical return spring force is 0.4/1.0 OZ as shown.

0 0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040 0.045 0.050 0.055 0.060 0.065 0.070 0.075 0.080 0.085 0.090 0.095 0.100

0 3 6 9 12 15

205 AT (100%)
290 AT (50%)
410 AT (25%)
650 AT (10%)

SPRING

STROKE (IN)

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Design and Stroke vs. Force

![Graph showing force vs. stroke for different designs: Flat, Conical 90°, Conical 60°. Diagrams of Back Stop and Plunger for each design.]}
### Typical Solenoid Spec.'s

<table>
<thead>
<tr>
<th>duty cycle</th>
<th>1</th>
<th>1/2</th>
<th>1/4</th>
<th>1/10</th>
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<tr>
<td>maximum &quot;ON&quot; time, (Sec.)</td>
<td>∞</td>
<td>25</td>
<td>6</td>
<td>0.5</td>
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<td>watts</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>20</td>
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<td>approximate ampere turns</td>
<td>205</td>
<td>290</td>
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<th>AWG number</th>
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<th>volts DC</th>
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<td>27</td>
<td>0.39</td>
<td>0.9</td>
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<td>30</td>
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<tr>
<td>42</td>
<td>281</td>
<td>24.0</td>
<td>33.9</td>
<td>47.9</td>
<td>76.0</td>
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</table>
DC Motors

- provide rotary motion
- where do you find them?
  - Clock
  - Phone - vibrator
  - Computer - Fan
  - LED

CARS
Motors in Cars

Fig. 1.1 Small motors in an automobile.
The Permanent Magnet DC Motor

Fig. 1.1. A cutaway view of a DC motor.
Fig. 3.37  Arrangement of coil, commutator segments, and brushes in a DC motor: (a) exploded diagram of lap winding; (b) coil connections.
Electrical Model of a DC Motor

\[ V - L \frac{dx}{dt} - IR - Ke ω = 0 \]

Back e.m.f.

Counter e.m.f.

Terminal

Motor terminal

Motor

Ke - speed constant

SI: \[ \frac{V}{\text{rad/s}} \]

(\[ \frac{V}{\text{rpm}} \])

(\[ \frac{\text{Nm}}{\text{A}} \])

Kt - torque constant

\[ T = K_t \cdot I \]

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Unit conversions

\[ k_T = 9.55 \times 10^{-3} \text{ kN m} \text{ A}^{-1} \text{ V/krpm} \]

\[ k_T = 1.35 \text{ N m} \text{ A}^{-1} \text{ V} \text{ krpm} \]

\[ k_T = \text{ kN m} \text{ A}^{-1} \text{ V/krpm} \]
DC Motor Relationships (1.3)

\[ V = IR + k_e \omega \quad T = k_T I \]

\[ \therefore I = \frac{T}{k_T} \]

\[ V = \frac{T}{k_T} R + k_e \omega \rightarrow \text{if} \ T = 0 \]

\[ V = k_e \omega_{NL} \]

\[ \omega_{NL} = \frac{V}{k_e} \]

\[ \omega = 0 \quad V = \frac{TR}{k_T} \quad \therefore T_{stall} = \left(\frac{V}{R}\right) k_T \]

\[ T_{stall} = I_{stall} \cdot k_T \]
DC Motor Relationships (2.3)

\[ V = \frac{TK}{KT} + k_e \omega \Rightarrow ke\omega = V - \frac{TK}{KT} \]

\[ \omega = \frac{V - \frac{TK}{K_eK_T}}{k_e} \rightarrow \omega = \omega_{NL} - \frac{K_m}{k_eK_T} \]

\[ \omega = \omega_{NL} - \frac{K_mT}{k_e} \]
DC Motor Relationships (3.3)

\[ P = T \omega = T (\omega_n e - k_m T) \quad \omega_n = \frac{V}{k_e} \]

\[ P = \frac{VT}{k_e} - k_m T^2 \quad @ T = T_o \text{ constant torque} \]

\[ P_1 = VA - B \quad @ Iv, A, B \text{ constant} \]

\[ P_2 = 3VA - B \quad @ 3V \]

\[ \Delta P = 2VA \]

So, \( \Delta P \propto \Delta U \) @ constant torque

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\[ P = \frac{TV}{k_e} - k_m T^2 \quad \rightarrow \quad \frac{dP}{dT} = 0 \]

\[ = \frac{V}{k_e} - 2k_m T \]

\[ \frac{V}{k_e} = 2k_m T \]

\[ T_{\text{peak}} = \frac{V}{2k_e k_m} = \frac{V}{2k_e \frac{R}{k_e k_T}} = \frac{1}{2} \left( \frac{V}{R} \right) k_T \]

\[ T_{\text{peak}} = \frac{1}{2} T_{\text{stall}} \]
DC Motors: \( P_{\text{max}} \)

\[
P_{\text{max}} = \frac{V}{K_e} \left( \frac{V}{2k_e R_m} \right) - R_m \left( \frac{V^2}{4k_e^2 R_m^2} \right)
\]

\[
= \frac{V^2}{k_e^2 2R_m} - \frac{V^2}{k_e^2 4R_m^2} = \frac{V^2}{4k_e^2 R_m}
\]

\[
P_{\text{max}} = \frac{1}{4} \left( \frac{V}{K_e} \right) \left( \frac{V}{K_e R_m} \right) = \frac{1}{4} \omega_{\text{NC}} T_{\text{stall}}
\]

\[\downarrow\omega_{\text{NC}} \quad \downarrow T_{\text{stall}}\]
DC Motor Graphs

Torque vs. Speed

Power vs. Torque

U_3 = 36 Volt

U_2 = 24 Volt

U_1 = 12 Volt

\[ \Delta P \Delta U \]
Torque vs. Everything

The diagram shows the most important motor and operating characteristics.

\( \eta \) - efficiency

The point \( \omega_M \) is effective speed.

The point \( I_A \) is needed for elect. (electrical) operation.

The point \( M_H \) is the stall torque.

\(~ \frac{1}{3} - \frac{3}{4} \) No speed

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## DC Motor Spec.'s

<table>
<thead>
<tr>
<th>Motor Data</th>
<th>930</th>
<th>933</th>
<th>934</th>
<th>948</th>
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<th>944</th>
<th>937</th>
<th>938</th>
<th>945</th>
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<td>1. Assigned power rating</td>
<td>W</td>
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<td>6.0</td>
<td>6.0</td>
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<td>2. Nominal voltage</td>
<td>Volt</td>
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<td>3. No load speed</td>
<td>rpm</td>
<td>5080</td>
<td>9270</td>
<td>9460</td>
<td>10700</td>
<td>8110</td>
<td>7770</td>
<td>8460</td>
<td>8240</td>
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<td>4. Stall torque</td>
<td>mNm</td>
<td>20.9</td>
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<td>51.7</td>
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<td>5. Speed/torque gradient</td>
<td>rpm/mNm</td>
<td>260</td>
<td>225</td>
<td>213</td>
<td>211</td>
<td>194</td>
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<td>6. No load current</td>
<td>mA</td>
<td>114</td>
<td>101</td>
<td>83</td>
<td>73</td>
<td>50</td>
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<td>7. Starting current</td>
<td>mA</td>
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<td>5910</td>
<td>5160</td>
<td>4920</td>
<td>3090</td>
<td>2440</td>
<td>2680</td>
<td>2100</td>
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<td>8. Terminal resistance</td>
<td>Ohm</td>
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<td>1.74</td>
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<td>3.88</td>
<td>4.92</td>
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<td>9. Max. permissible speed</td>
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<td>11000</td>
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<td>10. Max. continuous current</td>
<td>mA</td>
<td>1500</td>
<td>1500</td>
<td>1440</td>
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<td>972</td>
<td>865</td>
<td>809</td>
<td>656</td>
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<td>11. Max. continuous torque</td>
<td>mNm</td>
<td>7.92</td>
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<td>12. Max. power output at nominal voltage</td>
<td>mW</td>
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<td>9620</td>
<td>10800</td>
<td>13900</td>
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<td>13. Max. efficiency</td>
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<td>mNm/A</td>
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<td>rpm/V</td>
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<td>1330</td>
<td>1080</td>
<td>909</td>
<td>691</td>
<td>664</td>
<td>576</td>
<td>467</td>
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<td>16. Mechanical time constant</td>
<td>ms</td>
<td>29</td>
<td>22</td>
<td>20</td>
<td>19</td>
<td>18</td>
<td>18</td>
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<td>17. Rotor inertia</td>
<td>gcm²</td>
<td>10.8</td>
<td>9.23</td>
<td>9.07</td>
<td>8.68</td>
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<td>8.84</td>
<td>8.63</td>
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<td>mH</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
<td>0.26</td>
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<td>K/W</td>
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<td>17</td>
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<td>6</td>
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Operating Ranges

Speed ($n$), torque ($M$), current ($I$): The outer edges of the values depicted represent limits for continuous and short term motor operation. Values listed in the tables (lines 3, 4, 6, 7, 12 and 13) are valid for operation at nominal voltage (line 2). These are therefore values which are only reached when operating the motor at higher voltages.

- **Recommended operating range**
- **Continuous operation**
  In observation of above listed thermal resistances (lines 19 and 20) the maximum permissible rotor temperature will be reached during continuous operation at 25°C ambient. = Thermal limit

- **Short term operation**
  The motor may be briefly overloaded (recurring).

| Motor with high resistance winding (Line 8) |
| Motor with low resistance winding (Line 8) |

- **Assigned Power Rating** $P_{2T}$ (W) (Line 1)
- **Starting current** $I_A$ at nominal voltage (Line 7) as well as related stall torque
  \[ M_H (mNm) (Line 4) I_A = \frac{U}{R} \cdot 10^3 \text{ (mA)} \]

- **Winding number with the related current curve at the appropriate torque.**
Defining “Short Term Operation”

Short Term Operation

- Duty Cycle
- Multiple ON current

ON
Motor in operation

OFF
Motor inoperative

\( \dot{I} \)
max. peak current

\( I_{\text{cont.}} \)
max. permissible continuous current

Line 10

\( t_{\text{ON}} \)
ON time

\( T \)
cycle time \( t_{\text{ON}} + t_{\text{OFF}} \)

DCy
Duty Cycle in percent of the Cycle Time \( T \). The motor may be overloaded by the relationship \( \dot{I}/I_{\text{cont.}} \) during X% of the total Cycle Time.

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An example problem (1.2)

• You have been assigned to follow up on the design of a former employee who had not taken CMPE-118.
• Your supervisor suspects that they didn't know what they were doing.
• The only documentation that you can find shows that the motor chosen has $K_t = 9.33 \text{ in.-oz./A}$ and produces $2.8 \text{ in.-oz.}$ at stall when driven at $12\text{V}$.
• The design requires that the motor deliver $0.4 \text{ in.-oz.}$ at $1500 \text{ rpm}$.
• The motor was supposed to be driven from a $12\text{V}$ supply and switched by a $\text{ULN2003}$. Your boss has asked you:
An example problem (2.2)

1. How can I find out how much current the motor will draw at stall? \( I_{\text{stall}} = 30\mu\text{A} \)
2. Can the ULN2003 safely switch the required current? \( I_{\text{rms}} = 32.5\mu\text{A} \) if only 1 device used
3. How can I find the NL Speed? \( \omega_{\text{NL}} = 1732\text{rpm} \)
4. How can I find the coil resistance? \( R \)
5. How can I find the torque at a given speed? \( T = \Phi \omega \)
6. Will the design meet the requirements for torque & speed? If not, what changes could you suggest? \( V \approx 0 \)
7. To estimate the current required when running at the design point.
8. (You may assume that there are no internal losses) within the motor.
   \( K_T = 1.3524KE \text{ [oz-in/A ; V/krpm]} \)
ULN2003A Specifications (2.2)

Figure 14

Figure 15
Motor Design Solution (1.3)

1) $I_{stall} = ?$

$T = K_T I$

$I_{stall} = \frac{T_{stall}}{K_T} = \frac{2.8 \text{ in.-oz.}}{9.33 \text{ in.-oz.}} = 0.3A$

2) **Yes, barely** $325 \text{ mA}$ if always on or only 14

3) $\omega_{nl} = \frac{V}{K_e} = \frac{12}{9.33 \text{ in.-oz.}} \times 1.3514$

$= 1.079 \text{ krpm}$

$\omega_{nl} = 1739 \text{ rpm}$$K_t = 9.33 \text{ in.-oz./A}$

$T_{stall} = 2.8 \text{ in.-oz.} \leq$

$V_{stall} = 12 \text{ V.} \leq$

$T_{req} = 0.4 \text{ in.-oz.}$

$\omega_{req} = 1500 \text{ rpm.}$

$K_T = 1.3524 K_E \text{ [oz-in/A ; V/krpm]}$
Motor Design Solution (2.3)

4) Coil resistance

\[ R = \frac{V_{\text{stall}}}{I_{\text{stall}}} = \frac{12}{0.3} = 40 \, \Omega \]

\[ T = k_T I \quad V = IR + k_e \omega \]

\[ V = \frac{IR}{k_T} + k_e \omega \]

\[ T = k_T \left( V - k_e k_T \omega \right) \]

5) \[ T = \frac{k_T}{R} \left[ V - k_e \omega \right] = \frac{9.33}{40} \left[ 12 - 6.89 \omega \right] \]

\[ T = 2.791 \omega - 1.607 \omega \]

K_t = 9.33 \text{ in.-oz./A}

T_{\text{stall}} = 2.8 \text{ in.-oz.}

V_{\text{stall}} = 12 \text{V.}

T_{\text{req}} = 0.4 \text{ in.-oz.}

\omega_{\text{req}} = 1500 \text{ rpm.}

K_T = 1.3524K_E \left[ \text{oz-in/A ; V/krpm} \right]
Motor Design Solution (3.3)

(6) \( 0.9 \text{ in. oz} \leq 1500 \text{ rpm} \)

\[
T = 2.792 - 1.602 \times 1.5 = 0.3885
\]

\[
T = 0.202 \text{ oz-in @ 11.2V}
\]

They don’t meet spec

\[
T = k_T V - k_L k_T \omega
\]

How to fix?

Run at voltage +11V

\( K_T = 9.33 \text{ in.-oz./A} \)

\( T_{\text{stall}} = 2.8 \text{ in.-oz.} \)

\( V_{\text{stall}} = 12 \text{V.} \)

\( T_{\text{req}} = 0.4 \text{ in.-oz.} \)

\( \omega_{\text{req}} = 1500 \text{ rpm.} \)

\( K_T = 1.3524 K_E \text{ [oz-in/A ; V/krpm]} \)
Motor Design Solution (3.4)

1. Current @ design point

\[ T = k_T I \]

\[ I = \frac{T}{k_T} = \frac{0.4}{9.33} = 0.043 = 43\text{mA} \]

\[ T = k_T \left( U - k_e \omega \right) \]

\[ 0.4 = 9.33 \left( U - 10.34 \right) \]

\[ 0.4 = \frac{40}{40} \left( U - 10.34 \right) \]

\[ U = \frac{2.3325 V - 241}{0.23325} = 12.05 V + 0.8 V \]

We have a 15x PWM divider

\[ \text{PWM} = \frac{12.85 V}{15 \times 100} = 85\% \]

Output cycle

- 500 Hz
- 2 kHz
How to Change Directions

U-Bridge
Pulse Width Modulation

- Pulse Width Modulation (Pulse Width Modulation)
  - Duty Cycle: 60%
  - Frequency: 200 Hz, 20 kHz, 100 kHz

Use 500 kHz - 2 kHz

- Modulation Technique
- Waveform
- Distortion
- Ripple
DC Motor Drive Simulation

\[ V = L \frac{di}{dt} \approx L \frac{Di}{\Delta t} \]

Diagram with symbols and components:
- 12V
- 1.2mH
- 11.4
- 2N3055
- 50
- Ext File
- 0/0V

CMPE 118 – Intro. to Mechatronics
Transistor Current

Ref = Ground  X = 167uS/Div
Inductor Current

\[ \text{Ref} = \text{Ground} \quad X = 167\mu\text{S/Div} \]
Collector Voltage

Ref=Ground  X=167\mu S/Div
Snubbing: Diode Snubber

- 12V
- 50
- 1.2mH
- 1.4
- 2N3055
- Ext
- File
- 0/0V
- 50
Inductor Current w/Diode Snubber

Ref = Ground \ X = 167\mu S/Div
Collector Voltage w/Diode Snubber

Ref=Ground X=167uS/Div

Recirculation

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Where to put the diodes?

Peak current: \( I_{\text{peak}} = \frac{1}{2} \frac{L}{R} \)

Battery, Pulse, Rectify, Diode

Fly back diodes

- Fast recovery
- High pulse replay

Yes mate
Snubbing: Diode + Zener

1) Diode + low resistor
Inductor Current w/ Diode + Zener Snubber

Ref=Ground X=167uS/Div

CMPE 118 – Intro. to Mechatronics
Collector Voltage with Diode + Zener Snubber

Collector Voltage with Diode + Zener Snubber

\[ V_{Z} + V_{D} + V_{DC} \]

Ref=Ground X=167uS/Div
Snubbing: Zener only

12V
+V

1.2mH

11.4

2N3055

0/0V

Ext File

50

CMPE 118 – Intro. to Mechatronics
Inductor Current w/ Zener Only

Inductor Current with Zener Only Snubber

Ref=Ground X=167uS/Div

CMPE 118 – Intro. to Mechatronics
Collector Voltage w/ Zener Only

Collector Voltage with Zener Only Snubber

okay with that?

Vc + Vz

Ref = Ground  X = 167 uS/Div

Voltage

CMPE 118 – Intro. to Mechatronics
Where to put the Zeners?

typically we put them...
Snubbers Compared

Inductor Current Decay Comparison
Fig. 4.1. Disassembled view of a brushless DC motor: permanent magnet rotor, winding, and Hall element.
Fig. 4.2. Three-phase unipolar-driven brushless DC motor.
Hall Sensor Based Commutation

Fig. 4.20. Torque generation, revolution, and switching.
**Brushed vs. Brushless**

<table>
<thead>
<tr>
<th></th>
<th>Brushed Motor</th>
<th>Brushless Motor</th>
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<tbody>
<tr>
<td><strong>Mechanical Structure</strong></td>
<td>Field Magnets on stator Windings on Rotor</td>
<td>Field Magnets on Rotor Windings on stator</td>
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<tr>
<td><strong>Commutation Method</strong></td>
<td>Mechanical contact between brushes and commutator</td>
<td>Electronic switching using transistors</td>
</tr>
<tr>
<td></td>
<td>added friction, brush debris, RFI</td>
<td>low frequency harmonics due to ripple</td>
</tr>
<tr>
<td><strong>Rotor Position Detection</strong></td>
<td>Automatically detected by brushes</td>
<td>Hall Element, optical encoder, Back EMF</td>
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<td><strong>Reversing Method</strong></td>
<td>Reverse terminal voltage</td>
<td>Rearrange logic sequencer</td>
</tr>
<tr>
<td><strong>Distinctive Features</strong></td>
<td>Quick response</td>
<td>Long Lasting</td>
</tr>
<tr>
<td></td>
<td>Excellent controllability</td>
<td>Easy or no maintenance</td>
</tr>
<tr>
<td></td>
<td>Current limited by brush/commutator interface</td>
<td>Current limited by winding resistance only</td>
</tr>
<tr>
<td></td>
<td>Speed limited by brush bounce</td>
<td>No fundamental high frequency (speed) limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Usually more efficient than brushed</td>
</tr>
</tbody>
</table>
Questions?