Selection of Linear Precision Drives

- Linear Motion – Overview
- Main Selection Criteria
- Comparison of Common Linear Drive Mechanisms
- Screw Driven Solutions
- Application Examples
Linear Motion - Overview
Linear Motion - Overview

**Direct Drive Linear Motors**

- Linear Shaft Motor
  - No influence by change of gap
- Linear Motor
  - Cogging by concentration of flux
  - Absorption Force

**Rotary to Linear Conversion**

- Rack & Pinion
- Timing belts
- Ball screws
- Lead Screws
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Linear Motion – Main selection criteria

Electro-mechanical design: balancing the trade-offs

- Precision
  Resolution, Repeatability, Accuracy
- Throughput
  Speed, Duty Cycle, ...
- Life
  Wear, Contamination Resistance, Maintenance,…
- Cost
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Comparison of Linear Drive Mechanisms

Direct Drive Linear Motor

- Very high speed
- Very high precision
- No backlash
- Fast move and settle time

- Lower force density compared to other technologies
- Requires linear feedback for proper operation
- More difficult to use in vertical applications
- Can be expensive

AMETEK
PRECISION MOTION CONTROL
Comparison of Linear Drive Mechanisms

Rack and Pinion

- Very good for long travel applications
- High speed
- Requires precise alignment
- Can be noisy
- Difficult to remove backlash
- Typically lower precision
Comparison of Linear Drive Mechanisms

Timing Belt and Pulley

- ✓ High speed applications
- ✓ Long life
- ✓ Maintenance free

- ✓ Belt tensioning required
- ✓ Care must be taken in designing pulley bearing
- ✓ Specific errors (pulley out of round precision, lead error caused by pitch diameter precision,...)
- ✓ Form factor may be an issue
Comparison of Linear Drive Mechanisms

Ball Screws & Lead Screws

- High precision application with moderate speed
- Applications requiring good repeatability
- Applications requiring high force density
- When non-backdriving is required (lead screw)

- Precision alignment required (ball screws)
- Right lubricant, coating, nut materials, … required
- Specific potential issues to be addressed: critical speed, noise,…
- Ball screws require maintenance
Selection of Linear Precision Drives

- Linear Motion – Overview
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- Screw Driven Solutions
  - Technology Highlights
  - Limits of the technology
  - Components & Systems Selection
- Application Examples
Screw driven solutions

Q: Which component is the most critical one from a performance and life point of view?

A: The screw/nut assembly. It is usually the component that will be selected first.
Screws – A few definitions

- **Lead:** linear displacement for one revolution
- **Pitch:** distance between two consecutive threads

\[
\text{Lead} = \text{Pitch} \times \text{nb of starts}
\]
## Lead Screw versus Ball Screw

<table>
<thead>
<tr>
<th>Feature</th>
<th>Leadscrews</th>
<th>Ballscrews</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load</strong></td>
<td>light or moderate</td>
<td>moderate or heavy</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>20% up to 85%</td>
<td>above 95%</td>
</tr>
<tr>
<td><strong>Lead Accuracy</strong></td>
<td>0.1µm/mm-0.6µm/mm</td>
<td>0.1µm/mm or less (C10 to C7 grade)</td>
</tr>
<tr>
<td><strong>Repeatability</strong></td>
<td>1-2 microns (compensated backlash)</td>
<td>varies with C grade</td>
</tr>
<tr>
<td><strong>Backdriving</strong></td>
<td>sometimes</td>
<td>always</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>quiet operation</td>
<td>noisy-metal to metal recirculating balls</td>
</tr>
<tr>
<td><strong>Lubrication</strong></td>
<td>solutions without grease available</td>
<td>necessary</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>none or very little</td>
<td>required</td>
</tr>
</tbody>
</table>
## Lead Screw versus Ball screw

<table>
<thead>
<tr>
<th>Other criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Lead screw/nut assembly are much more compact for the same screw diameter</td>
</tr>
<tr>
<td>Lead (travel/revolution)</td>
<td>Small leads feasible only with lead screws (down to 0.3mm)</td>
</tr>
<tr>
<td>Alignment</td>
<td>Ball screws are highly sensitive to alignment</td>
</tr>
<tr>
<td>Environmental</td>
<td>Ballscrews are highly sensitive to dirty environments.</td>
</tr>
<tr>
<td>Life</td>
<td>Depends on the application</td>
</tr>
<tr>
<td>Customization</td>
<td>Lead screws are easier to customize than ball screws</td>
</tr>
<tr>
<td>Cost</td>
<td>Cost of leadscrew is less than a ground ball screw and a little less than rolled ballscrew</td>
</tr>
</tbody>
</table>
Lead Screws – useful formulas

- Torque to move the load
  \[ T_l = \frac{\text{load} \times \text{lead}}{2\pi \text{ efficiency}} \]

- Torque to hold the load
  \[ T_l = \frac{\text{load} \times \text{lead} \times \text{backdrive efficiency}}{2\pi} \]
Lead Screw efficiency

- Efficiency depends on lead angle and coefficient of friction
- Back drive efficiency is lower than forward drive efficiency
- A lead screw is non-backdrivable if backward efficiency is zero (or forward efficiency lower than approx. 50%)
Selection of Linear Precision Drives

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  - Limits of the technology
  - Components & Systems Selection
- Application Examples
# Limits of Lead Screw Driven Solutions

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>Open loop: repeatability down to 5-6µm (*)</td>
</tr>
<tr>
<td></td>
<td>Closed loop: sub-micron accuracy achievable</td>
</tr>
<tr>
<td>Speed/Throughput</td>
<td>Compromise between speed and force</td>
</tr>
<tr>
<td>Expected life</td>
<td>From a few thousand cycles to a few million cycles</td>
</tr>
<tr>
<td></td>
<td>Depends on a lot of different application parameters</td>
</tr>
</tbody>
</table>

(*): with backlash compensation and constant preload
Limits of Lead Screw Driven Solutions

Precision limiting factors in open loop:

- **Motor resolution (steppers)**
  Linear resolution (mm): lead (mm) / number of steps per revolution

- **Backlash, Lost motion, hysteresis**
  Backlash = clearance between nut and screw (can be compensated)
  Material deflection may add additional error (cannot be compensated)

- **Lead accuracy**
  Cumulative error defined in µm/mm

- **« One revolution errors »**
  Screw straightness and various alignment issues contribute to creating an error with a period of one revolution
Limits of Lead Screw Driven Solutions

Lost motion = backlash + stiffness

Backlash = clearance between the nut and the screw

Stiffness of anti-backlash nuts with « soft » material
Limits of Lead Screw Driven Solutions

- Axial preload

- Radial preload
Limits of Lead Screw Driven Solutions

Stiffness: several different plastics available

<table>
<thead>
<tr>
<th></th>
<th>ACETAL WITH LUBRICATION ADDITIVES</th>
<th>KERKITED KNR</th>
<th>KERKITED KFDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE MATERIAL</td>
<td>Acetal</td>
<td>Nylon</td>
<td>Polyethylene Suddle</td>
</tr>
<tr>
<td>ADDITIVES</td>
<td>TFE &amp; Silcon</td>
<td>Carbon Fiber &amp; PTFE</td>
<td>Carbon Fiber &amp; PTFE</td>
</tr>
<tr>
<td>COLOR</td>
<td>Black</td>
<td>Blue</td>
<td>Black</td>
</tr>
<tr>
<td>TENSILE STRENGTH (PSI)</td>
<td>7,000 – 10,000</td>
<td>22,000</td>
<td>26,000</td>
</tr>
<tr>
<td>FLEXURAL MODULUS (GPa)</td>
<td>300,000 – 450,000</td>
<td>1,730,000</td>
<td>2,500,000</td>
</tr>
<tr>
<td>DEFLECTION TEMP (°F)</td>
<td>200</td>
<td>480</td>
<td>500</td>
</tr>
<tr>
<td>THERMAL EXP. COEFF (mm/°F)</td>
<td>3.8 x 10⁻⁶</td>
<td>1.1 x 10⁻⁶</td>
<td>0.8 x 10⁻⁶</td>
</tr>
<tr>
<td>WATER ABSORPTION (%)</td>
<td>.27</td>
<td>.45</td>
<td>.93</td>
</tr>
<tr>
<td>COEFF. OF FRICTION</td>
<td>.30 - .19</td>
<td>.12 - .29</td>
<td>.10 - .11</td>
</tr>
<tr>
<td>STATIC DYNAMIC</td>
<td>.10</td>
<td>.11</td>
<td>.8</td>
</tr>
<tr>
<td>PV LIMIT (°F) @ 10 mips</td>
<td>15,000</td>
<td>45,000</td>
<td>72,000</td>
</tr>
<tr>
<td>WEAR FACTOR</td>
<td>19</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>KERN WEAR FACTOR (Kerk Life Test)</td>
<td>19</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**Metal nuts:**
- **Stiff**
- Lubrication required (maintenance)
- Shorter life than plastic nuts

**Thermoplastic nuts:**
- Longer life
- No maintenance required
- Various materials available depending on stiffness and application conditions (PV, temperature, environment…..)
Limits of Lead Screw Driven Solutions

Lead accuracy and « one revolution » errors

Error vs. Displacement

One revolution error: 4 µm

Lead accuracy: 0,6 µm/mm
Limits of Lead Screw Driven Solutions

Potential issues limiting the velocity:

- Nut Material PV (pressure x velocity)
- Screw Critical speed
- Noise
- Motor Torque/speed characteristics
Limits of Lead Screw Driven Solutions

![Critical Speed Graph]

- **LEADScreW DIAMEters**
  - 1/4-in (6 mm) Diam.
  - 1/2-in (13 mm) Diam.
  - 3/4-in (19 mm) Diam.
  - 7/8-in (22 mm) Diam.
  - 3/8-in (10 mm) Diam.

<table>
<thead>
<tr>
<th>RPM</th>
<th>30</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
<th>210</th>
<th>240</th>
<th>270</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid/Free</td>
<td>12</td>
<td>24</td>
<td>36</td>
<td>48</td>
<td>60</td>
<td>72</td>
<td>84</td>
<td>96</td>
<td>108</td>
<td>120</td>
</tr>
<tr>
<td>Simple/Free</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>120</td>
<td>140</td>
<td>160</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>Rigid/Simple</td>
<td>24</td>
<td>48</td>
<td>73</td>
<td>97</td>
<td>121</td>
<td>145</td>
<td>170</td>
<td>194</td>
<td>218</td>
<td>242</td>
</tr>
<tr>
<td>Rigid/Rigid</td>
<td>30</td>
<td>60</td>
<td>90</td>
<td>119</td>
<td>149</td>
<td>179</td>
<td>209</td>
<td>239</td>
<td>269</td>
<td>298</td>
</tr>
</tbody>
</table>

Column Length Between Bearings (Inches) Adjusted for Bearing Support

![Support Options]

- **Least Support**
- **Free**
- **Simple**
- **Rigid**
- **Most Support**
Limits of Lead Screw Driven Solutions

Overcoming the critical speed issue: the RGS slides

screw supported at regular intervals
Limits of Lead Screw Driven Solutions

Torque/speed characteristics: Stepper versus DC motors

Size 17 (42mm) stepper & DC motors (*)
with 1,27mm lead screw

(*) Without gearbox
Limits of Lead Screw Driven Solutions

Torque/speed characteristics: Stepper versus DC motors

Size 17 (42mm) stepper & DC motors (*)
with 3,17mm lead screw

(*) Without gearbox
Limits of Lead Screw Driven Solutions

Torque/speed characteristics: Stepper versus DC motors

Size 17 (42mm) stepper & DC motors (*)
with 6.35 mm lead screw

(*) Without gearbox
Limits of Lead Screw Driven Solutions

Main factors impacting life:

- Life is increasing with load derating
- Lubrication (dry, grease, teflon coating?)
- Alignment issues
- Environmental issues
- Anti-backlash nuts with wear compensation increase life

![Life expectancy graph](attachment:life_expectancy_graph.png)
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Selection of Linear Precision Drives

- Select the base technology: force, speed, accuracy, life, ...
  - High speed, high accuracy: direct drive linear motors
  - Speed:
    - > 1m/s: linear motor, belt & pulley, rack & pinion
    - 0.5 - 1m/s: ball screw,…
    - < 0.5 m/s: lead screw,…
  - Duty cycle, efficiency:
    - > 50%: usually ball screws
    - <50% lead screws,…
  - Application specific parameters:
    - Accuracy
    - Force density, form factor
    - Back drive
    - Environmental issues,…

- Select the motor technology (rotary to linear conversion): DC motor (brush, brushless), stepper motor

- Select the guide technology: ball guides, friction guides,…
Selection of Linear Precision Drives

Separate Components or Integrated Systems?

- Driver
- Rotary Motor
- Precision Lead Screw and Nut
- Linear guide
Selection of Linear Precision Drives