Experimental Verification of a Consequent-Pole Magnetic Lead Screw

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Katsuhiro Hirata  Hiroshi Ishiguro
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- Background

- Consequent-pole magnetic lead screw
  - Basic structure
  - Operating principle

- Prototype development
  - Static force analysis
  - Prototype

- Experiment
  - Static force measurement
  - Verification of CPMLS’s motion

- Conclusion & Future works
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**Category and characteristics of feed screw**

<table>
<thead>
<tr>
<th>Force transmission</th>
<th>Surface contact</th>
<th>Point contact</th>
<th>Hydrostatic oil</th>
<th>Magnetic coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding screw *1</td>
<td>Large</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ball screw *2</td>
<td></td>
<td>Large</td>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>Hydrostatic feed screw *3</td>
<td>Small</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic lead screw (MLS)</td>
<td></td>
<td></td>
<td></td>
<td>Large</td>
</tr>
</tbody>
</table>

- **Issue in feed screw**
  - Mechanical contact causes ...
    - noise and heat
    - particle emission

*1: NTN, Sliding screw for high load  
*2: Tohokuseiko corp., Ball screw  
*3: TOSHIBA MACHINE, Hydrostatic Feed Drive and Assembly Technologies
# Category and characteristics of feed screw

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<tr>
<td>Friction</td>
<td>Large</td>
<td>Small</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Small</td>
<td>Large</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Sliding screw**
  - Large friction
  - Small efficiency

- **Ball screw**
  - Small friction
  - Large efficiency

- **Hydrostatic feed screw**
  - Large friction

- **Magnetic lead screw (MLS)**
  - Small friction

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**Issue in feed screw**

- Magnetic lead screw can convert rotary to linear motion without mechanical contact

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What is magnetic lead screw?

- Rotary-to-linear convertor without mechanical contact

Advantages due to non-mechanical contact ... 
- Low noise and heat
- Few particle emission
- No lubrication
Category and characteristics of MLS

(a) Spiral SPM type MLS
(b) Discrete spiral SPM type MLS
(c) IPM type MLS

Issue in MLS
- Complicated structure
- Difficult to guarantee air gap length between the nut and screw

(a) J. Wang et al., “Analysis of a Magnetic Screw for High Force Density Linear Electromagnetic Actuators” (2011)
(b) Z. Ling et al., “Design of a New Magnetic Screw With Discretized PMs” (2016)
(c) A. Heya et al., “Force Estimation Method for a Magnetic Lead-Screw-Driven Linear Actuator” (2018)
Purpose

Consequent-pole magnetic lead screw (CPMLS)

Magnetic nut

Arc-shape PM

Purpose: Experimental verification of a consequent-pole magnetic lead screw
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Basic structure

IPM type MLS (Conventional)
- PMs and magnetic poles are stacked in radial direction
  - Difficult to guarantee air gap length
  - Large number of parts

Consequent-pole type MLS (Proposed)
- Introduced Consequent-pole (PMs and magnetic poles are separated)
  - Easy to guarantee air gap length
  - Reduced number of parts

Magnetization direction
Basic structure

IPM type MLS (Conventional)
- PMs and magnetic poles are stacked in radial direction
  ➡️ Difficult to guarantee air gap length
  ➡️ Large number of parts

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- Introduced Consequent-pole (PMs and magnetic poles are separated)
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  ➡️ Reduced number of parts

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- Difficult to guarantee air gap length
- Large number of parts

- Introduced Consequent-pole (PMs and magnetic poles are separated)
- Easy to guarantee air gap length
- Reduced number of parts
Operating principle

Nut is driven by $F$ that is dependent on $\varphi_\theta$ or $\varphi_l$

\[ F = F_r(\varphi_l(\theta_s, l_n)) \]

**Magnetic attraction force**

**Translational magnetic phase difference**

\[ \varphi_l(\theta_s, l_n) = l_n - l_s, \quad l_s = \frac{L}{2\pi} \theta_s \]

**Rotational magnetic phase difference**

\[ \varphi_\theta(\theta_s, l_n) = \theta_s - \theta_n, \quad \theta_n = \frac{2\pi}{L} l_n \]
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### Parameters of Consequent-pole MLS (CPMLS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nut</th>
<th>Screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter [mm]</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Inner diameter [mm]</td>
<td>10.5</td>
<td>×</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Air gap length [mm]</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Length [mm]</td>
<td>20</td>
<td>144</td>
</tr>
<tr>
<td>Material</td>
<td>SUY</td>
<td></td>
</tr>
<tr>
<td>Permanent magnet</td>
<td>Br = 1.2 T (N40SH)</td>
<td></td>
</tr>
</tbody>
</table>
Analysis condition

Calculates static force applied to nut when screw is rotated with nut fixed

- Rotation angle $\theta_s : 0 \sim 360$ deg

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>CPU</td>
</tr>
<tr>
<td>Intel(R)Core(TM)i7-3770T <a href="mailto:CPU@2.50GHz">CPU@2.50GHz</a></td>
</tr>
<tr>
<td>Number of elements</td>
</tr>
<tr>
<td>Number of nodes</td>
</tr>
<tr>
<td>Calculating time (min/step)</td>
</tr>
</tbody>
</table>
Analysis result

Calculates static force applied to nut when screw is rotated with nut fixed

- Maximum static force : 8.7 N

Rotational magnetic phase difference

\[ \varphi_\theta(\theta_s, l_n) = \theta_s - \theta_n, \ \theta_n = 0 \]
Prototype

- Spacers were arranged between PMs and magnetic poles
- Air gap is held by an oil-less bearing
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Experimental setup

Measure static force applied to nut when nut is moved with screw fixed
Experimental result

Measure static force applied to nut when nut is moved with screw fixed

- Maximum static force: 8.6 N

Rotational magnetic phase difference

\[ \varphi_\theta(\theta_s, \theta_n) = \theta_s - \theta_n, \quad \theta_s = 0, \quad \theta_n = \frac{2\pi L}{l_n} \]
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Experimental setup

- PID controller was used for a position feedback control
- Target position: 8 mm (The pitch of the screw is 4 mm)
Experimental result

Position feedback control
Target position : 8 mm (The pitch of the screw is 4 mm)

Displacement of the nut : 7.99 mm
Angle of the screw : -715.7 deg.

Steady-state deviation : 0.01 mm

Position feedback control could be performed
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Conclusion & Future works

Conclusion

• Showed measured and calculated static forces

• Investigated that proposed MLS can work as lead screw

Future works

• Further research is required to clarify the dynamic characteristics of consequent-pole magnetic lead screw

Thank you for your attention!