A Magnetic Lead Screw with Variable Stiffness Mechanism

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Contents

- Introduction
- Magnetic structure
- Variable stiffness mechanism
- Characteristics analysis
- Conclusion
Introduction

Collaborative robots and exoskeleton robots

• Safety for human-robot interaction
• Need force-controllable actuators

Lightweight, compact, and backdrivable
Introduction

Variable stiffness actuator* (VSA)

- Stiffness changed by moving pivot point
- Consists of ball screw, two motors, and springs

Problem
- vibration, noise, decrease in drive efficiency

Magnetic Lead Screw (MLS)

Transmits forces without mechanical contact

**Advantage**
- Reduction of particle emission
- Low noise
- High efficiency drive
- Force limit when overloaded

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Previous research

(a) Spiral surface permanent MLS
- Back yoke
- Inner yoke
- Spiral PM

(b) Interior permanent MLS
- Magnetic teeth
- Screw
- Arc-shape PM
- Back yoke

(c) Consequent-pole MLS (CPMLS)
- Magnetic teeth
- Screw
- Arc-shape PM

Operating principle

① Nut
② Nut
Screw

Force
Displacement

(b) Heya et al., Force Estimation Method for a Magnetic Lead-Screw-Driven Linear Actuator, IEEE Trans. Magn., 2018
(c) Heya et al., Analysis of a Consequent-Pole Magnetic Lead Screw, Proc. CEFC2018, 2018
Previous research

(a) Spiral surface permanent MLS

(b) Interior permanent MLS

(c) Consequent-pole MLS (CPMLS)

Stiffness of magnetic spring is depend on its hardware design
Purpose

Proposal of a novel MLS which can actively change the stiffness

Flexible interaction & High-power operation
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- Introduction
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Conceptual diagram of VSA

System configuration

**Conventional**
- Rotary motor A
- Rotary motor B
- Mechanical spring

Displacement of spring: Changed by motor rotation

**Proposed**
- Rotary motor A
- Rotary motor B
- Nut A
- Nut B
- Screw
- Nut part

Relative rotational angle between nuts: Changed by motor rotation

Rotary motor A: For driving
Rotary motor B: For adjusting stiffness
Proposed structure

Overview
- Design based on the CPMLS

Magnetic flux path

Consequent-pole
Screw thread
Back yoke
Magnetization → Magnetic flux

Rotation $\theta_n$
Linear motion $p$

Output plate

Divided nut B
Divided nut A
Screw (double-thread)

PM of divided nut A
Variable stiffness mechanism

Stiffness can be adjusted by changing the angle of divided nut A

1. $\theta_n$: 0deg.  $\theta_s$: 0deg.
2. $\theta_n$: 30deg.  $\theta_s$: -15deg.
3. $\theta_n$: 60deg.  $\theta_s$: -30deg.
4. $\theta_n$: 90deg.  $\theta_s$: -45deg.

Divided nut A

Divided nut B

Screw

① ② ③ ④
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Characteristics analysis

**Evaluated model**

- Number of elements: 2,330,085
- Number of nodes: 403,724

![Diagram showing the evaluated model with dimensions](image)

- 3 mm
- 1.5 mm
- 38 mm
Characteristics analysis

Analysis conditions

- Rotation angle: -90 to 90 deg.
- Displacement: -3 to 3 mm

Displacement $p$

Rotation $\theta_n$

Divided nut A

Divided nut B
Analysis results

**Thrust/Torque characteristics:**
Changed by rotation of the nut A
- Max. thrust/torque: 67.3 N / 63.8 mNm
Analysis results

**Stiffness characteristics:**
Changed by rotation of the nut A
Variable stiffness characteristics can be achieved
Analysis results

**Stiffness characteristics:**

- Changed by rotation of the nut A
- Variable stiffness characteristics can be achieved

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**Graphs:**

- **Left Graph:**
  - Stiffness characteristics
  - Displacement vs. Thrust
  - Legend: 0 deg., 30 deg., 60 deg., 90 deg.

- **Right Graph:**
  - Stiffness vs. Rotation angle $\theta_n$ [deg.]
  - Increase in stiffness value
Conclusion

- Proposal of a variable stiffness MLS
  - Variable stiffness mechanism using a rotation of divided nut
  - Designed the magnetic structure based on CPMLS
  - Characteristics were clarified by 3-D FEM

Variable stiffness were achieved by the proposed mechanism

Future work

Design of a prototype and validity verification
Thank you for your attention!
Previous research

(a) Spiral SPMLS

(b) Discrete spiral SPMLS

(c) Interior PMLS (IPMLS)

(d) Consequent-pole MLS (CPMLS)

(b) Ling et al.: “Design of a New Magnetic Screw With Discretized PMs”, 2016
(c) Heya et al.: “Force Estimation Method for a Magnetic Lead-Screw-Driven Linear Actuator”, 2018
(d) Heya et al.: “Analysis of a Consequent-Pole Magnetic Lead Screw”, 2018
Previous research

Upper limb mechanism
Flexible motion by compliance control