Novel bearingless motor concept with 26 poles and 24 slots

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Motivation and applications of bearingless slice motors

Properties of bearingless slice motors

- Ultra compact setup
- Passive axial and tilting bearing
- Active radial bearing and PMSM
- Large air-gap possible
- High torque

Application

- Hermetically encapsulated rotor in process chamber
- For biotechnology, pharma and semiconductor industry
Basic principle: passive axial and tilting PM bearing
Basic principle: passive axial and tilting PM bearing

- **Motivation**
  - Basic principle: passive bearing
  - Basic principle: active bearing and drive

**Basic principle: passive axial and tilting PM bearing**

- **Introduction**
  - Winding configurations
  - Parameter optimization
  - Conclusion and verification

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**Diagram**

- **Stator iron**
- **Rotor**
- **Permanent magnets** (NdFeB)

- **Equations**
  - $F_z$
  - $F_r$
  - $\omega$
  - $T_{x,y}$

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Basic principle: passive axial and tilting PM bearing

\[ \omega \]

\[ F_{z} \]

\[ F_{r} \]

\[ F_{\text{stator iron}} \]

\[ F_{\text{rotor}} \]

\[ F_{\text{permanent magnets}} \]

\[ \omega_{\text{stator iron}} \]

\[ \omega_{\text{rotor}} \]
Basic principle: passive axial and tilting PM bearing
Basic principle: passive axial and tilting PM bearing

\[ F_z \quad F_z \quad F_r \quad F_r \quad F \quad F \quad \omega \quad \omega \quad F_z \quad F_z \quad F_r \quad F_r \]
Basic principle: passive axial and tilting PM bearing

- **Motivation**
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**Basic principle:**

- Passive axial and tilting PM bearing

- **Parameters:**
  - $F_z$
  - $F_r$
  - $F_{x,y}$
  - $\omega$

**Diagram:**

- Schematic of the bearingless motor with 26 poles and 24 slots.
Basic principle: passive axial and tilting PM bearing
Basic principle: passive axial and tilting PM bearing

\[
\begin{align*}
E & \quad F_z \\
F_r & \quad F_z \\
F_r & \quad F_r \\
\omega & \quad T_{x,y}
\end{align*}
\]
Basic principle: passive axial and tilting PM bearing
Basic principle: active radial bearing and motor drive

Principle

- **Active radial magnetic bearing** for $\Delta x$ and $\Delta y$
- **Permanent magnet synchronous motor (PMSM)**
  - **Stator** with bearing and drive windings...
  - ...and position and angular sensors
  - **Rotor** with permanent magnets and back iron
Basic principle: active radial bearing and motor drive

**Principle**
- Active radial magnetic bearing for $\Delta x$ and $\Delta y$
- Permanent magnet synchronous motor (PMSM)
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  - ...and position and angular sensors
- **Rotor** with permanent magnets and back iron

**Key parameter**
- Number of stator teeth: $N = 24$
  - $\Rightarrow$ 12 motor teeth
  - $\Rightarrow$ 12 bearing teeth
- Number of rotor pole-pairs: $p = 13$
Basic principle: active radial bearing and motor drive

Motivation
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- Basic principle: passive bearing
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**Diagram:**
- Rotor with permanent magnets
- Stator iron
- Air gap

**Figure Description:**
- Novel bearingless motor with 26 poles and 24 slots.
Basic principle: active radial bearing and motor drive

- **drive coils**
- **air gap**
- **stator iron**

**Rotor with permanent magnets**

**Motivation**
- Basic principle: passive bearing
- Basic principle: active bearing and drive

**Basic principle: active radial bearing and motor drive**

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Basic principle: active radial bearing and motor drive

**Motivation**
- Basic principle: passive bearing
- Basic principle: active bearing and drive

**Basic principle: active radial bearing and motor drive**

- Drive coils
- Bearing coils
- Air gap
- Rotor with permanent magnets
- Stator iron

Novel bearingless motor with 26 poles and 24 slots
Basic principle: active radial bearing and motor drive

- Drive coils
- Bearing coils
- Air gap
- Rotor with permanent magnets
- Stator iron
- Angular and position sensors
Permanent magnet synchronous drive

Drive windings

Drive windings

Permanent magnet synchronous drive

Parameter optimization

Conclusion and verification

Active radial magnetic bearing
Permanent magnet synchronous drive

Drive windings

Drive phase $D_1$

$D_2$

$D_3$

$T_D$
Permanent magnet synchronous drive

Permanent magnet synchronous drive

Active radial magnetic bearing

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Active radial magnetic bearing

Bearing windings

bearing phase B₁

B₂
B₃

Bearingless motor with 26 poles and 24 slots
Active radial magnetic bearing

Bearing windings

dense flux region

bearing phase $B_1$

sparse flux region

F_x
Active radial magnetic bearing
Parameter Optimization

Parameter to be optimized
- Rotor and stator length $l$
- Magnet thickness $\delta_{magnet}$
- Magnet shape
- Tooth width $w_{tooth}$
- Number of windings

Criteria
- Maximum motor torque $T_M$
- Minimum cogging torque $T_{cogging}$
- Maximum levitation $F_x$
- Maximum axial stiffness $k_z$
- Minimum radial stiffness $k_r$

⇒ Optimization using 3D-FEM simulation
Motor torque optimization (example)

![Graph showing motor torque optimization](image)

- $T_{D,16000\text{A} \cdot \text{turns}}$ [Nm]
- $100 \cdot T_{\text{cogging}}$ [Nm]
- $T_{D,8000\text{A} \cdot \text{turns}}$ [Nm]
- $T_{D,4000\text{A} \cdot \text{turns}}$ [Nm]

$r_{\text{tooth}}$ [mm] vs. $T_{\text{cogging}}$, $T_D$ [Nm]
Bearing force optimization (example)

![Graph showing bearing force optimization for different current densities and slot widths.](image)

- $F_x, 16000 \text{ A-turns} \ [\text{N}]$
- $F_x, 8000 \text{ A-turns} \ [\text{N}]$
- $F_x, 4000 \text{ A-turns} \ [\text{N}]$
- $k_r \ [\text{N/mm}]$
- $k_z \ [\text{N/mm}]$

**Graph Key:**
- $F_x$: Axial force
- $w_{tooth}$: Tooth width
- $k_r, k_z$: Coefficients
- $A$: Current density

**Notes:**
- The graph illustrates the optimization of axial forces for varying slot widths and current densities.
- The coefficients $k_r$ and $k_z$ are critical in determining the bearing force optimization.
- The trend lines show how the forces change with different parameters.
Laboratory Prototype

- Rotor with permanent magnets (NdFeB)
- Stator with drive and bearing windings
- Position and angular sensors
- Air gap $\delta = 7$ mm
Performance Results

Prototype properties
- Outer diameter: $D = 500$ mm
- Rotor weight: $m = 3.1$ kg
- Air-gap: $\delta = 7$ mm

Bearing performance
- Max. bearing force: $F_x = 155$ N
- Max. displacement during acceleration: $\Delta x = 69 \mu m$
- Radial stiffness: $k_r = -70.0$ N/mm
- Axial stiffness: $k_z = 20.1$ N/mm

Motor performance
- Max. speed: $n_{\text{max}} = 1800$ rpm
- Acceleration time: $t_{0-1500} = 1.5$ s
- Rated torque: $T = 13.1$ Nm
Thank you for your attention!
Please feel free to ask questions.
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Motor Performance

- \( r_{max} \)
- \( n_r \)
- \( t_{0-1500} = 1.5 \text{ s} \)
- \( I_{drv} \)
- \( \Delta r \)
- \( \Delta r_{max} = 69 \mu m \)
- \( I_{bng} \)
**Bearing Performance**

- **$I_{bng,\text{max}} = 3.1\,\text{A}$**
- **$\Delta T = 160\,\text{ms}$**
- **$\Delta x = 90\,\mu\text{m}$**
- **$1\,\text{V} \approx 50\,\mu\text{m}$**

![Graph showing bearing performance](image-url)