Analysis of Force Capacity in Magnetic Bearings and Bearingless Motors from the Perspective of Airgap Space Harmonic Fields

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1. Introduction

Active magnetic bearings (AMBs)

Bearlingless motors

Low force capacity (specific load capacity) compared to other types of bearings:

\[
\text{force capacity} = \frac{\text{rated force}}{\text{projected rotor area} (DL)} \quad [1]
\]

• AMBs: 30-40 N/cm\(^2\), 65 N/cm\(^2\) with cobalt-alloys [2], [3]

• Bearingless motors: 9 N/cm\(^2\) [1]


Analysis of Force Capacity in Magnetic Bearings and Bearingless Motors from the Perspective of Airgap Space Harmonic Fields
1. Introduction

• This paper explores the theoretical basis of force capacity for magnetic bearings and bearingless motors.
• Analyses are conducted from the perspective of airgap space harmonic fields.

**Contributions of this paper:**
1. Explanation of the force capacity in AMBs from the perspective of multiple controllable airgap space harmonic fields.
2. Explanation of the force capacity in bearingless motors when only two space harmonics are controlled.
3. Enhancement of the force capacity in bearingless motors by controlling multiple airgap space harmonics.

\[
\text{force capacity} = \frac{\text{rated force}}{\text{projected rotor area}}
\]
2. Force Creation from the Perspective of Airgap Harmonics

Pole-based force vector model (conventional) [1]

- Each pole $i$ creates an attraction force:
  \[ F_i = \frac{A}{2\mu_0} B_i^2 \]

- Total force vector:
  \[ \vec{F} = \frac{A}{2\mu_0} \sum_{i=1}^{n_p} a^{i-1} B_i^2 \]

2. Force Creation from the Perspective of Airgap Harmonics

Harmonic-based force vector model (used in this paper) [1]

Space harmonic field of order $h$: $B_{n,h}(\alpha) = \hat{B}_{n,h} \cos(h\alpha - \phi_h)$

- Force is created from the interaction between harmonics $h_i \leftrightarrow h_j = h_i + 1$:
  $$\vec{F}_{h_i h_j} = k C_{h_{ij}} \hat{B}_{n_i} \hat{B}_{n_j} e^{j(\phi_j - \phi_i)}$$

- Total force:
  $$\vec{F} = k \sum_{h_i=1}^{n_h-1} C_{h_{ij}} \hat{b}_{n_i} \hat{b}_{n_j}$$

Each force depends on the product of adjacent harmonic amplitudes and difference in their angles

2. Force Creation from the Perspective of Airgap Harmonics

• Another form of harmonic-based model – uses “current sequences”. Useful to:
  • identify airgap harmonic content,
  • determine independently controllable harmonics and force vector components.
• AMB currents are viewed as multiphase currents with $m$-phases.

\[
i = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_m \end{bmatrix} = \begin{bmatrix} i_{1,1} \\ i_{1,2} \\ \vdots \\ i_{1,m} \end{bmatrix} + \begin{bmatrix} i_{2,1} \\ i_{2,2} \\ \vdots \\ i_{2,m} \end{bmatrix} + \cdots + \begin{bmatrix} i_{s,1} \\ i_{s,2} \\ \vdots \\ i_{s,m} \end{bmatrix} + \cdots + \begin{bmatrix} i_{s_m,1} \\ i_{s_m,2} \\ \vdots \\ i_{s_m,m} \end{bmatrix}
\]

• Each sequence:
  • independently controls one harmonic.
  • has its complex space vector representation $\vec{i}_s$

\[
\vec{F} = \sum_{i=1}^{n_f} \vec{k}_{q,h_{ij}} \vec{i}_i^* \vec{i}_j
\]
2. Force Creation from the Perspective of Airgap Harmonics

\[ \mathbf{\hat{F}} = \sum_{i=1}^{n_f} k C_{h_i h_j} \mathbf{\hat{B}}_{h_i} \mathbf{\hat{B}}_{h_j} e^{j(\phi_{h_j} - \phi_{h_i})} = \sum_{i=1}^{n_f} k_{q,h_i} \mathbf{\hat{B}}_{h_i} \mathbf{\hat{B}}_{h_j} e^{j(\phi_{h_j} - \phi_{h_i})} \]

**AMBs with** \( m \in \mathbb{N}_{\text{even}} \) **can control:**
- Oscillating fields: 2 \((s = 0, m/2)\)
- Rotating fields: \( n_{\text{ind}} = \frac{m-2}{2} \) \((s = 1: n_{\text{ind}})\)
- Force vector components: \( \frac{m-2}{2} \)

Oscillating field – only \( \mathbf{\hat{B}}_{h_i} \) is controllable

**AMBs with** \( m \in \mathbb{N}_{\text{odd}} \) **can control:**
- Oscillating fields: 1 \((s = 0)\)
- Rotating fields: \( n_{\text{ind}} = \frac{m-1}{2} \) \((s = 1: n_{\text{ind}})\)
- Force vector components: \( \frac{m-1}{2} \)

Rotating field – both \( \mathbf{\hat{B}}_{h_i} \) and \( \phi_{h_i} \) are controllable

Increasing the number of phases/currents allows for more granular control over the suspension force
2. Force Creation from the Perspective of Airgap Harmonics

All example AMBs below have \( m = 4 \) independent currents.

- \( n_f = 1 \) controllable force vector.

\[
h = \frac{np}{2}
\]

\[
h = 1 \ (s = 1)
\]

\[
h = 2 \ (s = 2)
\]

\[
i_1 = -i_2 = i_3 = -i_4
\]

\[
h = \frac{np}{2} - 1
\]

\[
h = 1 \ (s = 1)
\]

\[
h = 3 \ (s = 1)
\]

\[
i_1 = i_2 = i_3 = i_4
\]

\[
s = 0,2 \ – \text{oscil. harm.}
\]

\[
s = 1 \ – \text{rotating harm.}
\]

Dominant harmonics

Analysis techniques used in multiphase electric machines are convenient when analyzing AMBs.
3. Force Capacity in AMBs

1. Explanation of the force capacity calculation in AMBs from the perspective of multiple controllable airgap harmonics.

Calculating force capacity [1]:
1. Find the maximum force $F_{\text{max}}(\phi)$ over all force angles $\phi$ without exceeding the airgap field limit $|B_n(\alpha)| \leq B_{\text{max}}$
2. Find $f_c = \frac{F_{\text{rated}}}{DL}$, where $F_{\text{rated}} = \min[F_{\text{max}}(\phi)]$

Dimensionless model can be used ($F_{\text{base}} = kB_{\text{max}}^2$)

$$\vec{F}' = \sum_{i=1}^{n_f} \vec{b}_{h_i}^* \vec{b}_{h_j}'$$
$$f_c = \frac{\pi}{4\mu_0} B_{\text{max}}^2 F_{\text{rated}}'$$

Force capacity does not depend on $DL$

3. Force Capacity in AMBs

Results

\( n_{\text{ind}} \) controllable harmonics \( \rightarrow 2n_{\text{ind}} \) control variables

\( B_{\text{max}} = 1.5 \, \text{T} \)

Optimal fields for \( n_{\text{ind}} = 6 \) (\( \phi = 0 \))

\[
f_c = \frac{\pi}{4\mu_0} B_{\text{max}}^2 F_{\text{rated}}'
\]

Results agree with the results reported in the AMB literature (\( \approx 40 \, \text{N/cm}^2 \))
4. Force Capacity in Bearingless Motors

2. Explanation of the force capacity in bearingless motors when only two space harmonics are controlled.

3. Enhancement of the force capacity in bearingless motors by controlling multiple airgap space harmonics.

Enhancement of force capacity in bearingless machines equivalent to that of AMBs can be achieved.
4.1. Torque-Force Capability from Two Airgap Harmonics

Creating torque and suspension forces in bearingless motors:

• Control harmonics/pole-pairs $p$ and $p_s = p \pm 1$.
• Pole-pair $p$: 1) torque creating $B_\tau$ and 2) magnetizing field $B_\delta$ components.

$B_\delta$ - affects both torque and force creation.

Force capacity calculation is similar to AMBs except that $B_\delta$:

• must have a fixed amplitude $\hat{B_\delta}$,
• angular location at the rotor rotational angle.

The optimal magnetizing field $B_\delta$ to create the max. force and torque can be identified.
4.1. Torque-Force Capability from Two Airgap Harmonics

Find optimal magnetizing field that creates maximum rated force and torque without exceeding the airgap field limit $B_{\text{max}}$.

\[
\tau'_{\text{rated}}^{2} = F'_{\text{rated}}^{2} - 2B'_{\delta}F'_{\text{rated}} + B'_{\delta}^{2}(1 - B'_{\delta}^{2})
\]

- $\hat{B}'_{\delta} = 0.5$ p.u. $\rightarrow$ maximum force
- $\hat{B}'_{\delta} = 0.707$ p.u. $\rightarrow$ maximum torque

The optimal range of the magnetizing field magnitude is between 0.5-0.707 p.u.
4.2. Force Enhancement Using Multiple Airgap Harmonics

- \( n_{\text{ind}} \) harmonics \( \rightarrow 1 \) fixed \( (B_\delta) \), \( n_{\text{ind}} - 1 \) free to control.
- Results below are presented for \( p = 1, \hat{B}_\delta = 0.5B_{\text{max}}, B_{\text{max}} = 1.5 \text{ T} \).

\[
\vec{F}' = \sum_{i=1}^{n_f} \vec{b}_{h_i}^* \vec{b}_{h_j}'
\]

\( n_{\text{ind}} = 4 \)

Increasing controllable harmonics from 2 to 4 can significantly increase force capacity (by 42%)
Conclusion

• The key factors affecting the force capacity:
  • Peak allowable airgap field $B_{\text{max}}$.
  • Distribution of the airgap harmonic fields.

• Bearingless motors have lower force capacity than AMBs:
  1. AMBs use more harmonics by controlling individual currents.
  2. Bearingless motors need to create $B_\delta$ with fixed magnitude and angle → constrains other harmonics’ behavior to create force.

• The optimal range of $B_\delta$: between 50% (max force) and 70% (max torque) of $B_{\text{max}}$.

• Bearingless motors can have potential force enhancement of over 40% when controlling 4 vs 2 harmonics (10 vs 6 phases).
Thank you!