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

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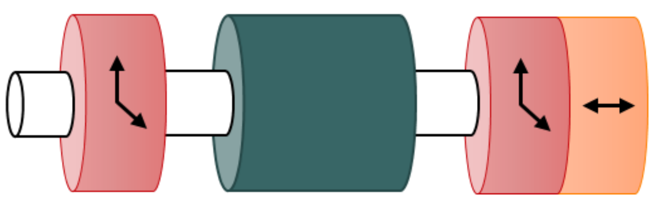
Outline

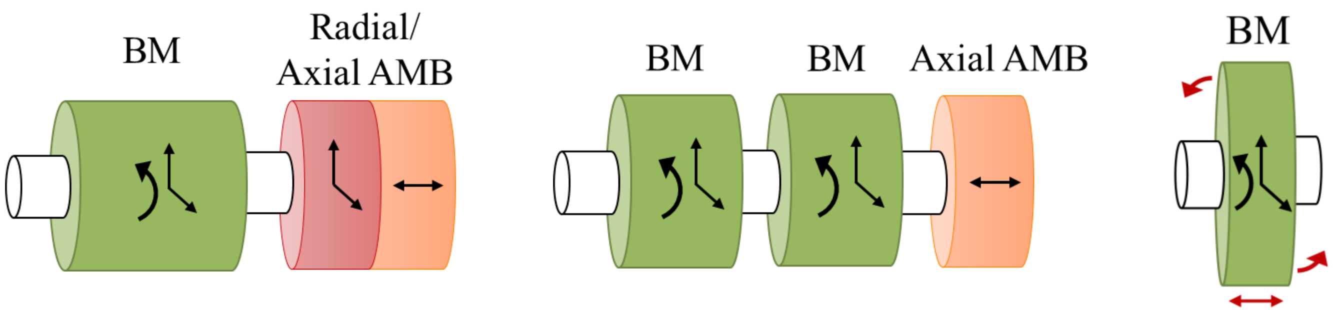
1. Introduction
2. Force Creation from the Perspective of Airgap Space Harmonic Fields
3. Force Capacity in AMBs
4. Force Capacity in Bearingless Motors
5. Conclusion

1. Introduction

Active magnetic bearings (AMBs)



Bearingless motors



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

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

- AMBs: 30-40 N/cm^2, 65 N/cm^2 with cobalt-alloys [2], [3]
- Bearingless motors: 9 N/cm^2 [1]

[1] Chiba, A., Fukao, T., Ichikawa, O., Oshima, M., Takemoto, M. & Dorrell, D. G. (2005), *Magnetic bearings and bearingless drives*, Elsevier.
[2] Maslen, E. H. & Schweitzer, G. (2009), *Magnetic bearings: theory, design, and application to rotating machinery*, Springer.
[3] Jastrzebski, R. P., Putkonen, A., Kurvinen, E. & Pyrhonen, O. (2021), 'Design and modeling of 2 mw amb rotor with three radial bearing-sensor planes', *IEEE Transactions on Industry Applications* **57**(6), 6892–6902.

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.

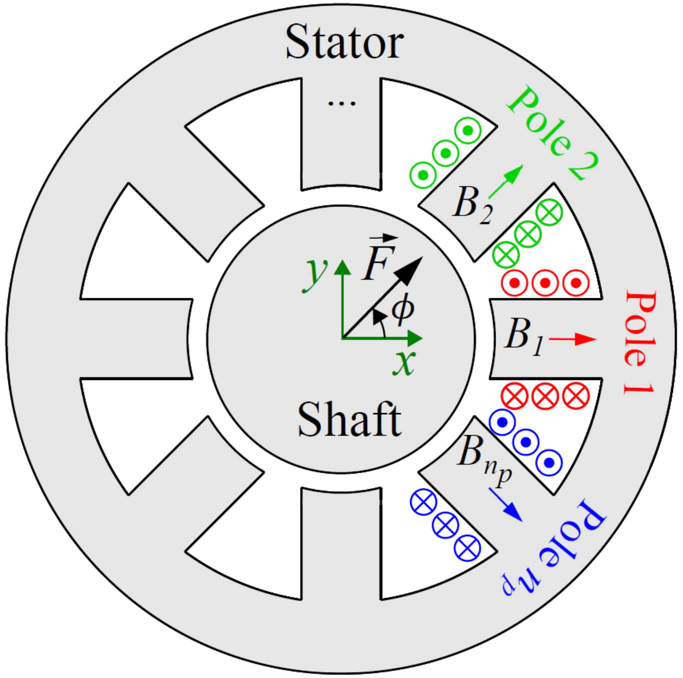
Contributions of this paper:

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:

$$\vec{F} = \frac{A}{2\mu_0} \sum_{i=1}^{n_p} a^{i-1} B_i^2$$

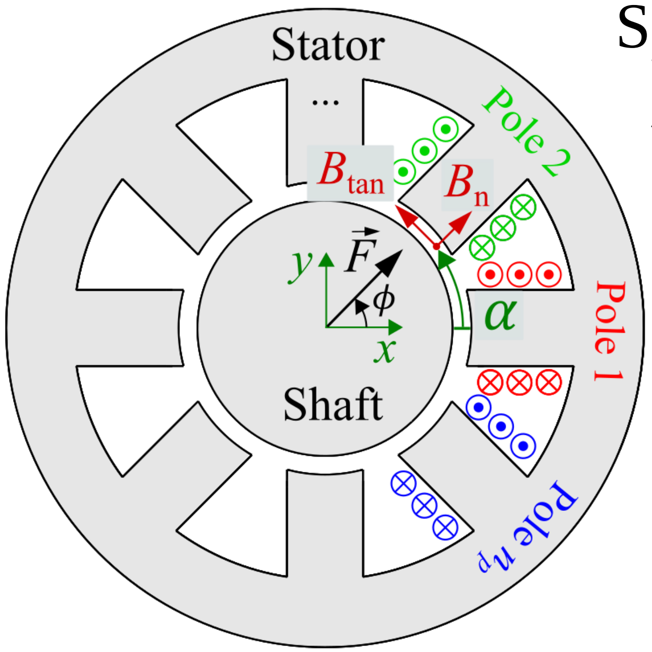
A – pole surface area
n_p – number of poles
$a = e^{j\frac{2\pi}{n_p}}$

[1] Maslen, E. H. & Schweitzer, G. (2009), *Magnetic bearings: theory, design, and application to rotating machinery*, Springer.

2. Force Creation from the Perspective of Airgap Harmonics

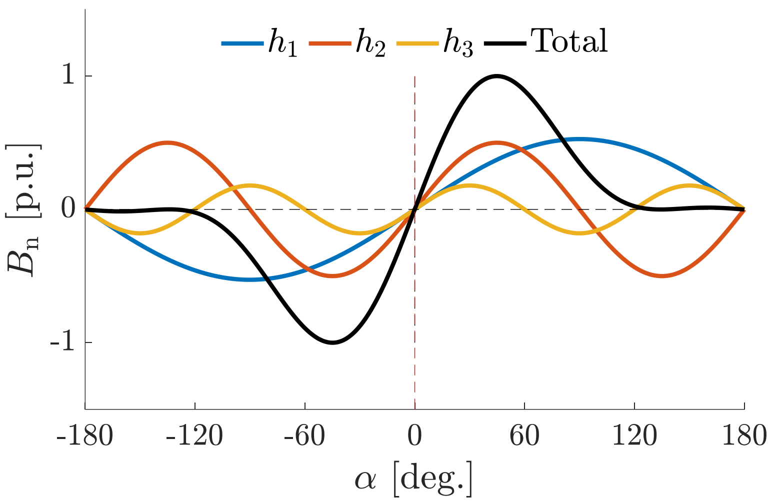
Harmonic-based force vector model (used in this paper) [1]

$$\vec{b}_{h_i} = \hat{B}_{\mathrm{n},h_i} e^{j\phi_{h_i}}$$



Space harmonic field of order h:

$$B_{\mathrm{n},h}(\alpha) = \hat{B}_{\mathrm{n},h} \cos(h\alpha - \phi_h)$$



- Force is created from the interaction between harmonics $h_i \leftrightarrow h_j = h_i + 1$:

$$\vec{F}_{h_i h_j} = k C_{h_{ij}} \hat{B}_{h_i} \hat{B}_{h_j} e^{j(\phi_{h_j} - \phi_{h_i})}$$

- Total force:

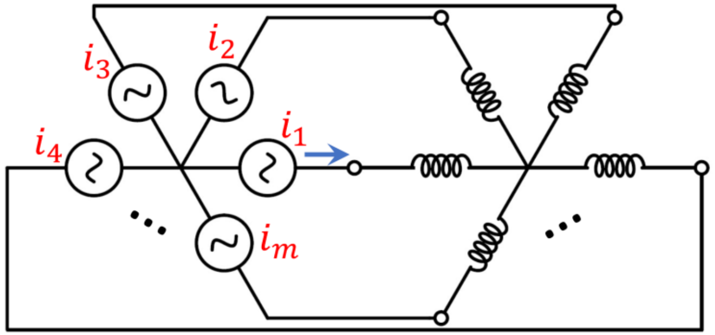
$$\vec{F} = k \sum_{h_i=1}^{n_h-1} C_{h_{ij}} \vec{b}^{*}_{h_i} \vec{b}_{h_j}$$

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

[1] Khamitov, A. & Severson, E. L. (2022), Exact torque and force model of bearingless electric machines, *in* ‘2022 IEEE Energy Conversion Congress and Exposition (ECCE)’, IEEE, pp. 1–8.

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.



seq. 1 seq. 2 seq. s Highest seq. $s_\mathrm{m} \propto m$

$$\boldsymbol{i} = \begin{bmatrix} i_1 \\ i_2 \\ \cdots \\ i_m \end{bmatrix} = \begin{bmatrix} i_{1,1} \\ i_{1,2} \\ \cdots \\ i_{1,m} \end{bmatrix} + \begin{bmatrix} i_{2,1} \\ i_{2,2} \\ \cdots \\ i_{2,m} \end{bmatrix} + \cdots \begin{bmatrix} i_{s,1} \\ i_{s,2} \\ \cdots \\ i_{s,m} \end{bmatrix} + \cdots + \begin{bmatrix} i_{s_\mathrm{m},1} \\ i_{s_\mathrm{m},2} \\ \cdots \\ i_{s_\mathrm{m},m} \end{bmatrix}$$

$$i_{s,k} = \hat{I}_s \cos\left(\phi_s - [k-1]s\frac{2\pi}{m}\right)$$

- Each sequence:
  - independently controls one harmonic.
  - has its complex space vector representation $\overrightarrow{i_s}$

$$\vec{F} = \sum_{i=1}^{n_f} \bar{k}_{q,h_{ij}} \overrightarrow{i_i^*}\, \overrightarrow{i_j}$$

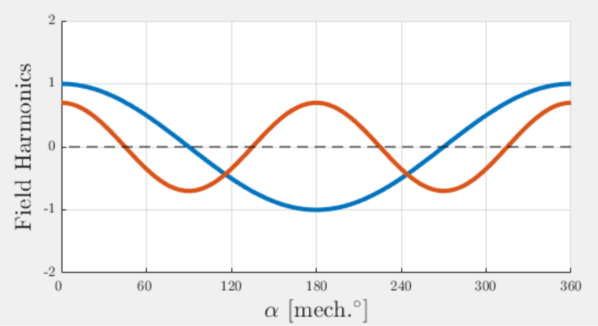
2. Force Creation from the Perspective of Airgap Harmonics

$$\vec{F} = \sum_{i=1}^{n_f} k C_{h_i h_j} \hat{B}_{h_i} \hat{B}_{h_j} e^{j(\phi_{h_j} - \phi_{h_i})} = \sum_{i=1}^{n_f} \bar{k}_{q,h_{ij}} \vec{i_i^*} \vec{i_j}$$

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: $\frac{m-2}{2}$

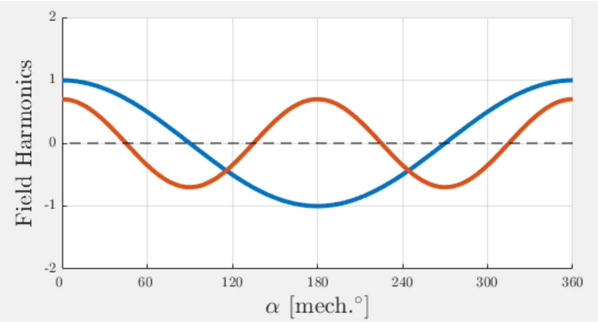
Oscillating field – only $\hat{B}_{\text{n},h}$ is controllable



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 $\hat{B}_{\text{n},h}$ and ϕ_h are controllable



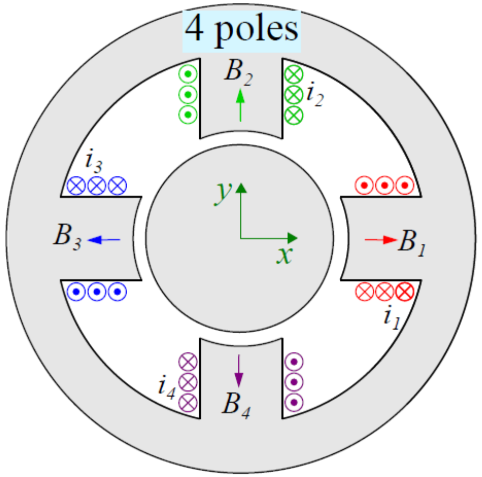
Increasing the number of phases/currents allows for more granular control over the suspension force

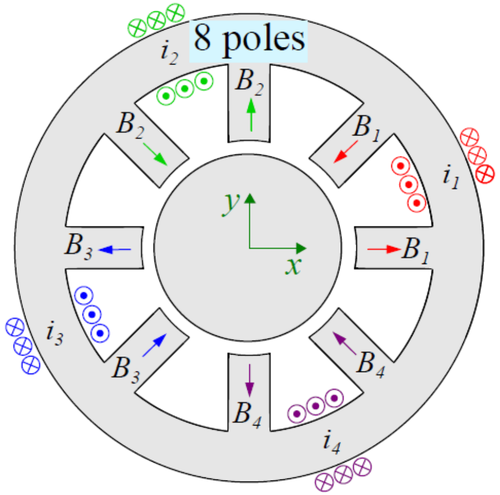
2. Force Creation from the Perspective of Airgap Harmonics

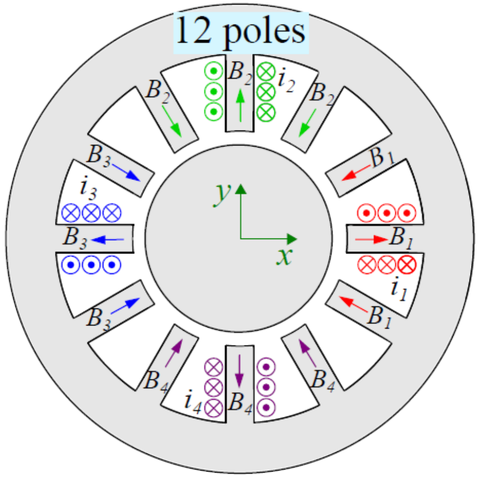
$s = 0, 2$ – oscil. harm.
$s = 1$ – rotating harm.

All example AMBs below have $m = 4$ independent currents.

- $n_f = 1$ controllable force vector.







Dominant harmonics

$h = \frac{n_p}{2}$ ➡ $h = 2\ (s = 2)$, $i_1 = -i_2 = i_3 = -i_4$ | $h = 4\ (s = 0)$, $i_1 = i_2 = i_3 = i_4$ | $h = 6\ (s = 2)$, $i_1 = -i_2 = i_3 = -i_4$

$h = \frac{n_p}{2} - 1$ ➡ $h = 1\ (s = 1)$ | $h = 3\ (s = 1)$ | $h = 5\ (s = 1)$

Currents phase separated by 90 degrees.

Analysis techniques used in multiphase electric machines are convenient when analyzing AMBs

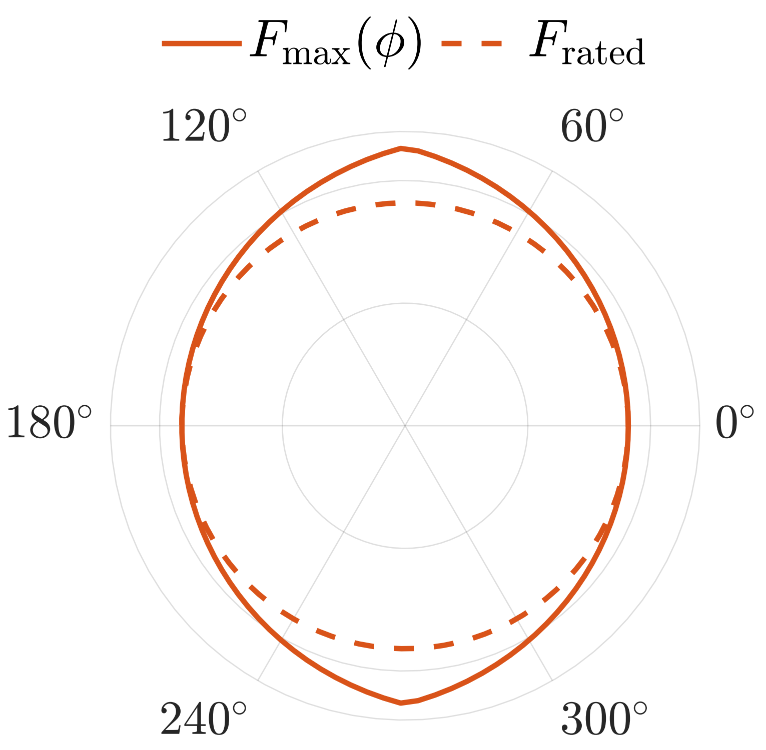
3. Force Capacity in AMBs

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

$$\vec{F} = k \sum_{i=1}^{n_f} C_{h_{ij}} \vec{b}_{h_i}^* \vec{b}_{h_j}$$

Calculating force capacity [1]:

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



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

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

Force capacity does not depend on *DL*

[1] Maslen, E. H. & Schweitzer, G. (2009), *Magnetic bearings: theory, design, and application to rotating machinery*, Springer.

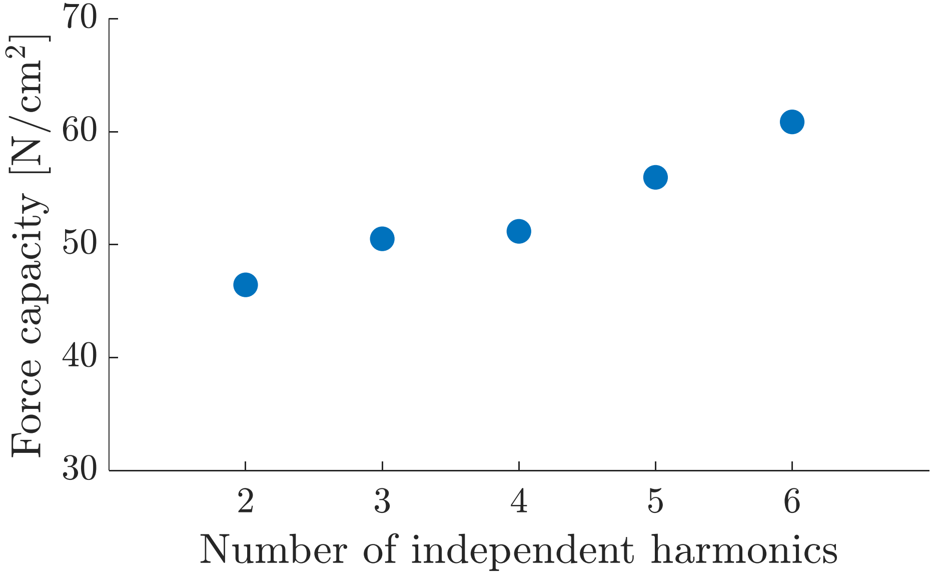
3. Force Capacity in AMBs

Results

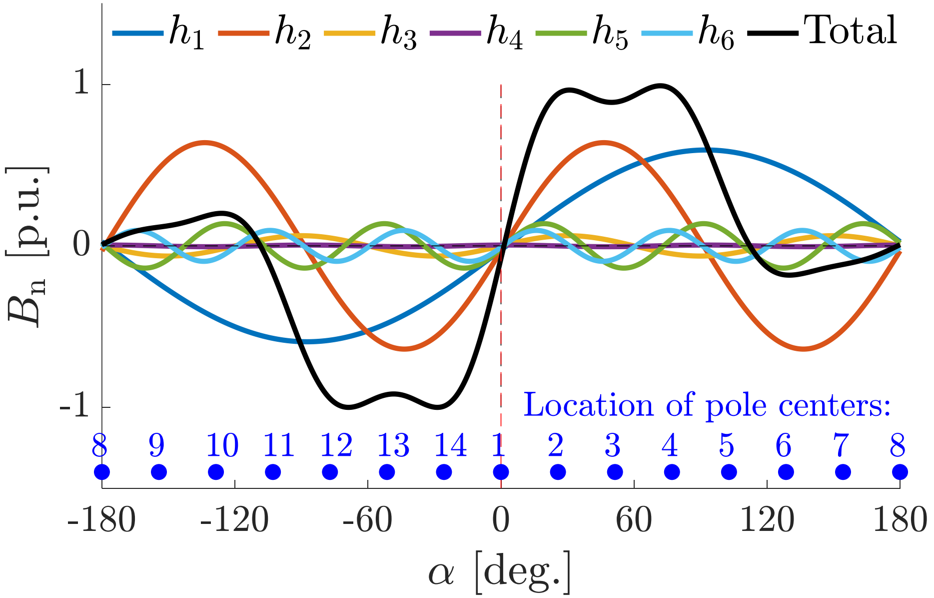
n_{ind} controllable harmonics → $2n_{\text{ind}}$ control variables

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

$B_{\max} = 1.5$ T



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



Results agree with the results reported in the AMB literature (≈ 40 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.

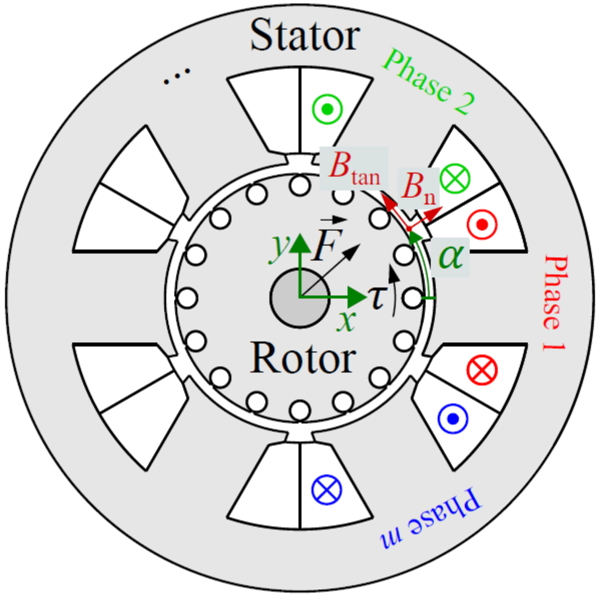
3. Enhancement of the force capacity in bearingless motors by controlling multiple airgap space harmonics.

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_τ and 2) magnetizing field B_δ components.



B_δ - affects both torque and force creation.

Force capacity calculation is similar to AMBs except that B_δ:

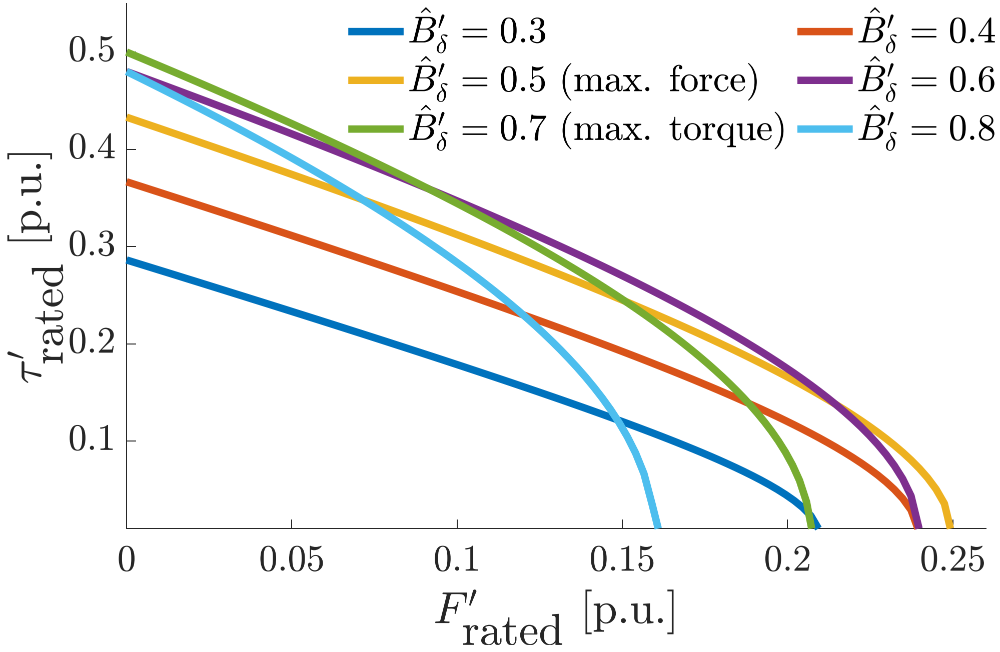
- must have a fixed amplitude $\hat{B}_\delta$,
- angular location at the rotor rotational angle.

The optimal magnetizing field B_δ 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_{max} .

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



$\hat{B}'_\delta = 0.5$ p.u. → maximum force

$\hat{B}'_\delta = 0.707$ p.u. → maximum torque

The optimal range of the magnetizing field magnitude is between 0.5-0.707 p.u.

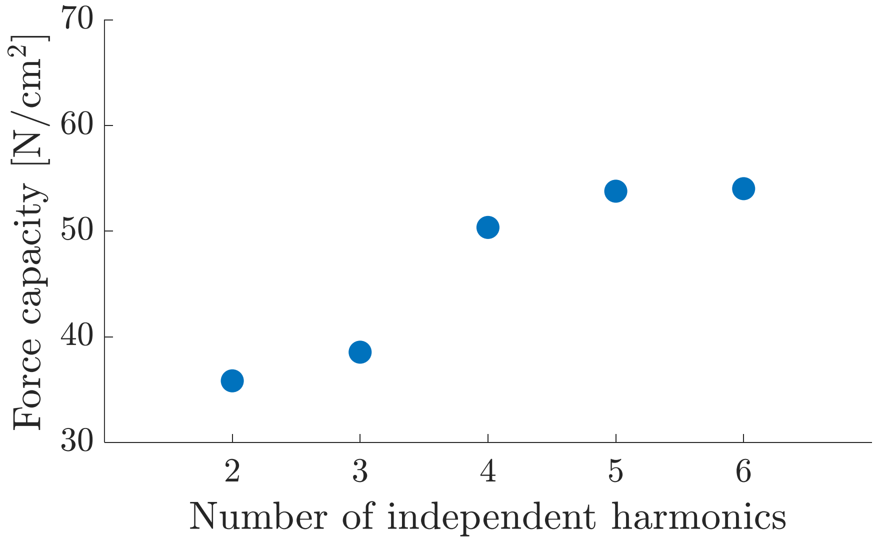
4.2. Force Enhancement Using Multiple Airgap Harmonics

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

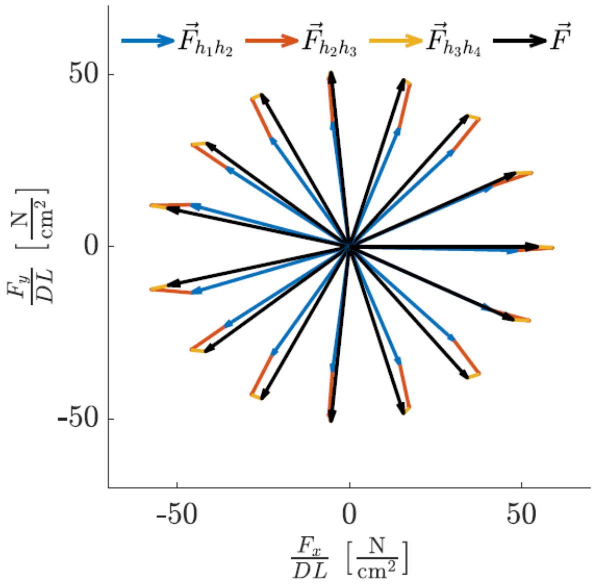
$$\vec{F}' = \sum_{i=1}^{n_f} \vec{b}_{h_i}^{*}{}' \vec{b}_{h_j}{}'$$

$n_{\text{ind}} = 4$

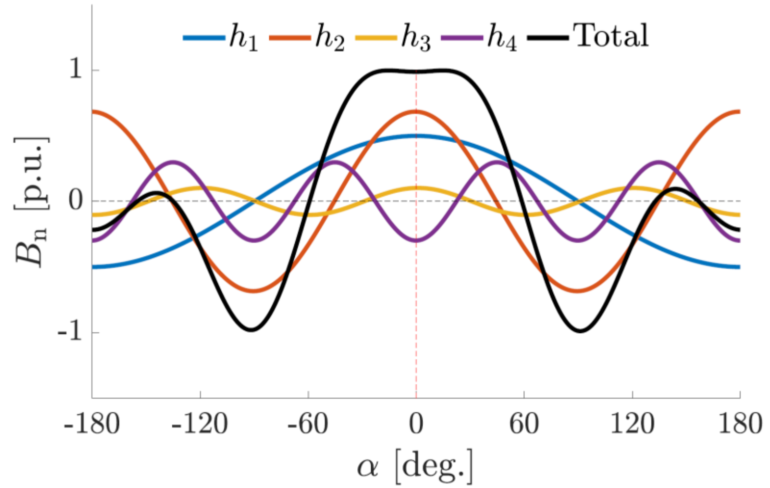
Force capacity



Optimal forces



Optimal fields to create F_x



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_{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_δ with fixed magnitude and angle → constrains other harmonics' behavior to create force.
- The optimal range of B_δ: between 50% (max force) and 70% (max torque) of B_{max}.
- Bearingless motors can have potential force enhancement of over 40% when controlling 4 vs 2 harmonics (10 vs 6 phases).

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Thank you!