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Comparison of Rotor Magnetic Circuit Topologies for Passively Levitated Self-bearing Machines

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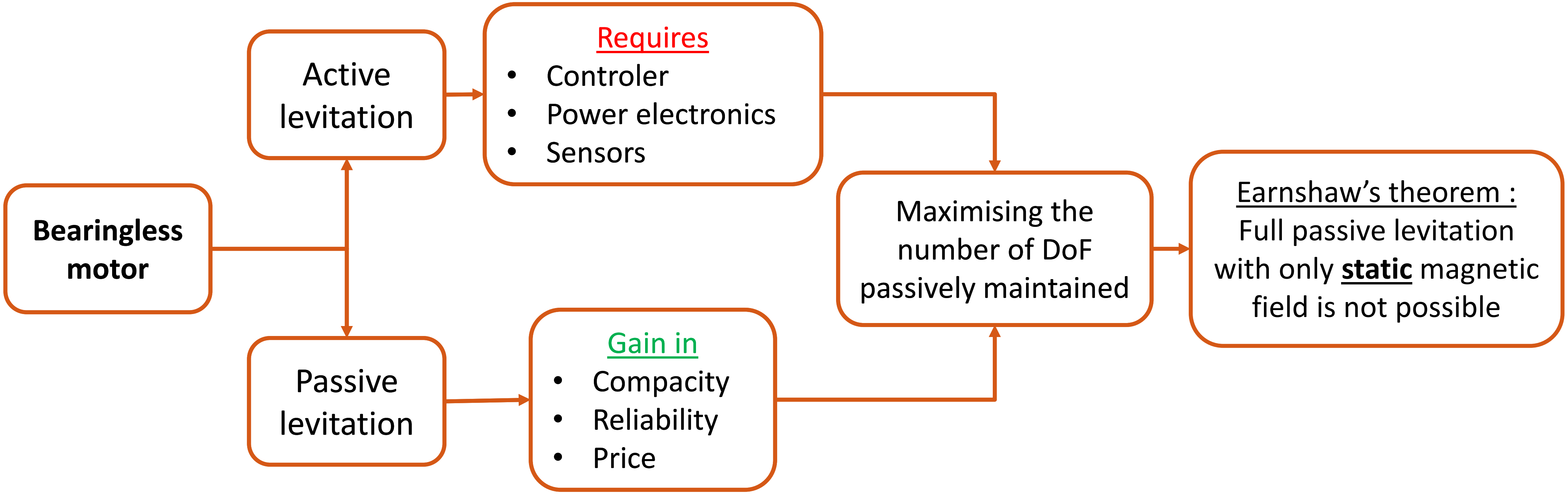
LOUVAIN-LA-NEUVE, BELGIUM

Research context



Research context

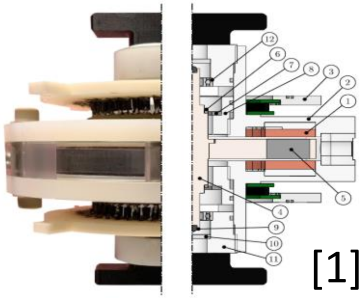
Earnshaw’s theorem :
Full passive levitation with only **static** magnetic field is not possible

→

Electrodynamic suspension :
Bypass Earnshaw’s theorem by using a rotating magnetic field

→

Two prototypes of fully passively Electrodynamic Thrust Self-Bearing Motor (ETSBM) :



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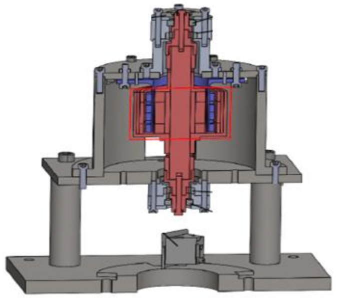

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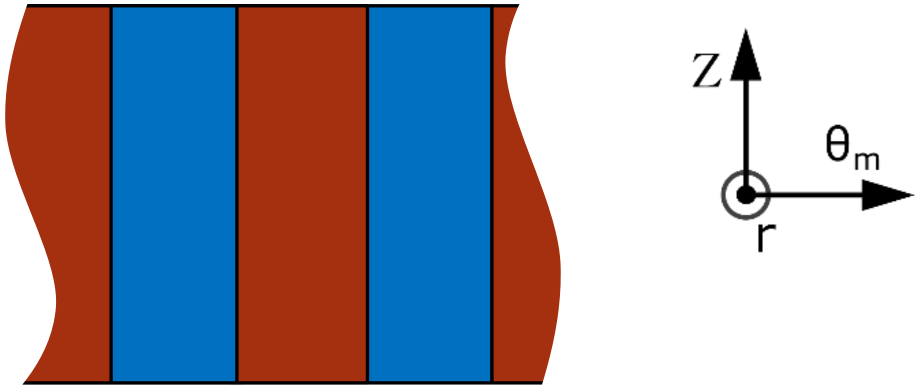
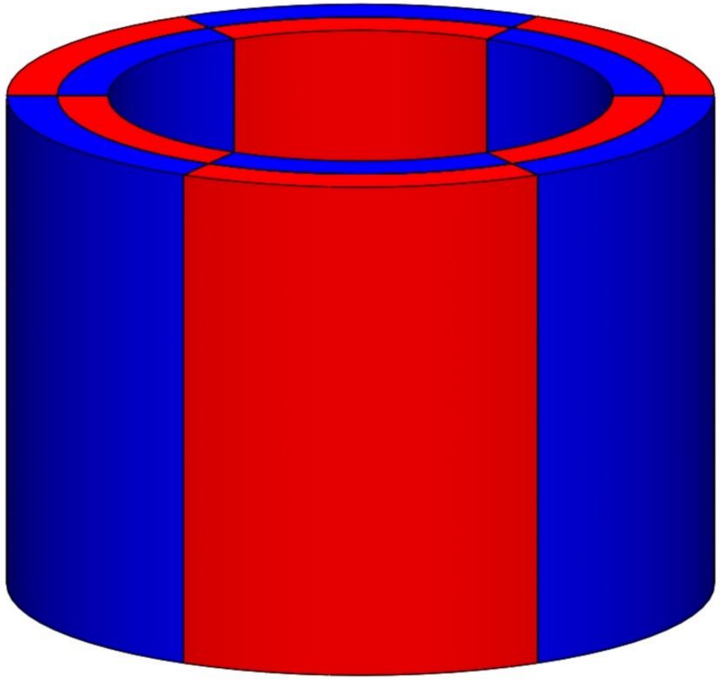
How is it working ?

Working principle

Initially based on an electrodynamic thrust bearing :





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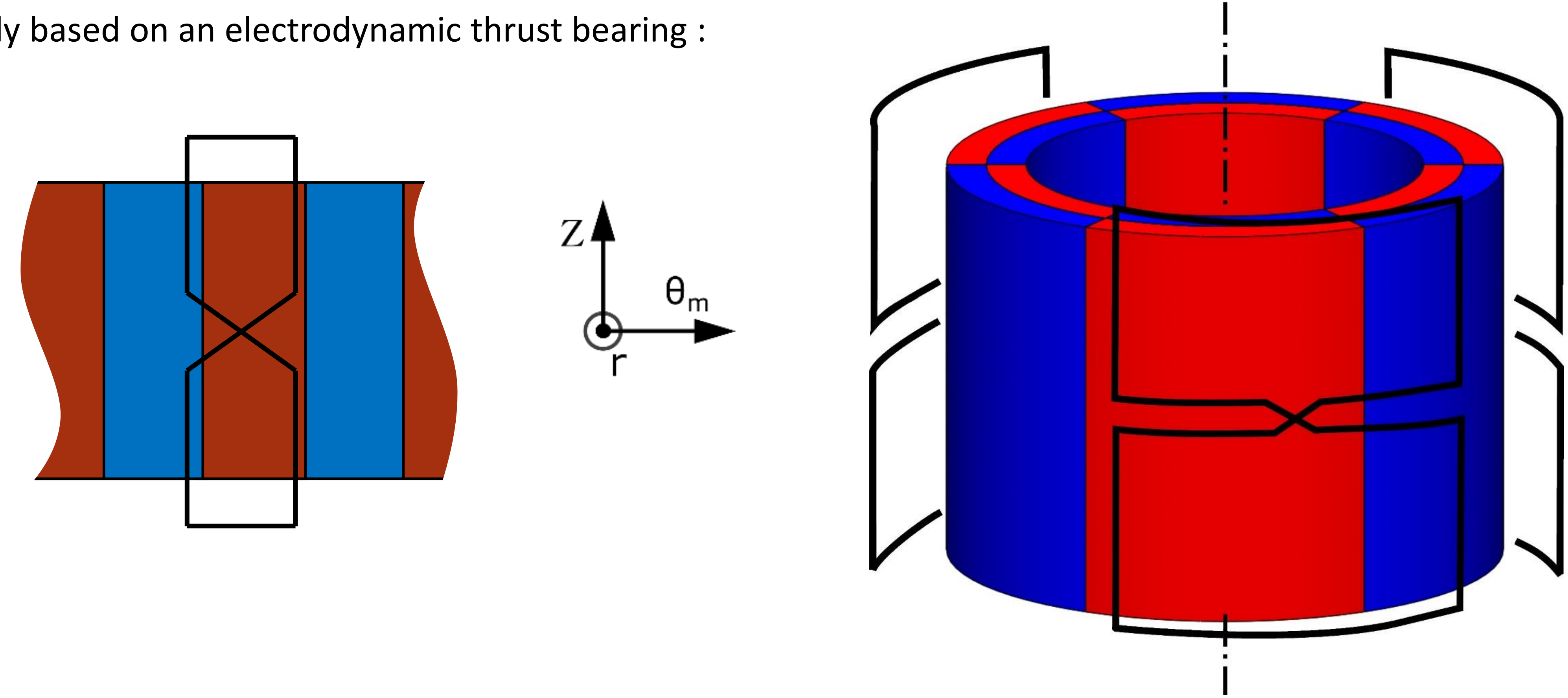

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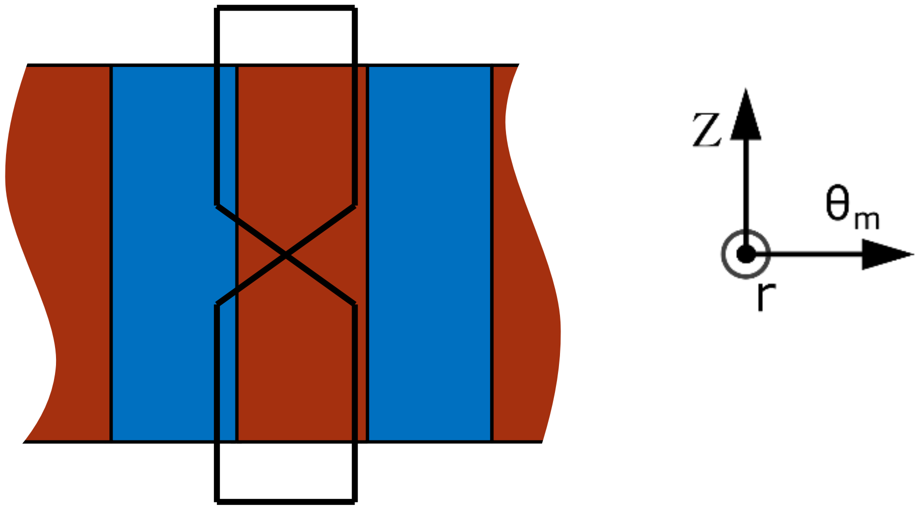

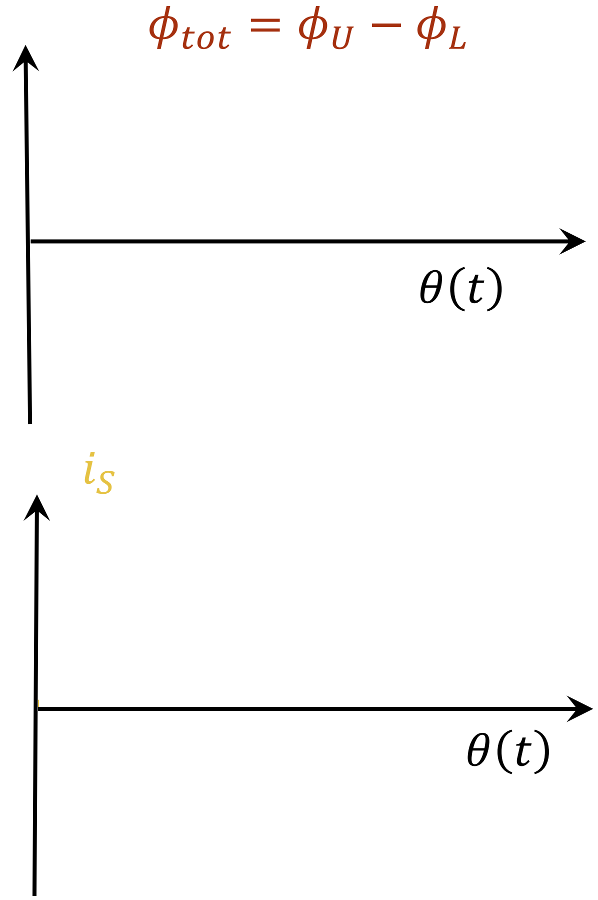

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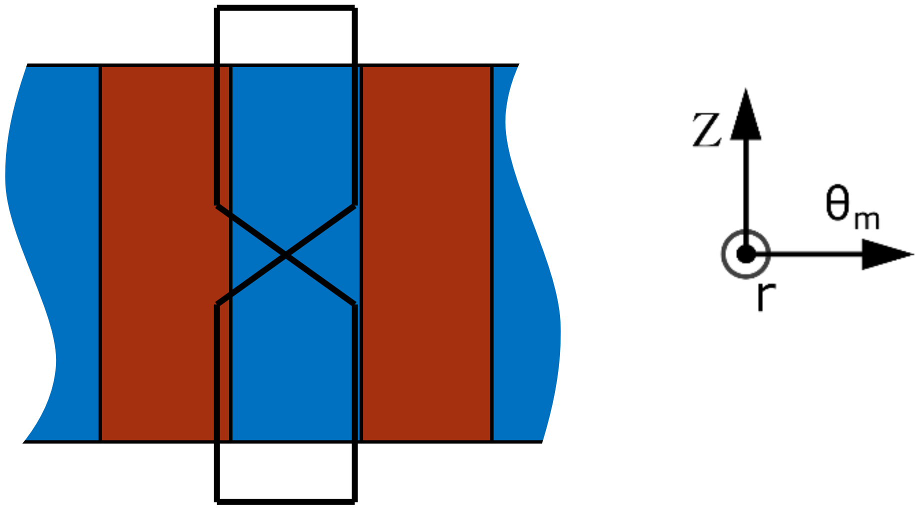

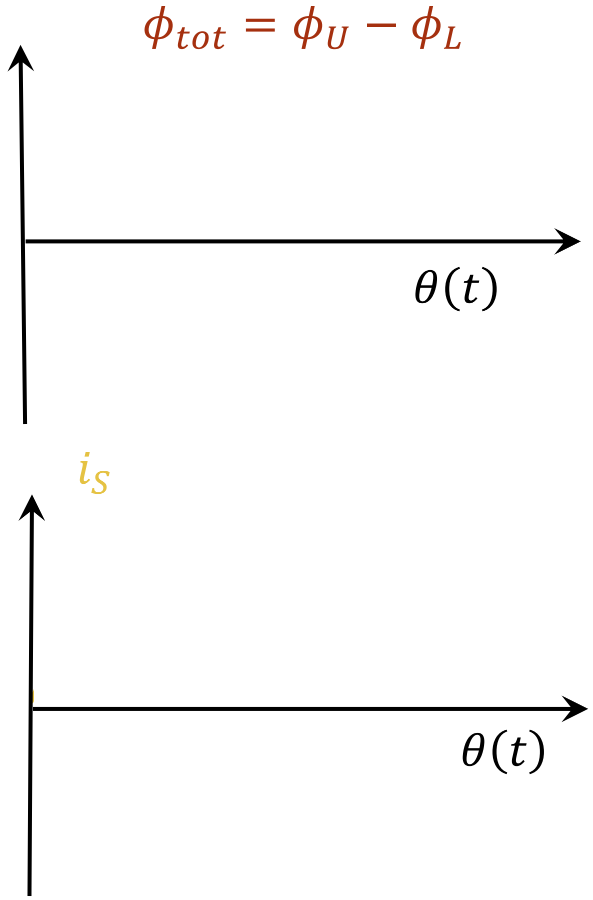

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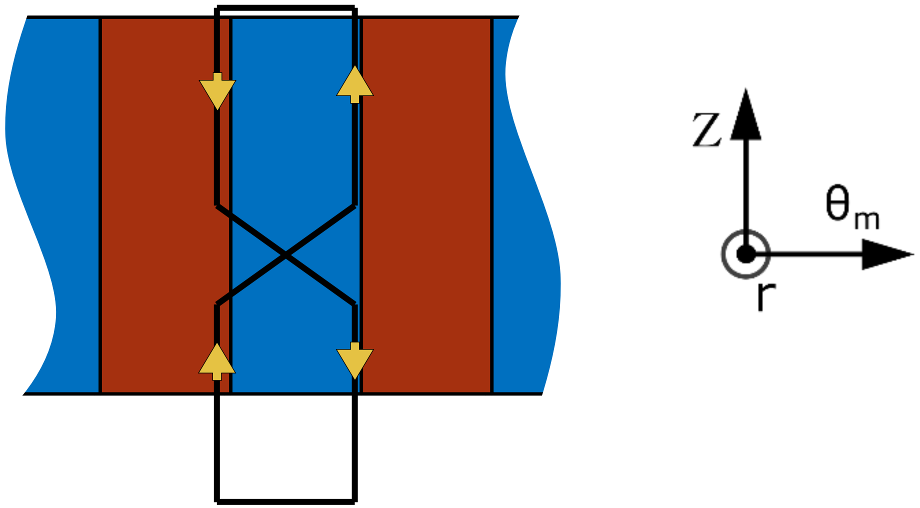

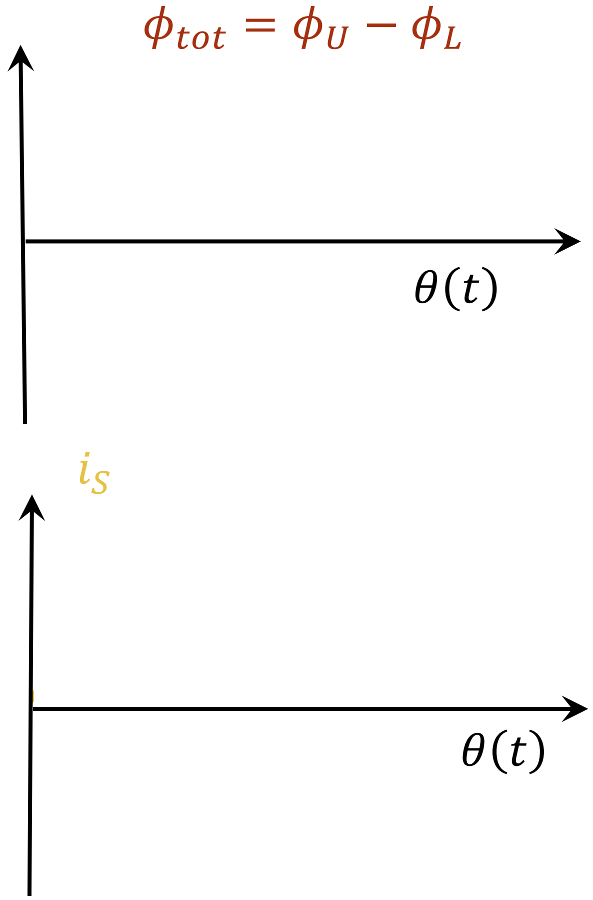

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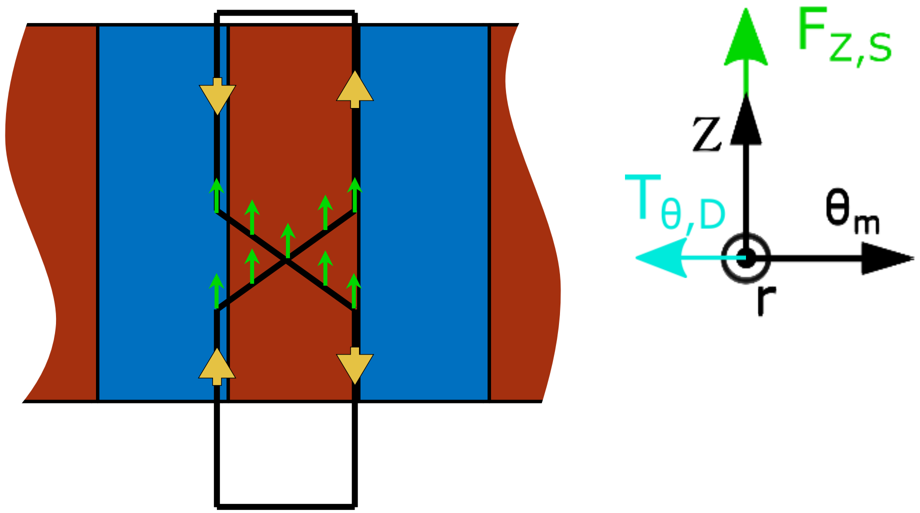

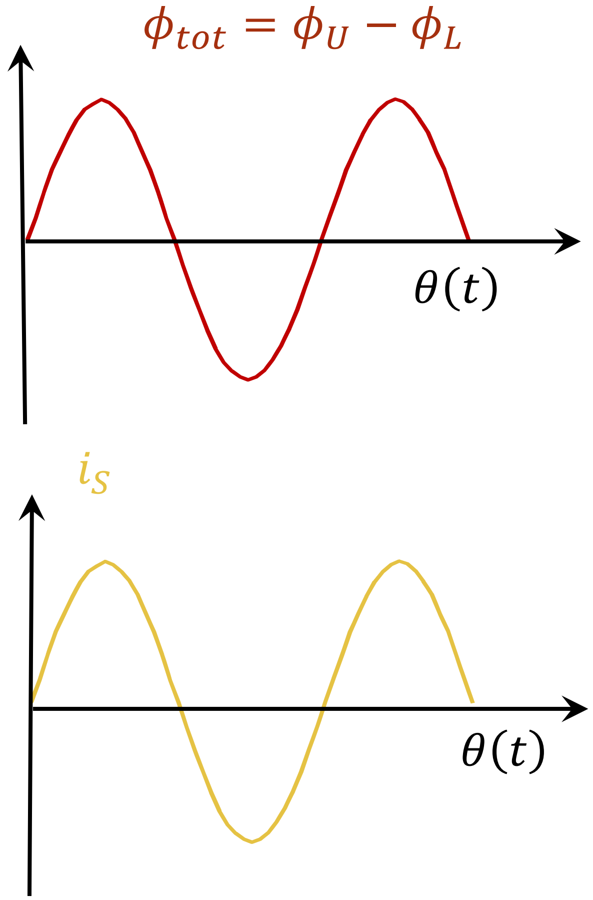

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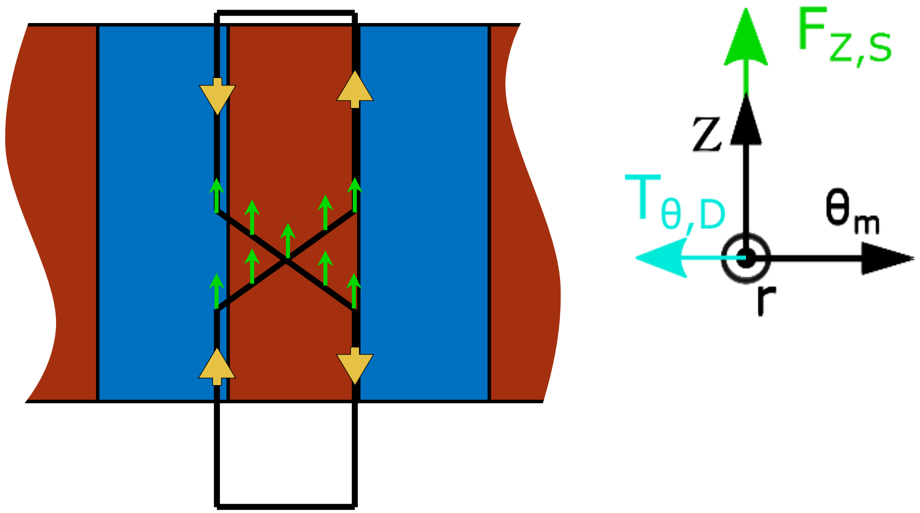
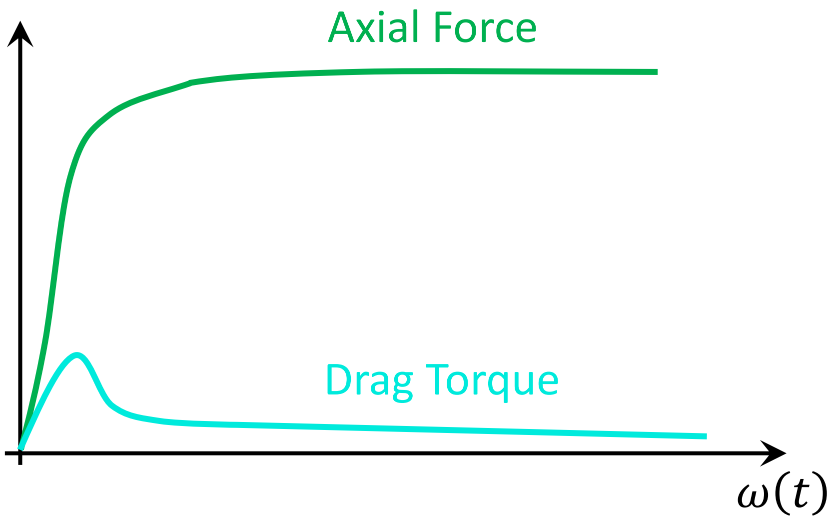
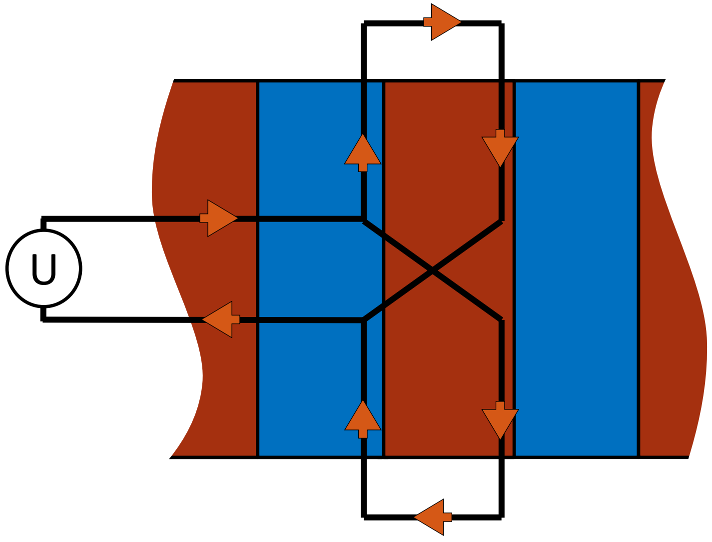
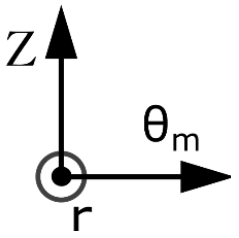




Working principle

Adding a power supply creates an electrodynamic thrust self-bearing motor:





Centred position

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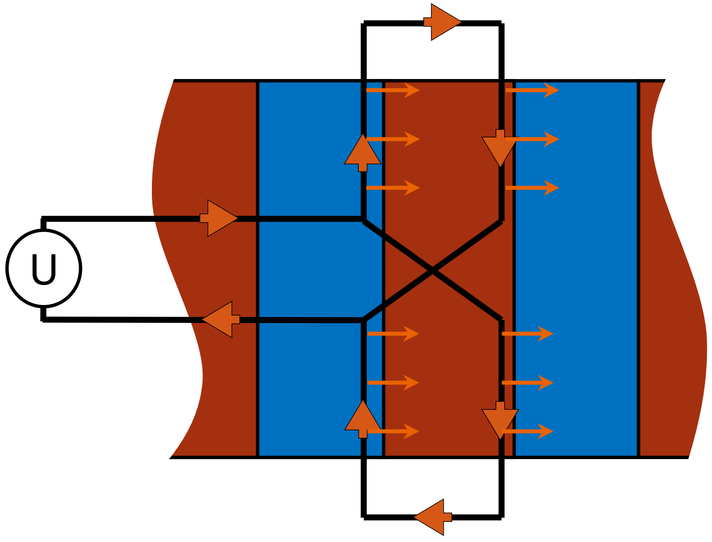

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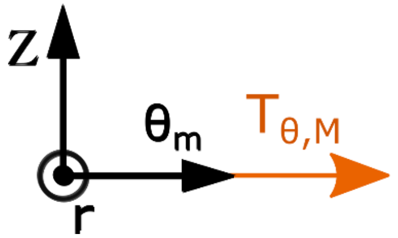

Driving torque

Working principle

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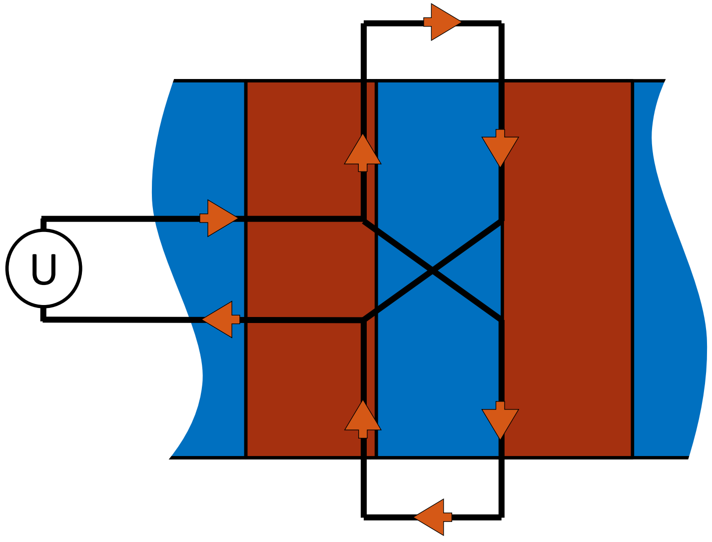
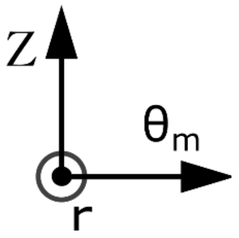


Uncentred position



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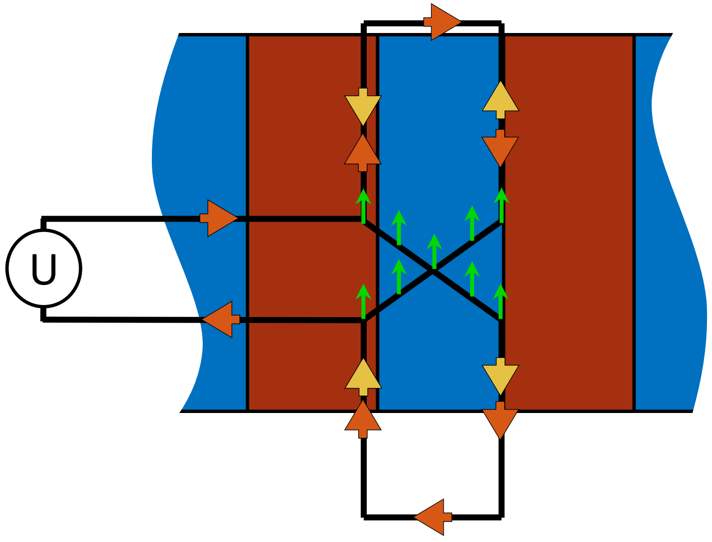

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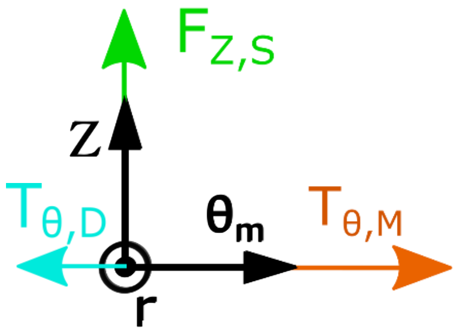
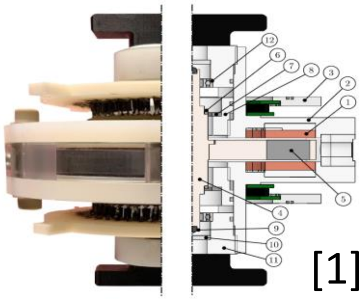


Driving torque
+
Electrodynamic suspension

Research context

Two prototypes of fully passively Electrodynamic Thrust Self-Bearing Motor (ETSBM) :



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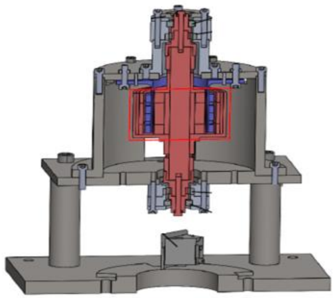


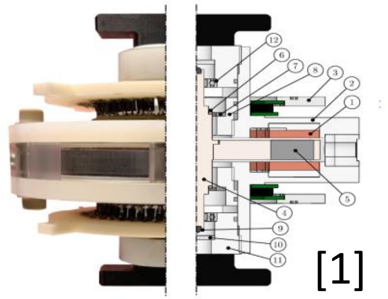
[2]

→ Only Surface Mounted Permanent Magnet are used

→ **Is there better rotor magnetic circuit topology for the ETSBM ?**

Research context

Two prototypes of fully passively Electrodynamic Thrust Self-Bearing Motor (ETSBM) :



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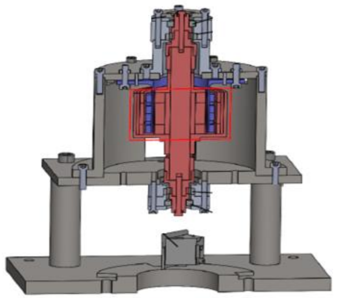

[2]

Only Surface Mounted Permanent Magnet are used

Is there better rotor magnetic circuit topology for the ETSBM ?

Research context

Is there better rotor magnetic circuit topology for the ETSBM ?

→ Development of an electromechanical model which takes into account the presence of ferromagnetic materials

→ Comparison of ferromagnetic circuits for ETSBM

✓ To be published

Presentation content

- Methodology
- Investigated topologies
- Performance criteria
- Results

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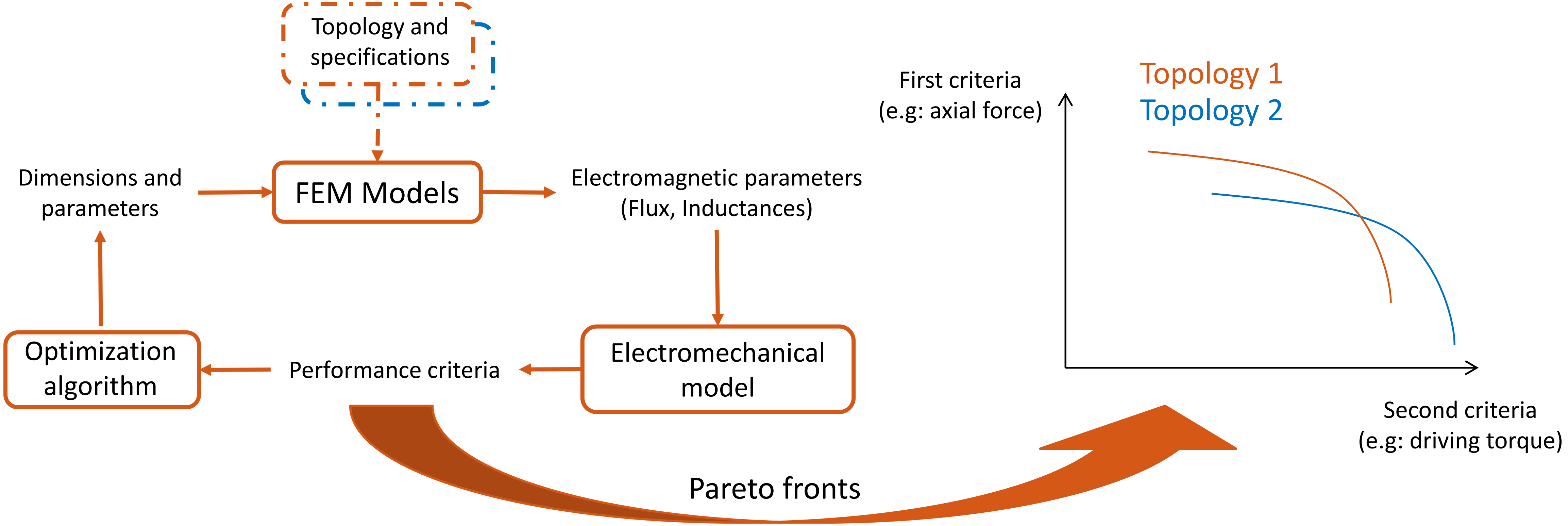
Methodology



Presentation content

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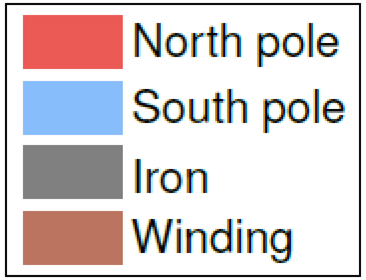
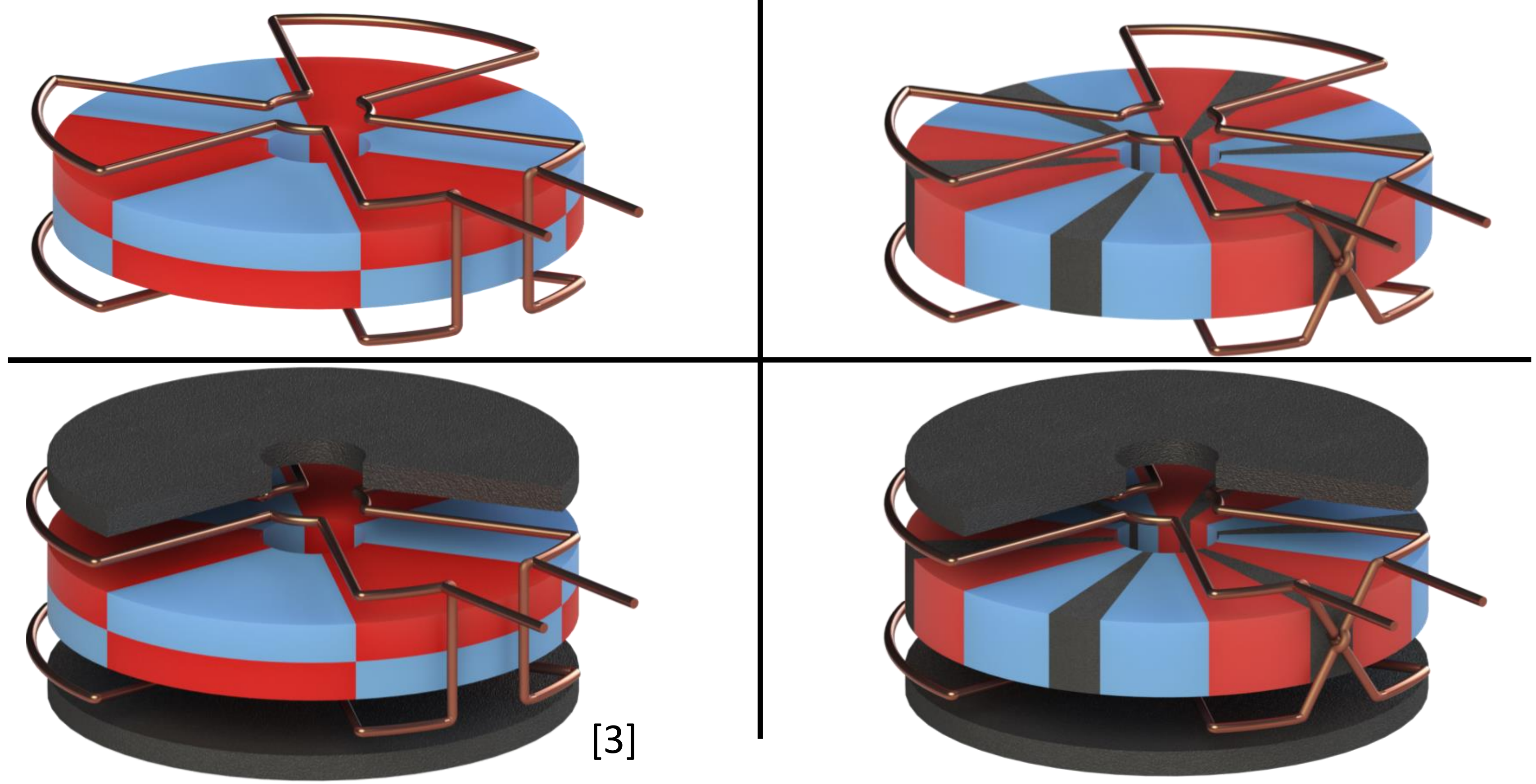


Investigated topologies

Surface Mounted Permanent Magnet (SMPM) | Spoke Type Permanent Magnet (STPM)

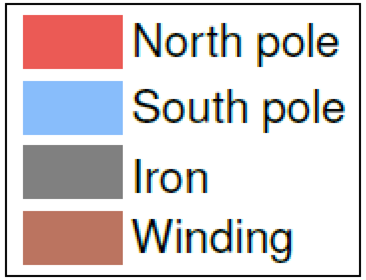
Without Back-Iron (BI)

With BI



[3]

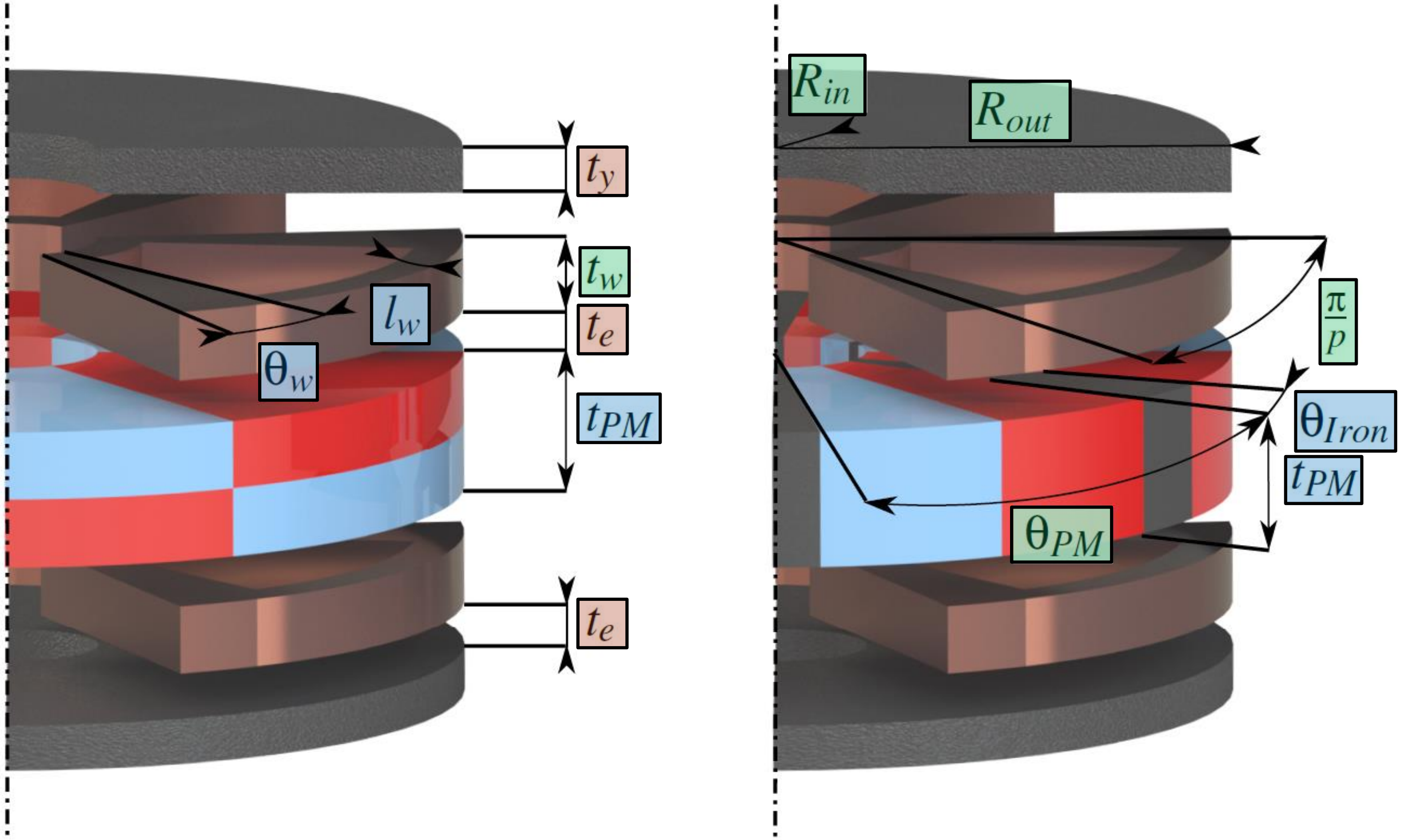
Machine parameters



Optimization parameters :
- Radius
- Pole pair number
- Winding thickness
- Angular proportion of PM

Fixed dimensions
- Volume of PM
- BI thickness
- Airgap

Dependent parameters
- Rotor thickness
- Winding dimensions
- Angular proportion of iron



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Performance criteria

Electromechanical model which takes into account the impact of ferromagnetic materials

1) Total torque developed by the motor

$$T_\theta = \sqrt{\frac{3}{2}} p \cdot I_{M,q} K_\theta + p \cdot \frac{I_{M,q} I_{M,d}}{2} \cdot (L_{M,d} - L_{M,q}) + T_{\theta,D}(z^2, \omega)$$

- $\sqrt{\frac{3}{2}} p \cdot I_{M,q} K_\theta$ → Electrodynamic torque
- $p \cdot \frac{I_{M,q} I_{M,d}}{2} \cdot (L_{M,d} - L_{M,q})$ → Reluctant torque
- $T_{\theta,D}(z^2, \omega)$ → Drag torque

Performance criteria

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1) Total torque developed by the motor

$$T_\theta = \underbrace{\sqrt{\frac{3}{2}} p \cdot I_{M,q} K_\theta \quad + \quad p \cdot \frac{I_{M,q} I_{M,d}}{2} \cdot (L_{M,d} - L_{M,q})}_{T_{\theta,M}} \quad + \quad T_{\theta,D}(z^2, \omega)$$

The torque is computed :

- For fixed Joule losses
- In centred position
- No current in the d-axis

Performance criteria

Electromechanical model which takes into account the impact of ferromagnetic materials

2) The total axial force depends on the position -> An axial stiffness can be defined :

$$k_z = \frac{\omega^2}{\omega_e^2 + \omega^2} \cdot \left(\frac{3K_{\theta,z}^2}{L_{S,d}} + \sqrt{6} \cdot K_{\theta,z} \cdot \frac{L_{d,z}}{L_{S,d}} \cdot I_{M,d} + \frac{L_{d,z}^2}{2L_{S,d}} \cdot I_{M,d}^2 + \frac{L_{q,z}^2}{2L_{S,q}} \cdot I_{M,q}^2 \right)$$

Electrodynamic term

Cross term

Reluctant term

Evolution with the rotation speed

$$\omega_e = \frac{R}{p\sqrt{L_{S,d} \cdot L_{S,q}}}$$

Performance criteria

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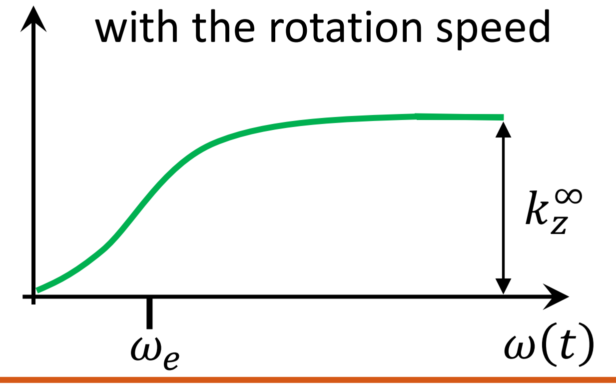
Two elements define a good suspension performance :

- A large asymptotic stiffness k_z^∞ ← Chosen criteria
- A small electrical pole ω_e

Computed in the same conditions as the torque



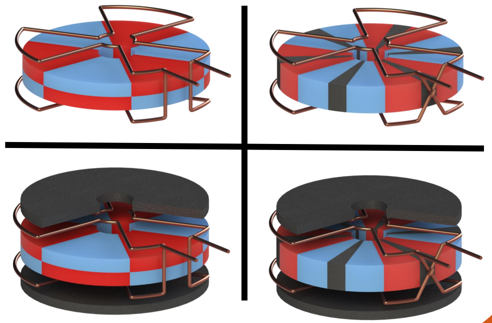
Optimization process : Summary

Bi-objective optimization :

- Maximizing the driving torque $T_{\theta,M}$
- Maximizing the asymptotic stiffness k_z^{∞}

4 Topologies :

	SMPM	STPM
Without BI		
With BI		



Fixed parameters :

- Joule losses : 12,5 [W]
- Volume of permanent magnet : 5cm³
- Load angle : 90° (All the current is injected on the q-axis)

Geometric parameters:

- Pole pair number
- Inner and outer radius
- Winding thickness
- Angular proportion of PM for STPM

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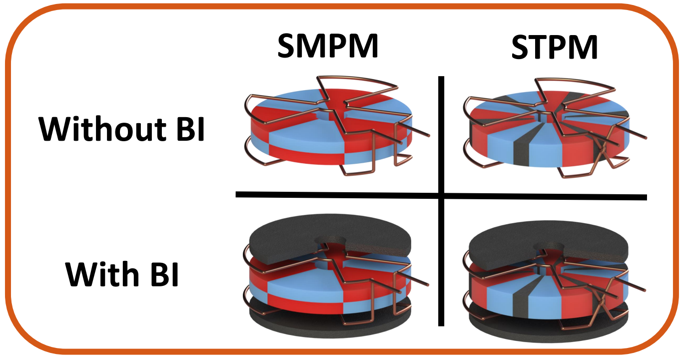
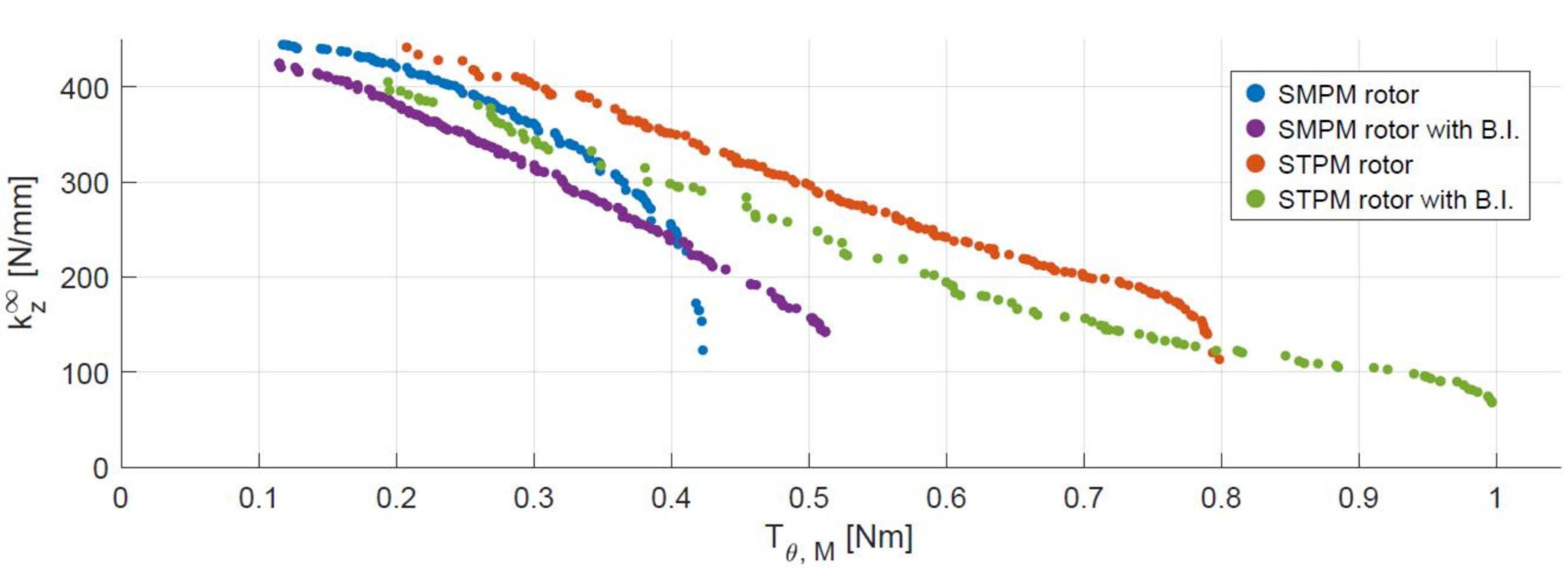


Optimisation Results



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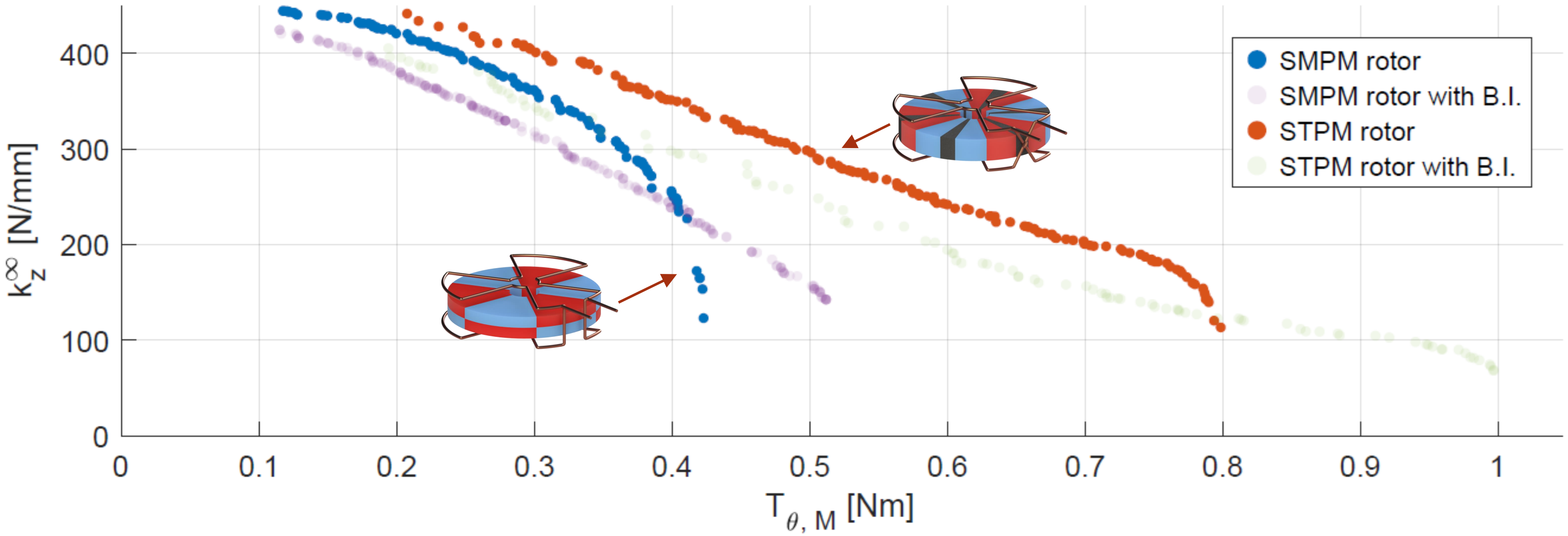
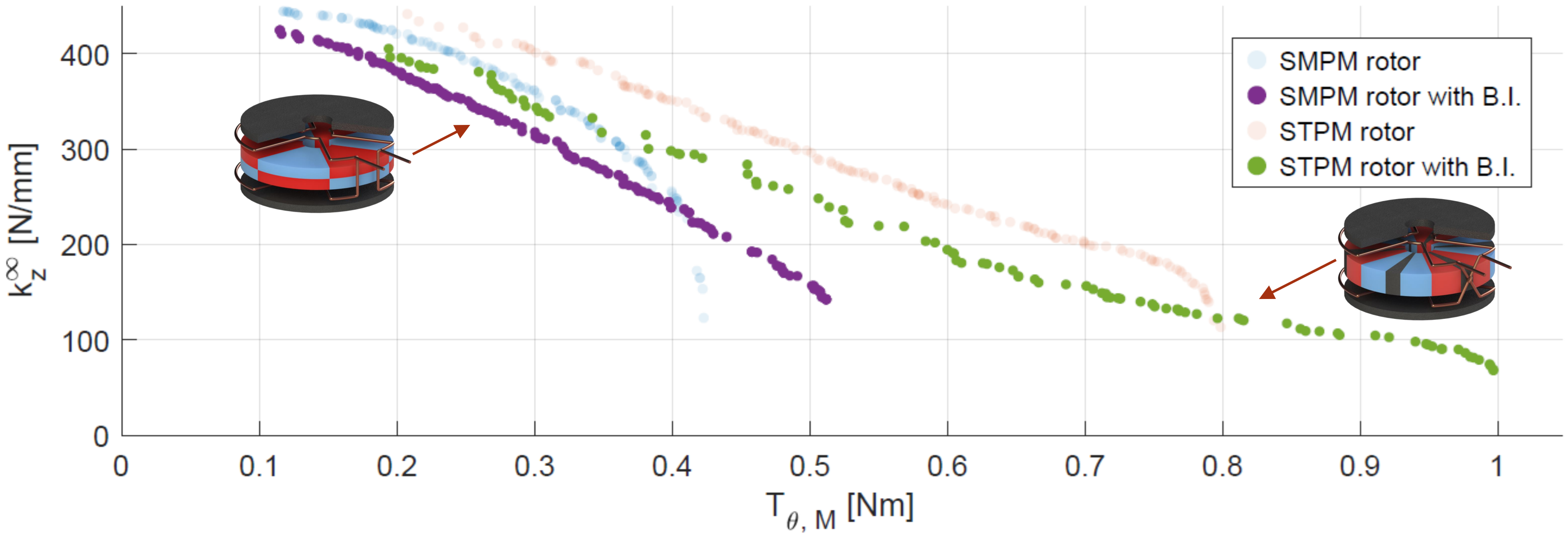


<u>SMPM versus STPM :</u>

- Same range of stiffness
- Higher and wider torque range
- STPM reaches torque two times bigger than SMPM

Optimisation Results



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<u>SMPM versus STPM, both with BI :</u>

- Same observations
- Range of stiffness reachable by STPM slightly smaller than SMPM

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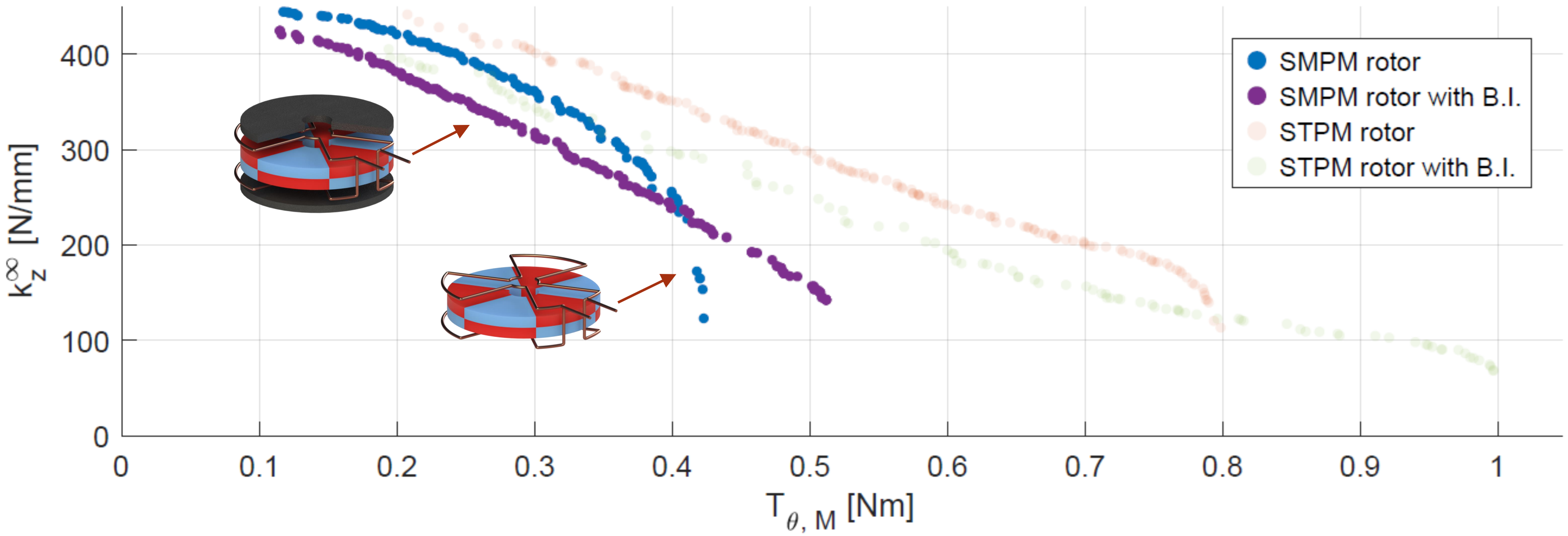

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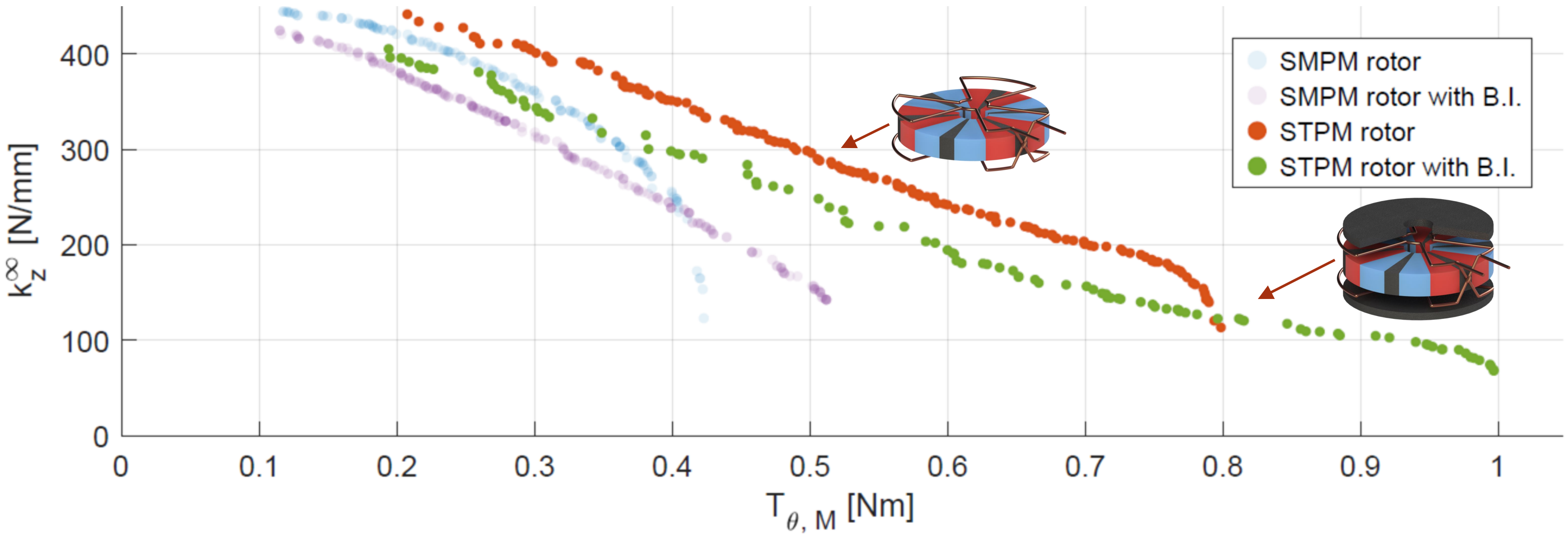
Impact of BI for both topologies:
- Reduce the asymptotic stiffness for low torque range
- Maintain a better stiffness for high torque range
- Allow to reach higher torque range for both topologies

Optimisation Results



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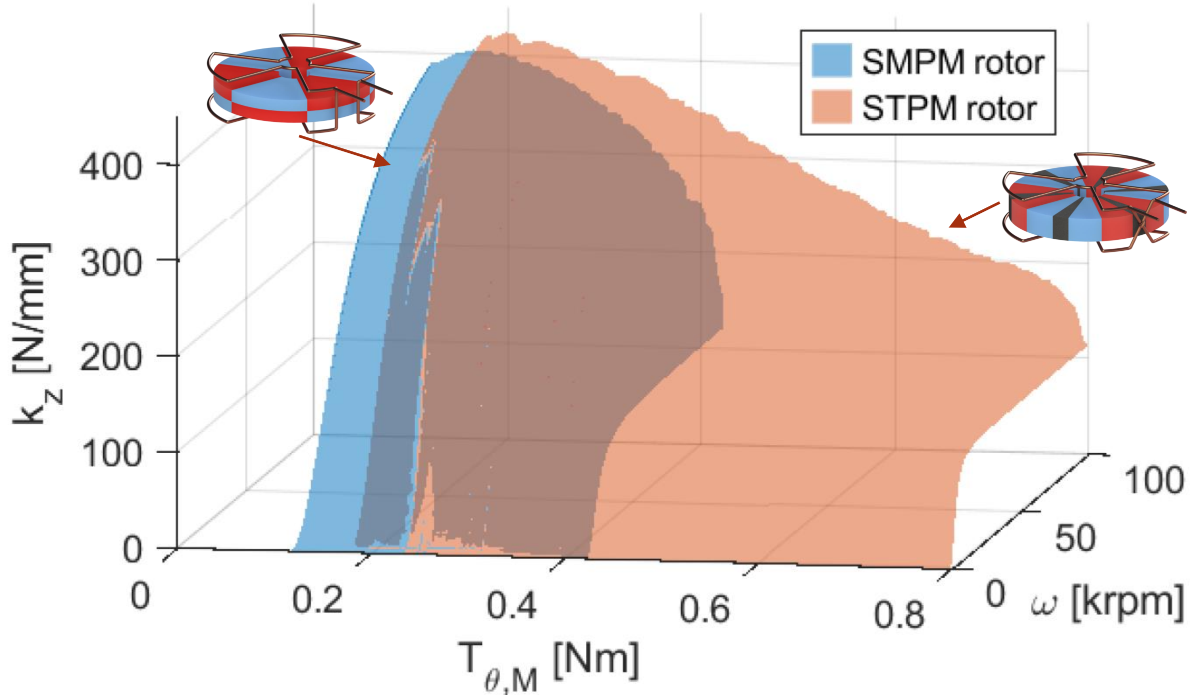
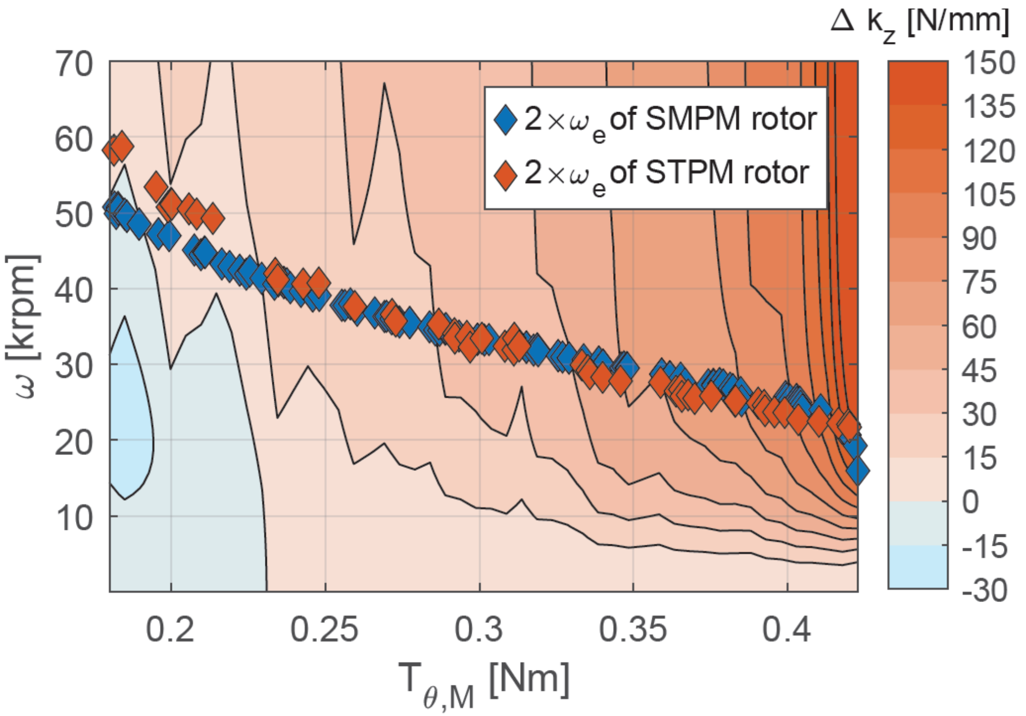
Comparison on the full speed range

Topologies without Back-Iron :





Comparison on the full speed range

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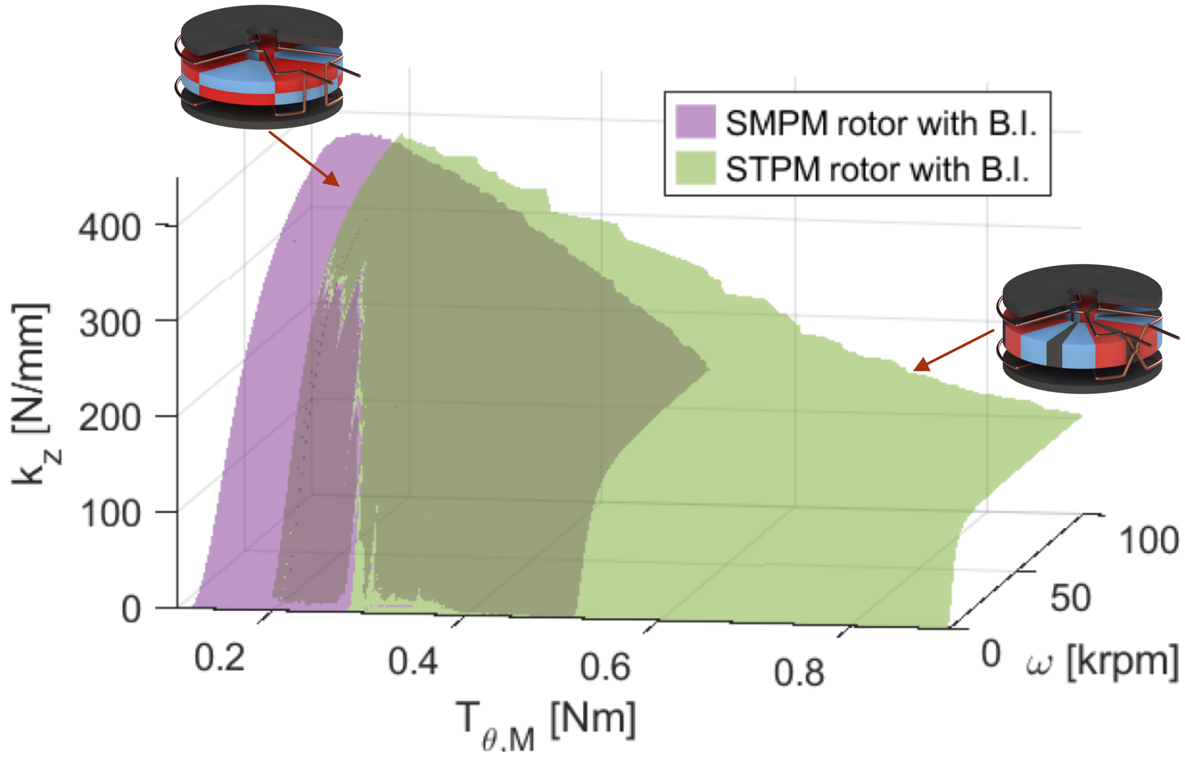

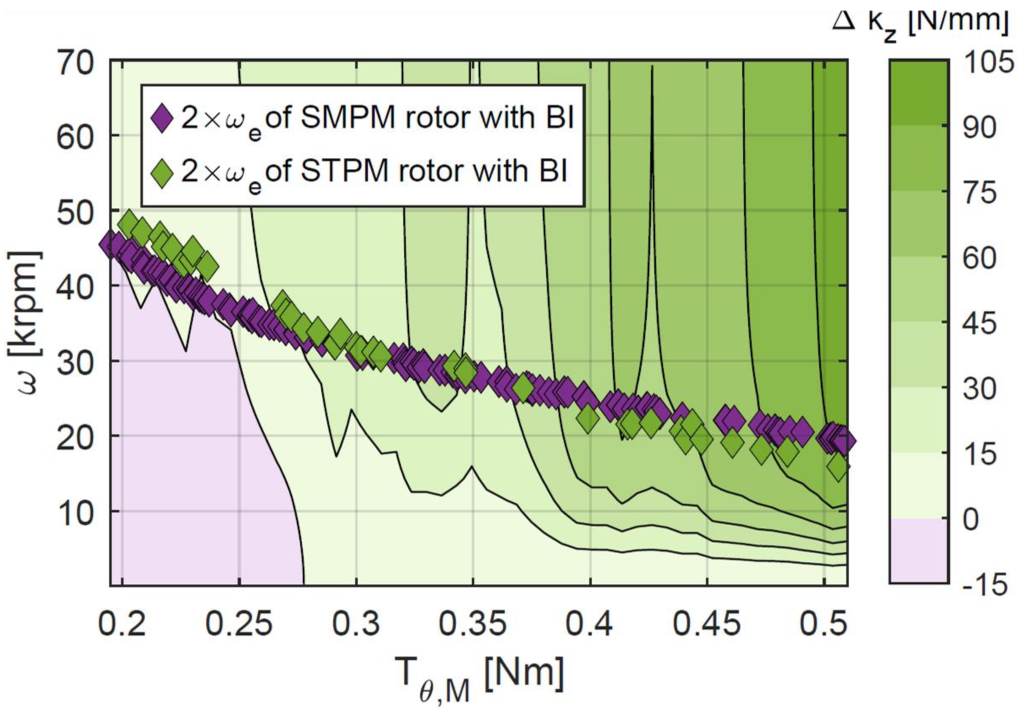

Conclusion

Purpose of research

Comparison of different magnetic circuit topologies for an ETSBM

Results

Topologies with ferromagnetic materials:

- Allow to reach higher torque range.
- Provide better suspension on the full speed range for almost all cases.

What's next

Further research:

- Impact of the d-axis current
- PM assisted synchronous reluctant motor (PMaSynRel)

Thank you for your attention !

References

[1] Van Verdeghem, J., & Dehez, B. (2020, October). Fully passively levitated self-bearing machines with combined windings. In *2020 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 254-261). IEEE.

[2] Rubio, G. C., Hothur Komal, V. C., Fujii, Y. & Chiba, A. (2023), ‘Experimental Verification of Passive Axial Electrodynamic Suspension in a Bearingless Motor’, IEEE Open Journal of Industry Applications pp. 1–12.

[3] Van Verdeghem, J., Robert, A., Herrman, S. & Dehez, B. (2022), Impact of Ferromagnetic Yokes on Axial Flux Passively Levitated Self-Bearing Machines, in ‘2022 25th International Conference on Electrical Machines and Systems (ICEMS)’, pp. 1–6

Thank you for your attention !