UCLouvain
Institute of Mechanics,
Materials and Civil Engineering

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FREEDOM TO RESEARCH

Stabilization of Passive Self-Bearing Motors Through D-axis Current Injection

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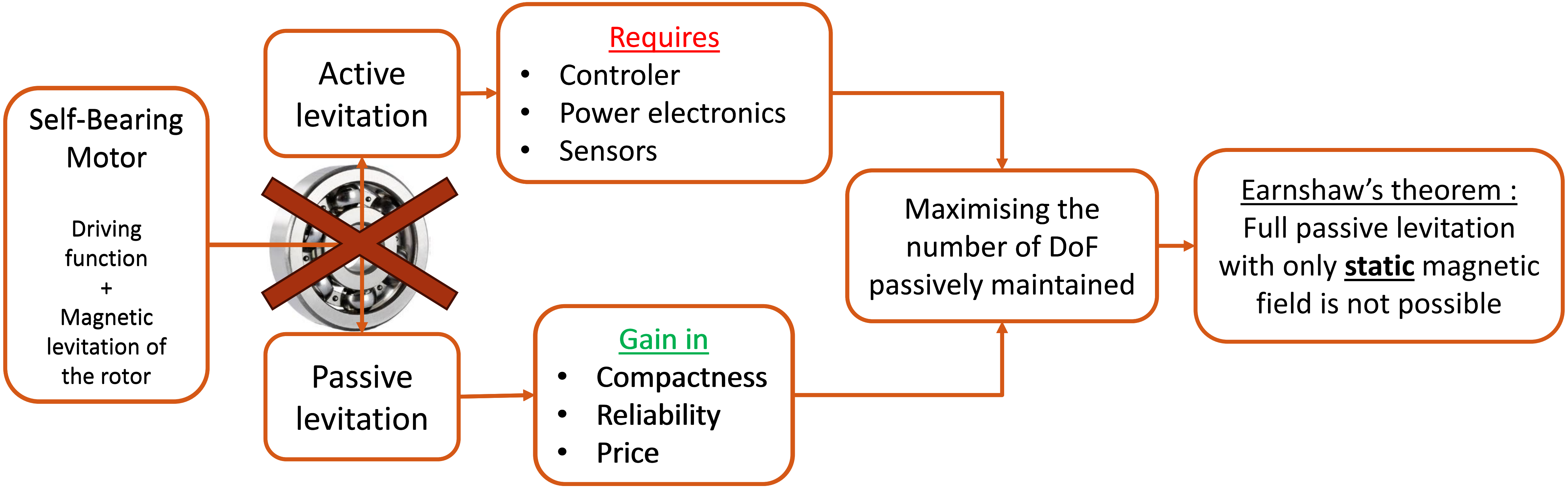
INTERNATIONAL SYMPOSIUM ON POWER ELECTRONICS, ELECTRICAL DRIVES, AUTOMATION AND MOTION (**SPEEDAM**)

Research context



Research context

<u>Earnshaw's theorem :</u>
Full passive levitation with only **<u>static</u>** magnetic field is not possible

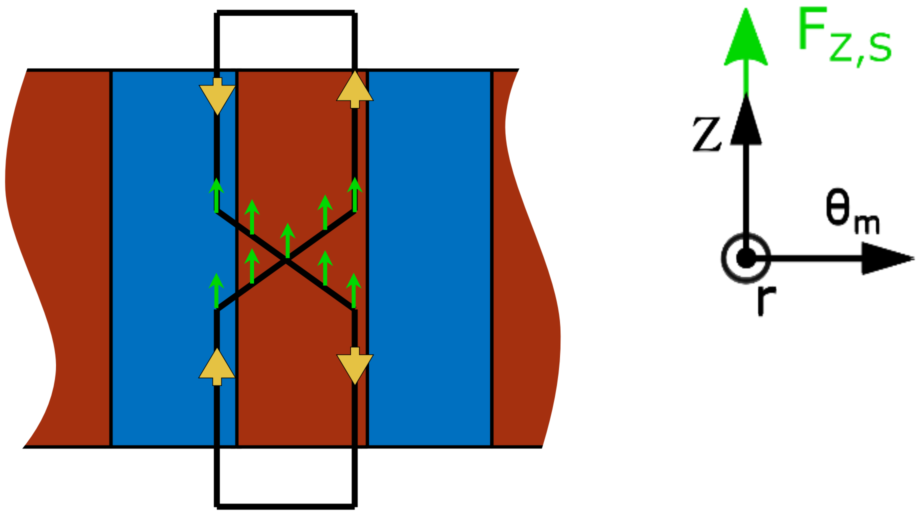
→

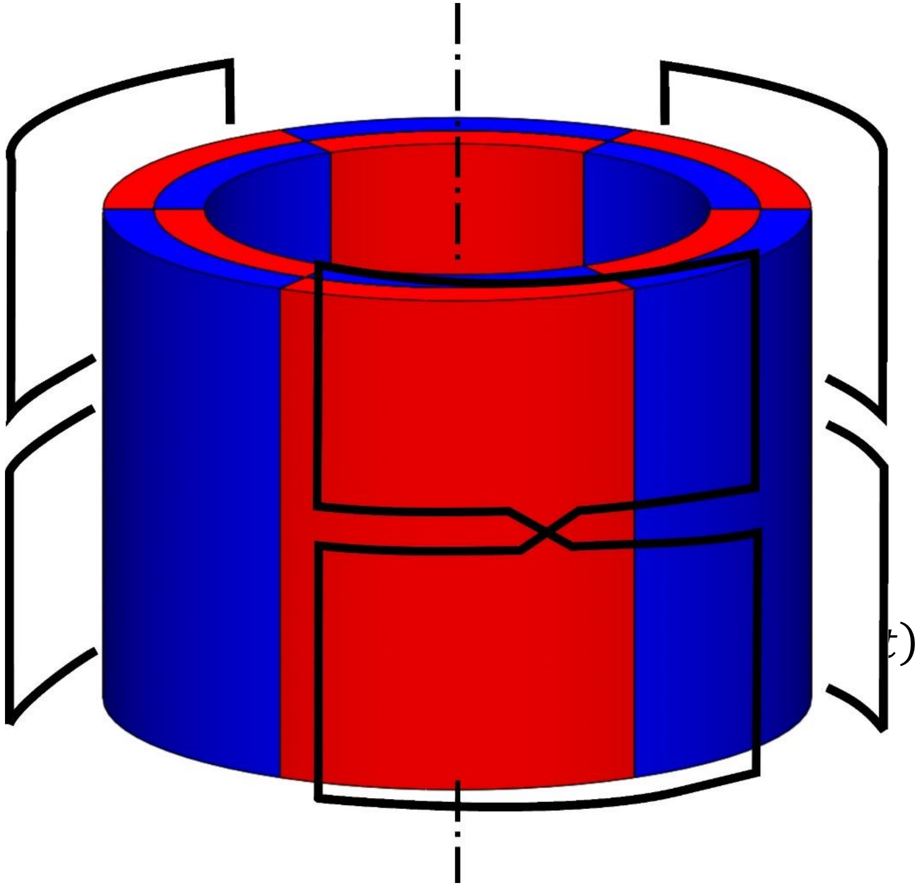
<u>Electrodynamic suspension :</u>
Bypass Earnshaw's theorem by using a <u>rotating</u> magnetic field

→

How does it work ?

How does the electrodynamic thrust bearing work ?

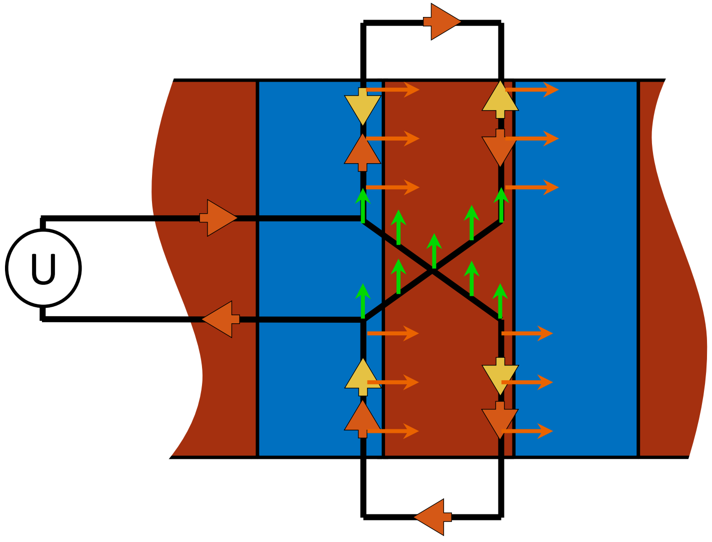




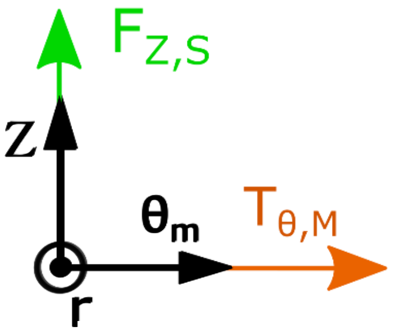
*only one phase is represented

From the thrust bearing to the motor

<u>Connection of a power supply:</u>



Off-Centered position



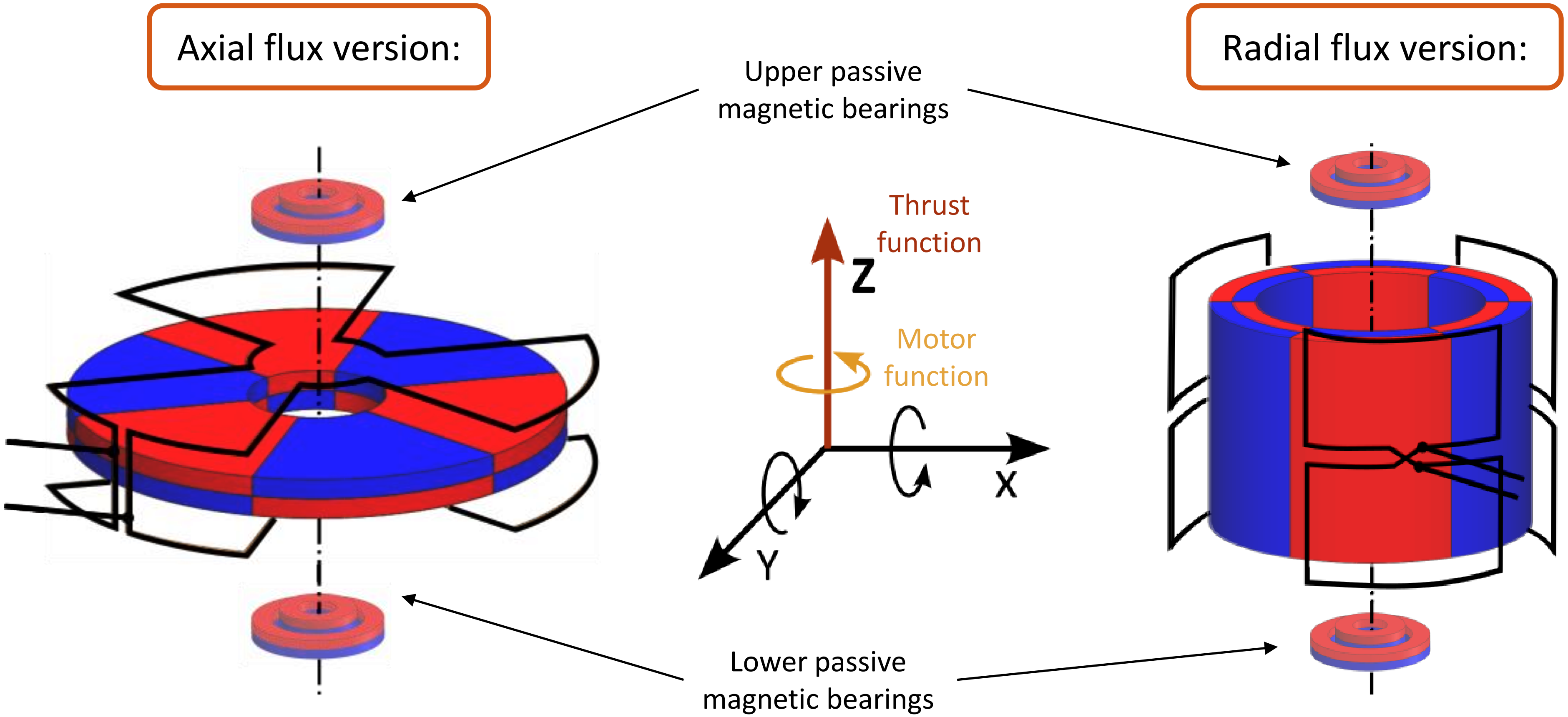
Driving torque

+

Electrodynamic suspension

*only one phase is represented

Reach the fully passive levitation



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Presentation content

- **Stability problem**
- **Damping principle**
- **Damping strategy implementation**
- **Damping gain design**
- **Case study**

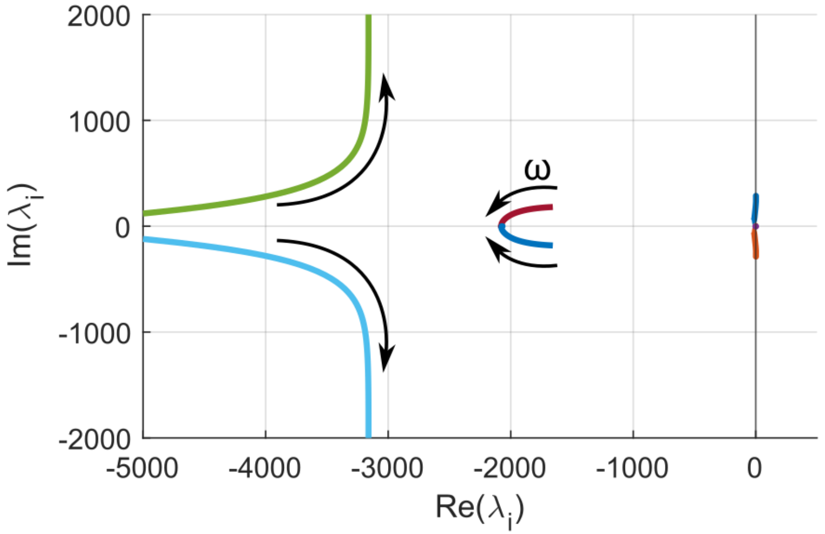
Stability problem

$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{x}) \cdot \mathbf{x} + \mathbf{B}(\mathbf{x}) \cdot \mathbf{u} + \mathbf{C} \cdot \mathbf{v}$$

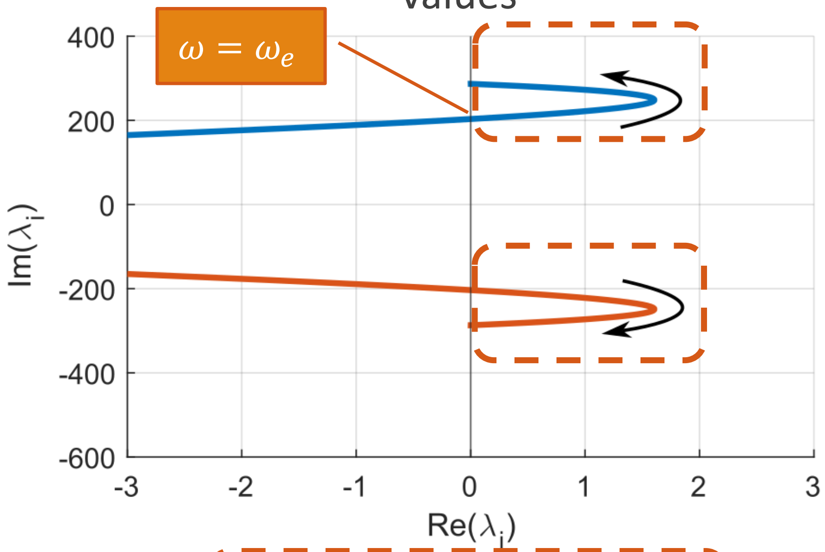
Linearisation around an equilibrium point

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A} \cdot \tilde{\mathbf{x}} + \mathbf{B} \cdot \tilde{\mathbf{u}} + \mathbf{C} \cdot \tilde{\mathbf{v}}$$

Evolution of the eigen values with the rotation speed



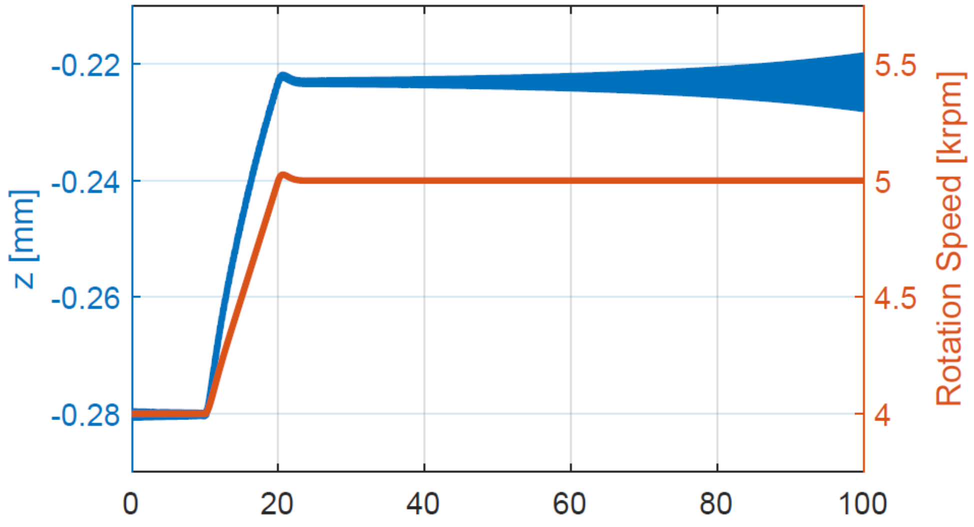
Zoom on the critical eigen values



Axial instability

Stability problem

Unstable levitation if $\omega > \omega_e$



Linear speed increase, from 4 to 5 [krpm] to exceed the electrical pole $\omega_e = 4{,}560\ [rpm]$ and enter in the zone of instability.

Damping allows to stabilize the machine on the whole speed range

Existing solutions:

External damping via

- Eddy current dampers
- Active bearings dedicated to damping
- Dampers placed on the stator and the frame

Is it possible to stabilize the machine without external device ?

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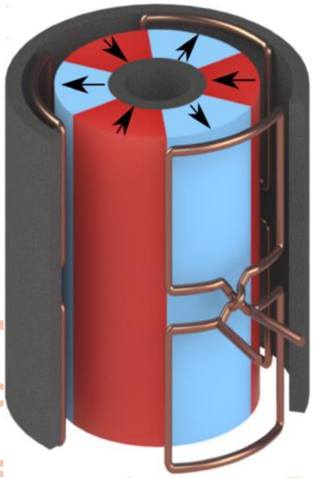
Damping strategy principle

Is it possible to stabilize the machine without external device ?

Some topologies can have reluctant effects



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

$$F_z \approx -z \cdot \frac{\omega^2}{\omega_e^2+\omega^2} \cdot \left(A + B \cdot I_{M,d} \right)$$

Proportional to the axial shift

Electrodynamic term

Cross term

Reluctant term

Evolution with the rotation speed

Possibility to modulate the suspension force

$I_{M,d}$ current can be used to create damping

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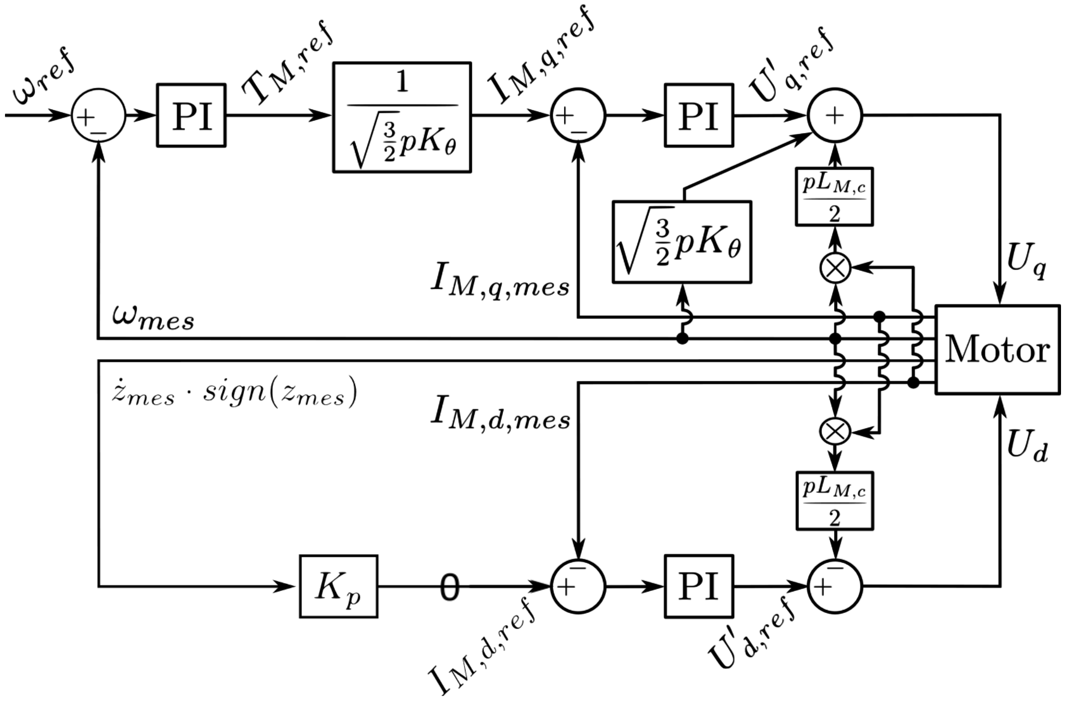
Damping strategy implementation

I_D current is initialy not exploited



$$F_z \approx -z \cdot \frac{\omega^2}{\omega_e^2+\omega^2} \cdot \left(A + \boxed{B \cdot I_{M,d}}\right)$$

$I_{M,d}$ current can be used to create damping

$I_{M,d} = K_p \cdot \dot{z} \cdot sign(z)$

Ensure $F_z >< \dot{z}$

Which value of K_p allows to stabilises the motor on the whole speed range ?

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Damping gain design

By neglecting the purely reluctant component, the expression of the force becomes:

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

$$I_{M,d} = K_p \cdot \dot{z} \cdot sign(z)$$

$$F_z = -z \cdot \frac{\omega^2}{\omega_e^2+\omega^2} \cdot \left(\frac{3K_{\theta,z}^2}{L_{S,c}}\right) - \dot{z} \cdot \boxed{\frac{\boldsymbol{\omega^2}}{\boldsymbol{\omega_e^2+\omega^2}} \cdot |z| \cdot \left(\sqrt{6}K_{\theta,z}\right.} \left.\frac{L_{z,c}}{L_{S,c}} \cdot K_p\right)$$

$$F_z = -z \cdot k_z - \dot{z} \cdot \mathrm{C}_{\mathrm{z},\mathrm{I}_{\mathrm{M,d}}}$$

How to characterize a damping coefficient which depends on the speed ω and the position z ?

Damping gain design

$$C_{z,I_{M,d}} = \boxed{\frac{\omega^2}{\omega_e^2+\omega^2} \cdot |z|} \cdot \left(A_2 \cdot K_p\right)$$

Considering a equilibrium point with a given external force F_e

$$|z| = \frac{|F_e|}{k_z} \quad \text{with} \quad k_z = \frac{\omega^2}{\omega_e^2+\omega^2} \cdot A_1$$

$$C_{z,I_{M,d}} = \frac{|F_e|}{A_1} \cdot \left(A_2 \cdot \boxed{K_p}\right)$$

Minimal damping for the stability:

$$C_{z,min} = \frac{k_{tot}^{\infty} \cdot L_{s,c}}{16R}$$

Threshold gain which ensures the stability:

$$K_p = \frac{\alpha}{|F_e|}$$

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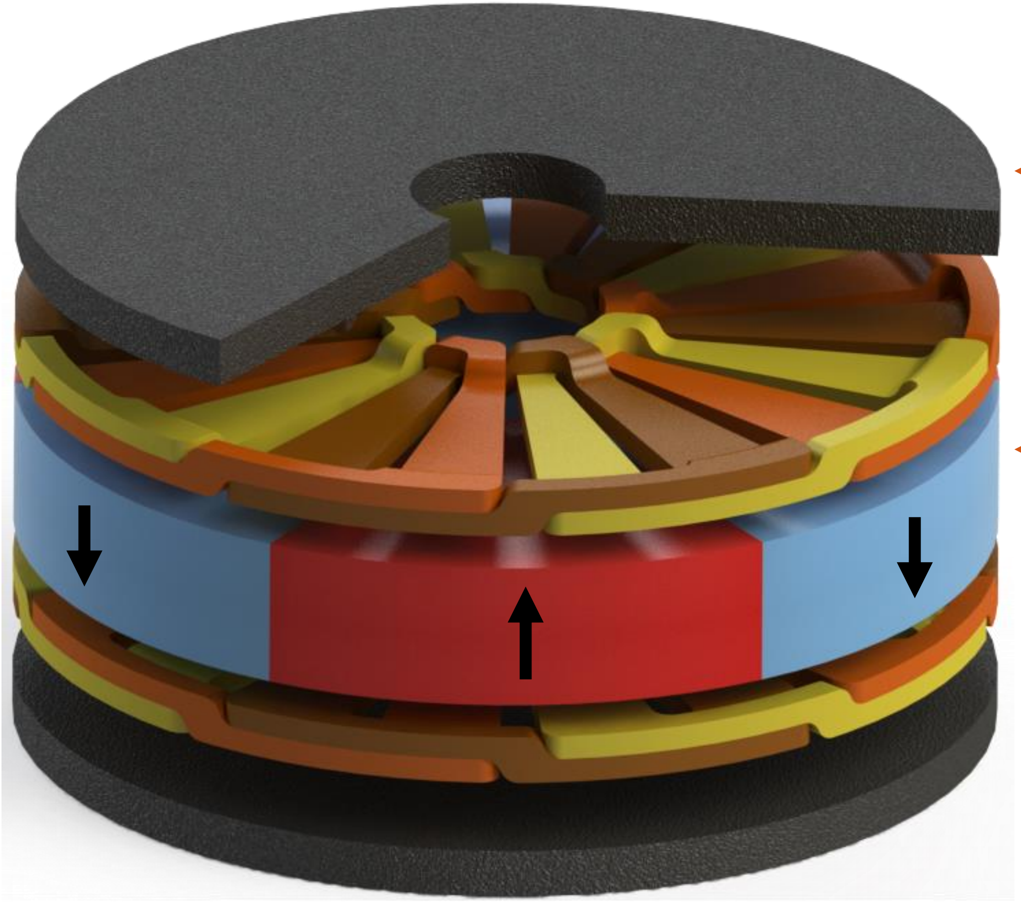
Selection of a motor



Axial flux surface mounted permanent magnets rotor

Three-phase winding

Ferromagnetic yoke connected to the rotor

Main characteristics

Driving torque : 0,4 [Nm]

External radius : 60 [mm]

Total axial length : 34 [mm]

Number of pole pair : 4

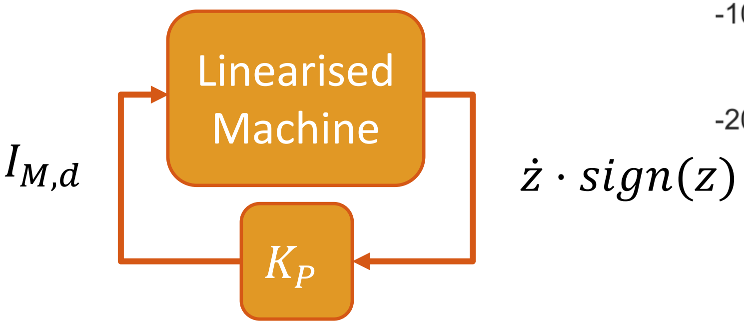
Evolution of the eigen values

Threshold gain which ensures the stability:
$$K_p = \frac{\alpha}{|F_e|}$$

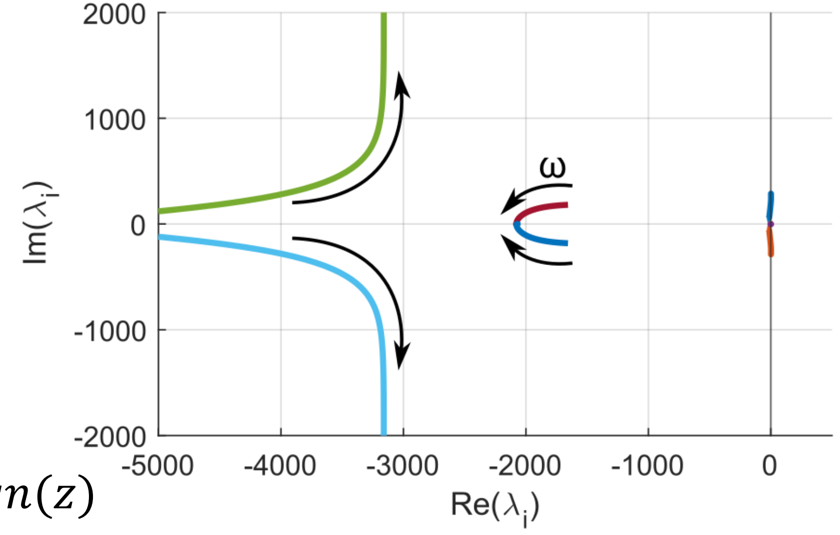
$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{x}) \cdot \mathbf{x} + \mathbf{B}(\mathbf{x}) \cdot \mathbf{u} + \mathbf{C} \cdot \mathbf{v}$$

Linearisation around an equilibrium point

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A} \cdot \tilde{\mathbf{x}} + \mathbf{B} \cdot \tilde{\mathbf{u}} + \mathbf{C} \cdot \tilde{\mathbf{v}}$$

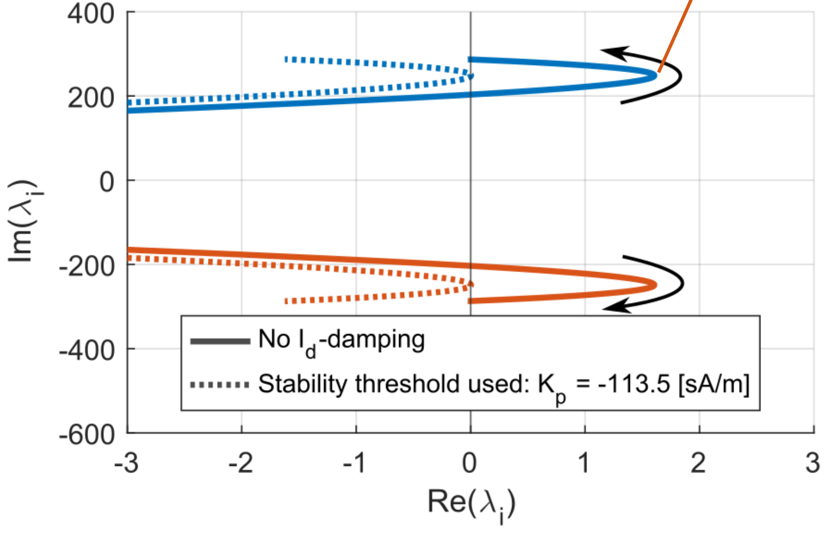


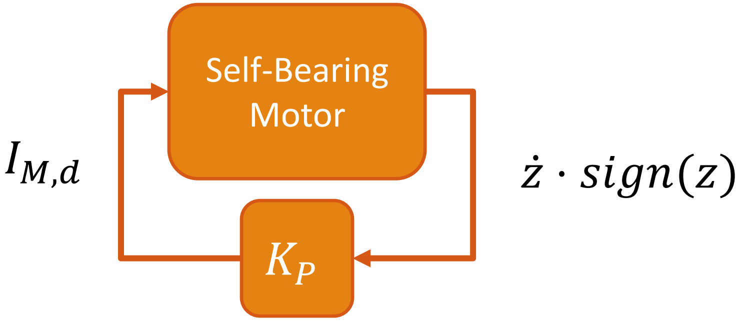
Evolution of the eigen values with the rotation speed



$$\omega = \sqrt{3} \cdot \omega_e$$

Zoom on the critical eigen values

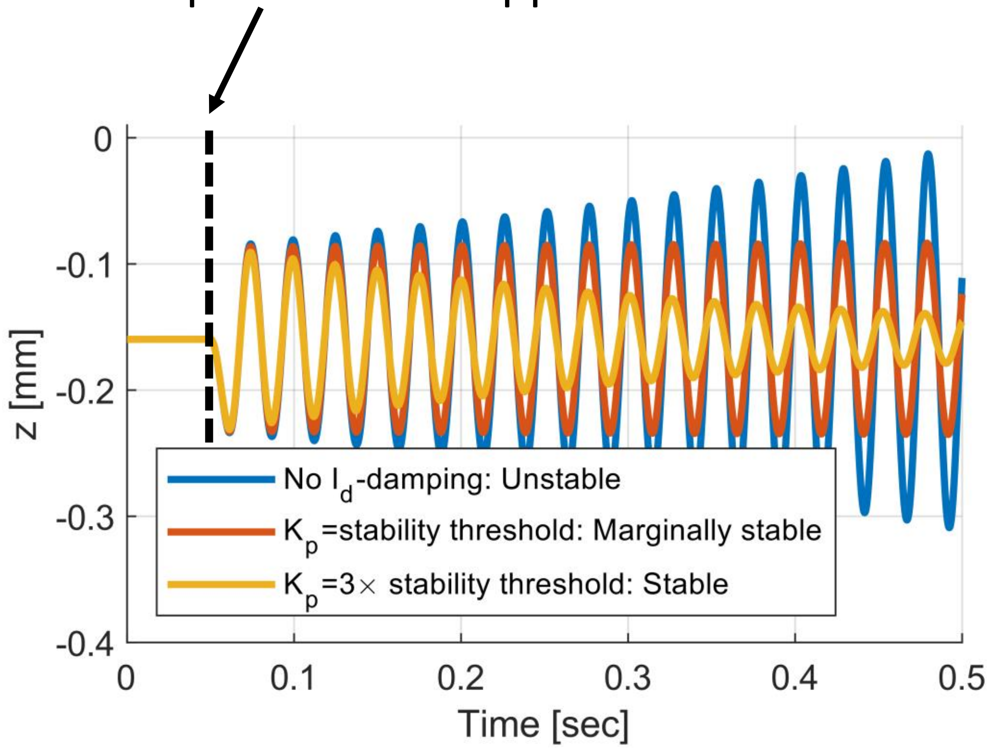


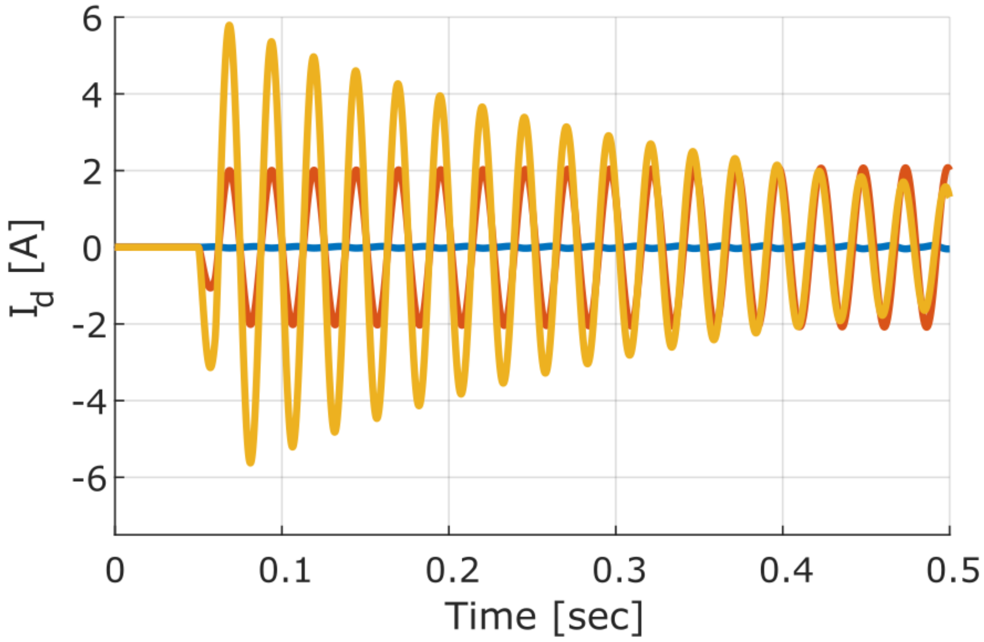


Dynamical study

Dirac of perturbation applied on the rotor at critical rotation speed

$\omega = \sqrt{3} \cdot \omega_e$



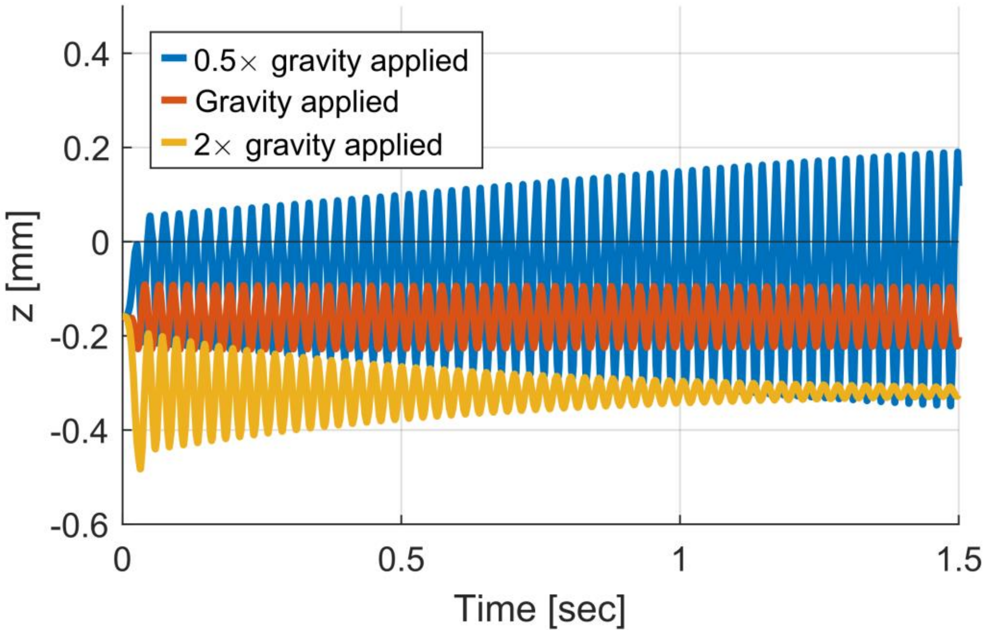


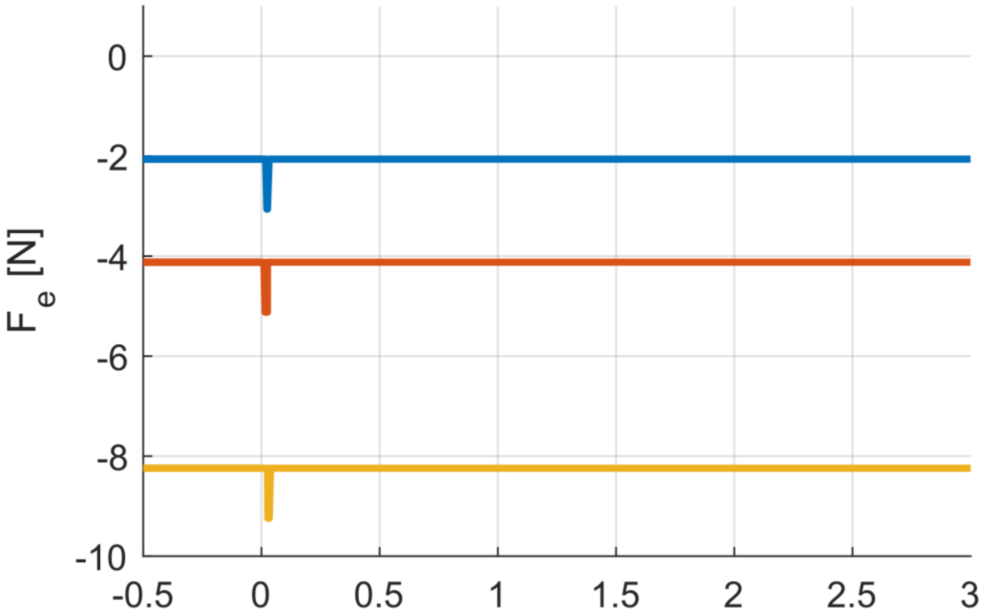
Minimal gain which ensures the stability:

$$K_p = \frac{\alpha}{|F_e|}$$

Variation of the equilibrium point

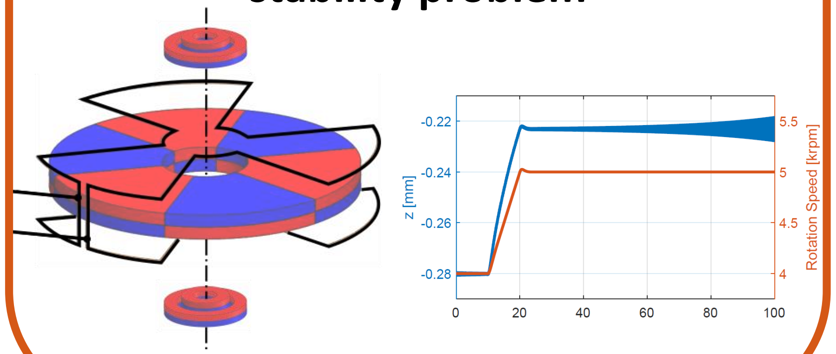
Constant K_p and variation of the real external force



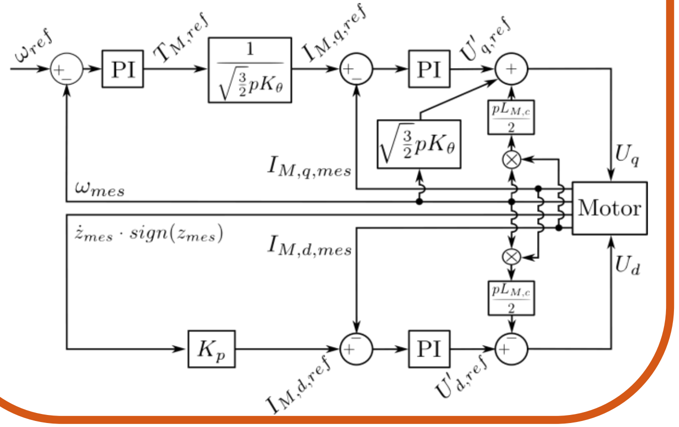


Take-home message

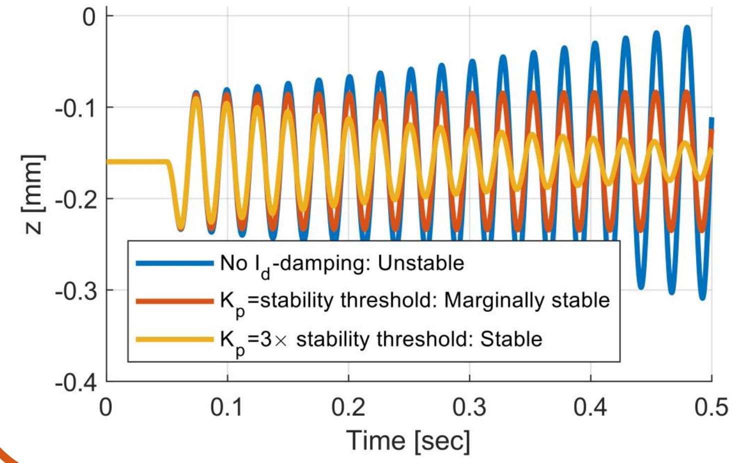
Principle of the electrodynamic self-bearing machine and its stability problem



Damping strategy which does not require additional component except a position sensor



Design methodology which ensures stability on the whole speed range



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