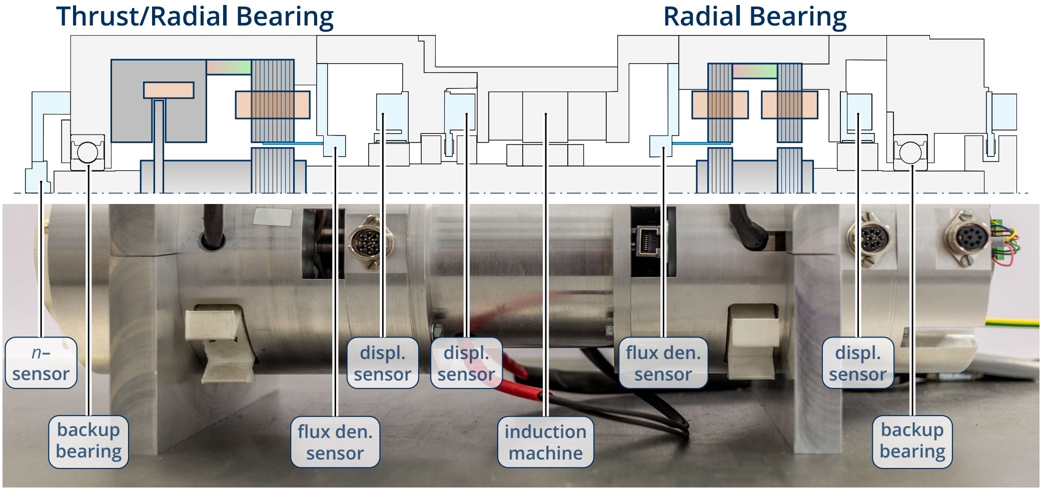
Limitations of Reluctance Networks to Model the Frequency-Dependent Leakage and Fringing Fluxes in Active Magnetic Thrust Bearings

18th International Symposium on Magnetic Bearings

Robert Seifert
VEM GmbH, Dresden, Germany

Lyon, 19th July, 2023

5-axis active magnetic bearing test bench



■ Nonlaminated Core ▥ Laminated Core ■ Coils ■ PMs □ Sensors

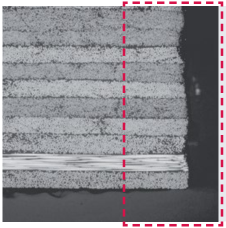
Application: Aerospace

Vibration Assisted Drilling of CFRP–Titanium–Composites

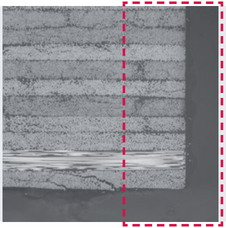
Example: KEBA LeviSpin

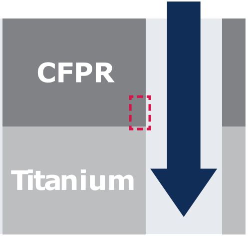
"6D Drilling"

Conventional Drilling



Vibration Assisted Drilling





© LTI Motion GmbH, IWT Bremen, Walter Tools

- **Radial:** Maximization of bearing stiffness
  - Low inductances and voltages, fast controllers
  - Maximization of bandwidth of current control 4…5 kHz ➧ **Eddy currents**
- **Axial:** 100 Hz–vibration with 10 μm precision ➧ **Eddy currents**

How do eddy currents affect the macroscopic leakage and fringing flux distribution?

Active Magnetic Thrust Bearing

Working Principle

Combined active radial- and thrust bearing

Focus: Thrust bearing with nonlaminated core

- Homopolar pm–bias flux Φ_b
  - Constant for small displacements
  - Evenly distributed between both halves of the thrust bearing, back iron over radial bearing
- Homopolar control flux Φ_x with toroidal coil and control current *i*
  - Linear behavior achieved by differential principle::

$$F = k_{\text{Geo}} \cdot \Phi_v \cdot \Phi_x$$

$$\Rightarrow \boxed{F \sim \Phi_x}$$

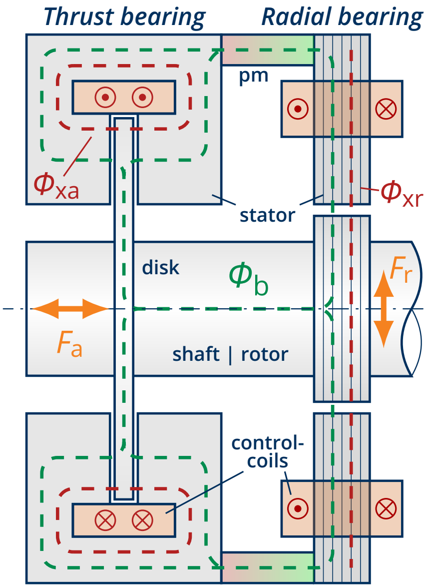


Figure: Cross–section through active magnetic bearing

Active Thrust Bearing
Magnetic Field

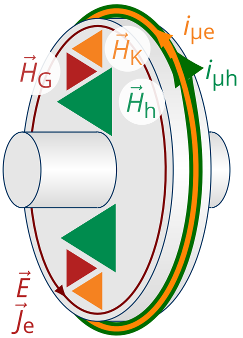
- **Common assumption:** $\boxed{F \sim \Phi_x \sim i}$ with $\boxed{\Phi_x = \frac{L_h}{N} i}$ ➧ **Current control**

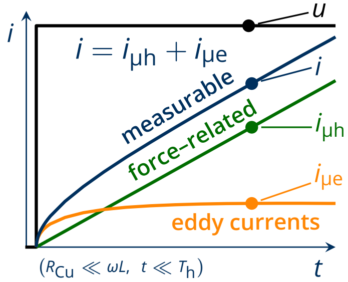
  Condition: *Neglectable eddy currents (for radial bearings w/ laminated cores)*

- **But:** Eddy Currents require additional magnetizing current
  - ➧ Magnetic skin effect caused by eddy currents lowers inductance for high frequencies: $L = \underline{L}_\text{eff}(j\omega)$ and **not** $L = L_h = \text{const.}$

- **Correct:** $\boxed{F \sim \Phi_x \sim i_{\mu h}}\boxed{\not\sim i}$ with $\boxed{\Phi_x = \left|\frac{\underline{L}_\text{eff}(j\omega)}{N}\right| i}$
  - ➧ **Flux control**

- **Problem:** Φ_x is not known to the controller
  - ➧ ***Fractional–order flux estimator***



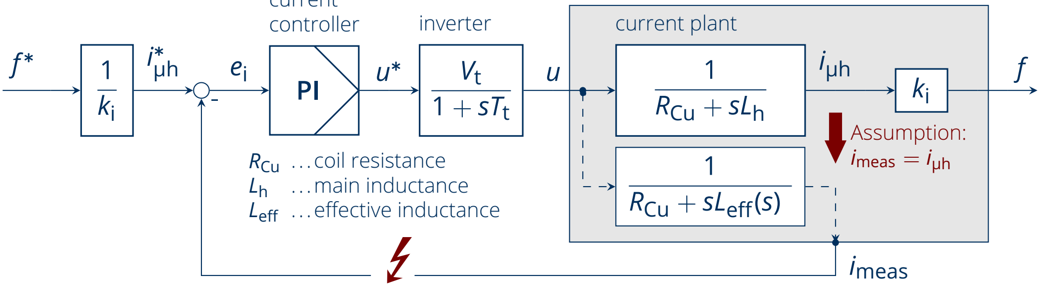


Magnetic Bearing Control

Current control with direct current measurement

- **Problem:** force–generating current $i_{\mu h}$ cannot be measured and is unknown to the controllers
- **Assumption:** $\boxed{i_{\text{meas}} = i_{\mu h}}$ is only valid in quasi–stationary state ~~$f_{\text{eddy currents}} \gg f_{\text{position control}}$ ➡ $L_h \approx L_{\text{eff}}$~~
- **Consequence:** Decrease of dynamic, bandwidth and stability of the position control

bearing: simulation/experiment



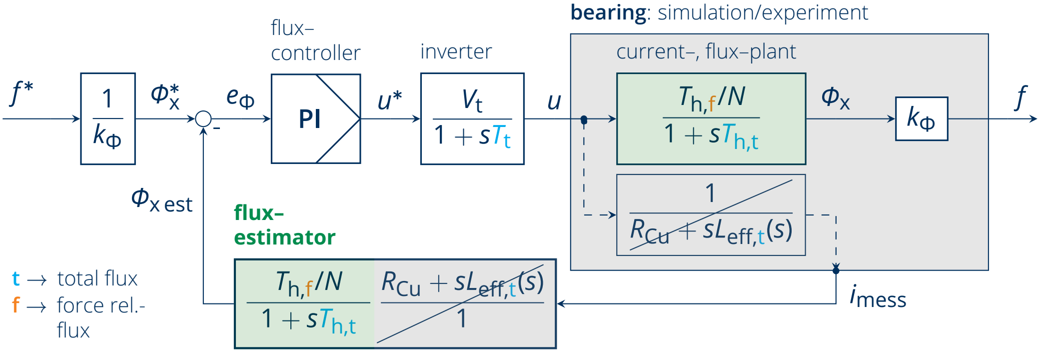
R_{Cu} …coil resistance
L_h …main inductance
L_{eff} …effective inductance

no feedback of force generating current

Magnetic Bearing Control

Flux Control with Flux Estimation

- **Solution:** Determination of flux from measured coil current with flux estimator
- **Ansatz:** Modeling of eddy currents with frequency–dependent *effective inductance* $\underline{L}_{\mathrm{eff}}(j\omega)$
- **Optional:** Consideration of leakage and fringing fluxes (stationary)
- **Controller design:** small time constant T_{t} + large time constant T_{h} ➧ **Amplitude Optimum**



Modeling – What is included?

Effective Inductance

- **Eddy currents:** Solving of diffusion equation

$$B \xrightarrow{\int \mathrm{d}A} \Phi \xrightarrow{N i_x / \Phi} \mathcal{R}_i \xrightarrow{\sum \mathcal{R}_i} \mathcal{R}_\mathrm{eff} \xrightarrow{N^2/\mathcal{R}_\mathrm{eff}} L_\mathrm{eff}$$

➡ Sum of fractional transcendent systems $f(\sqrt{j\omega})$

- **Saturation:** Coefficients of flux estimator cannot be implemented dependent on current load

➡ Choice of pre–defined relative permeability μ_r according to current load point. ➡ ***ISMB17***

- **Hysteresis:** Fractional All–Pass Filter

Frequency–dependent consideration *for single load point*

➡ High effort, little benefit

- **Leakage and fringing fluxes:** reluctance network (RN)

Flux distribution heavily depends on magnetic skin effect

➡ Hardly representable with RN over entire bandwidth ➡ Stationary correction factors?

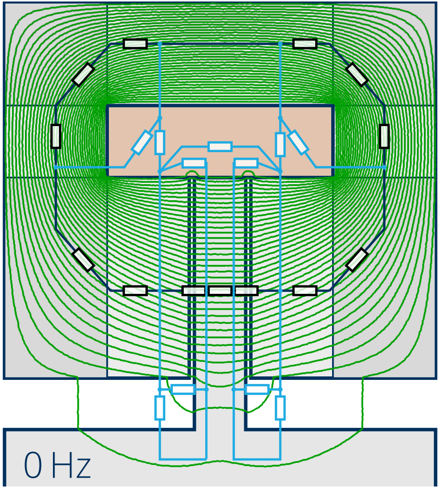
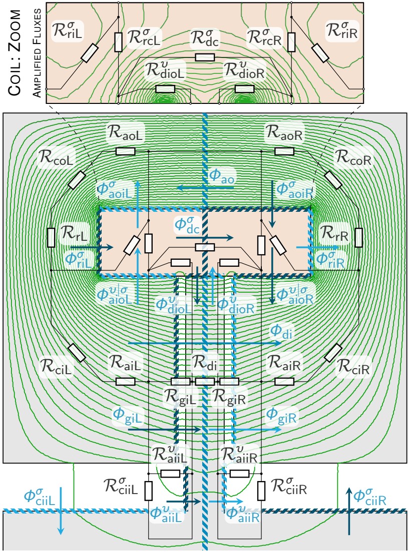
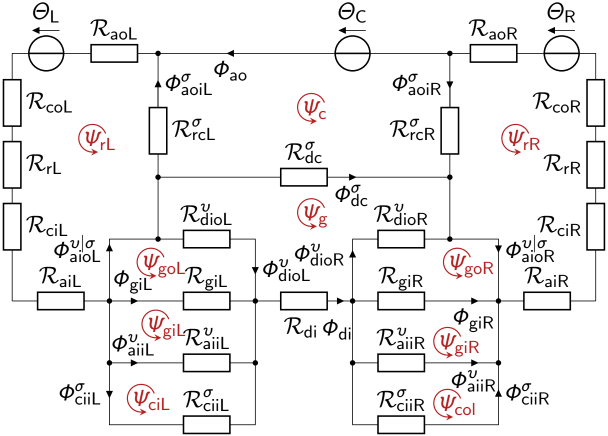


Figure: **Magnetic circuit of thrust bearing separated into part reluctances**

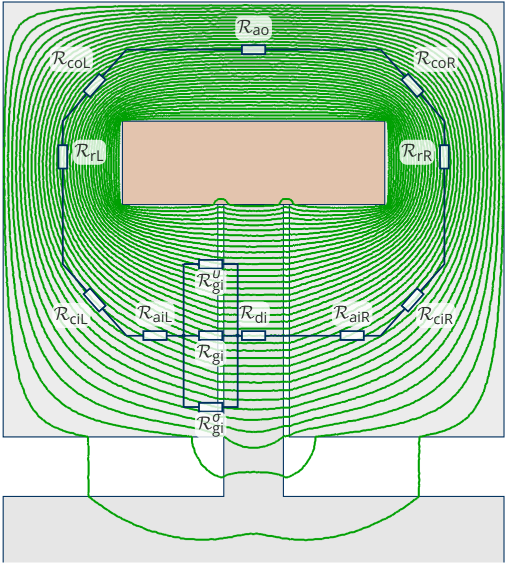
Determination of Full Reluctance Network (Static)



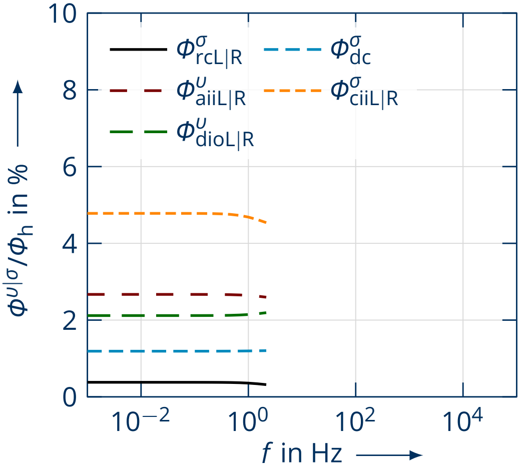
- Identification of all fluxes $\boldsymbol{\Phi}$ by FEA for known mmf $\boldsymbol{\Theta}$
- Analytical calculation of core reluctances (high accuracy)
- Computed of Leakage/fringing reluctances by solving of SLE



Simplification of Full Reluctance Network (Static)



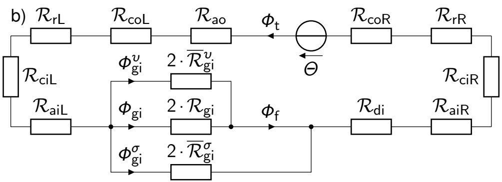
- 0) Static analysis of impact of leakage and fringing flux paths



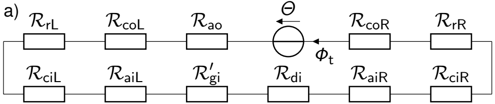
Simplified Reluctance Network (Static)

What is the purpose of the network?

Determination of ***force****:* $L_{\mathrm{h\,f}}$



Determination of ***measurable current****:* $L_{\mathrm{h\,t}}$



- Distinction between total and force-generating flux necessary ➡ flux divider
- Most simple network is possible
- $\underline{L}_{\mathrm{h\,f}} = k_{\mathrm{u\sigma\,f}} \cdot N^2 \frac{\Phi_{\mathrm{f}}}{\Theta} = 1.043 \cdot L_{\mathrm{h}}$
- $\underline{L}_{\mathrm{h\,t}} = k_{\mathrm{u\sigma\,t}} \cdot N^2 \frac{\Phi_{\mathrm{t}}}{\Theta} = 1.098 \cdot L_{\mathrm{h}}$

Conclusions:

➡ **Unexpected:** $k_{\mathrm{u\sigma}} > 1$ ➡ presence of fringing and leakage fluxes actually increases force!

Cause: Fringing more dominant than leakage ➡ Most likely general rule for similar thrust bearings

➡ Both factors $k_{\mathrm{u\sigma\,t}}$ and $k_{\mathrm{u\sigma\,f}}$ differ significantly and should be considered separately!

Frequency–dependent flux density distribution

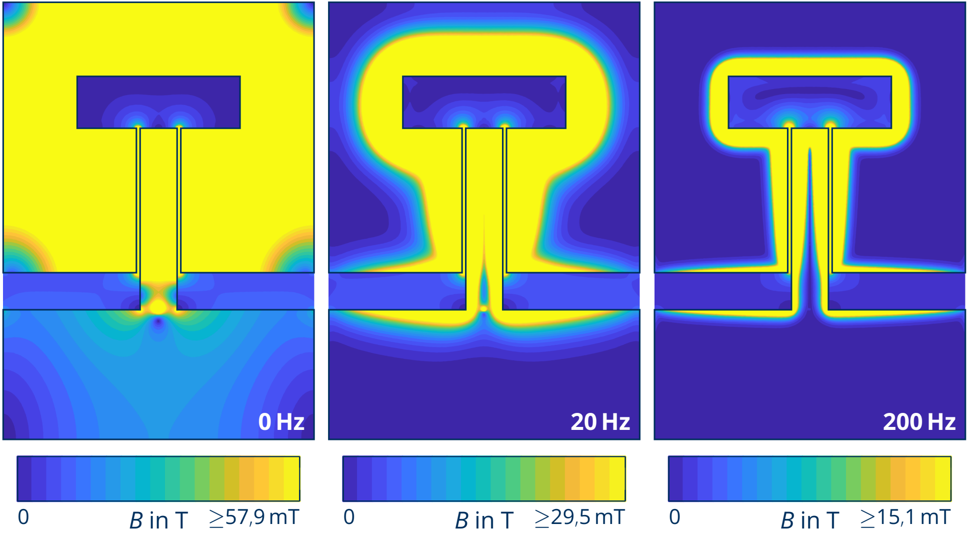
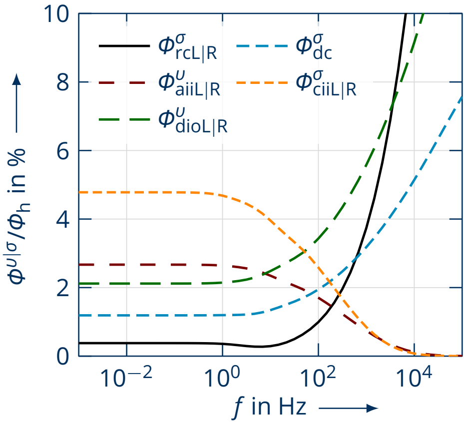


Figure: Flux density distribution in the core of the thrust bearing without permanent magnets for various frequencies, displayed flux density limit is kept constant at 1 T , displayed flux density limit is set to mean value inside air gap when exited with1 A

Frequency–dependency of leakage and fringing fluxes

Influence of the magnetic skin effect



Change of behavior above 100 Hz:

- Leakage flux swirls crossing entire coil are not negligible anymore
  - ➧ Network simplifications barely possible
  - ➧ Not usable in real–time control systems

- Leakage and fringing fluxes close to shaft disappear
- ... close to the coil they are amplified
  - ➧ Complete shift of flux distribution

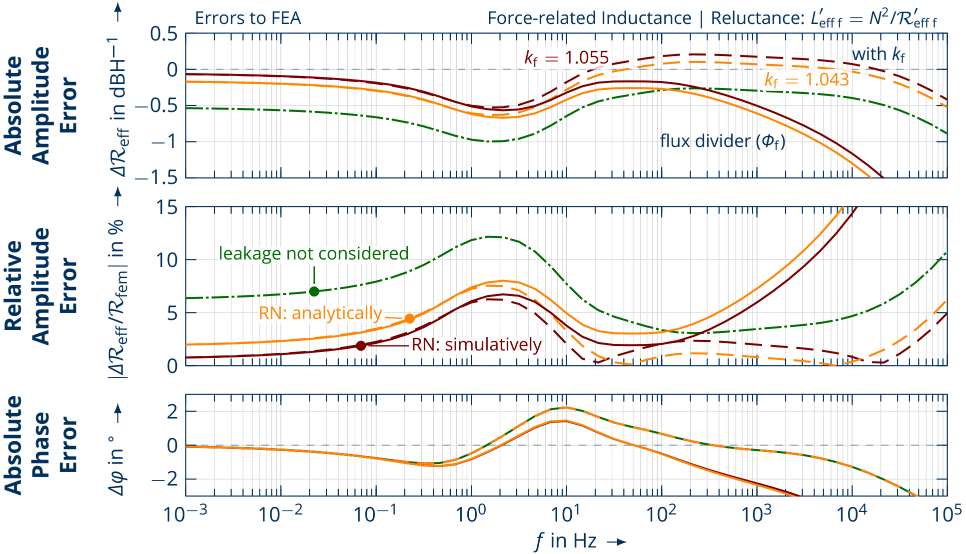
➧ Little impact on total flux Φ_{t}, as effects cancel each other out

➧ Force-related flux Φ_{f} calculated by network basically becomes meaningless

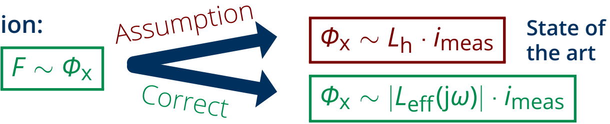
- **No known approach to consider the influence of magnetic skin effect on leakage and fringing flux distribution**

Frequency–dependency of leakage and fringing fluxes

Error of Reluctance Network (RN) to FEA



Conclusion



Motivation:

$F \sim \Phi_x$

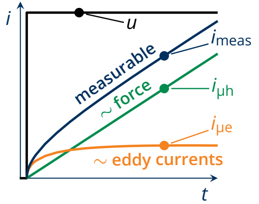
Assumption

$\Phi_x \sim L_h \cdot i_{\mathrm{meas}}$

State of the art

Correct

$\Phi_x \sim |L_{\mathrm{eff}}(j\omega)| \cdot i_{\mathrm{meas}}$



- Position Control with underlying ***flux control and fractional–order flux estimator***
- **Aim:** Improvement of estimator by including leakage and fringing fluxes
- **Siginificant Impact: 5 % on $L_{\mathrm{h\,f}}$ and 10 % on $L_{\mathrm{h\,t}}$ | $L_{\mathrm{eff\,t}}$ (Accuracy)**

measurable:

$$\underline{G}'_{\mathrm{FE}}(j\omega) = \frac{\underline{\Phi}_{\mathrm{f\,est}}(j\omega)}{\underline{i}_{\mathrm{meas}}(j\omega)} = \underbrace{\frac{L_{\mathrm{h\,f}}}{N}}_{\text{field}} \cdot \frac{\overbrace{R_{\mathrm{Cu}} + s\underline{L}_{\mathrm{eff\,t}}(j\omega)}^{\text{magnetizing current}}}{\underbrace{R_{\mathrm{Cu}} + sL_{\mathrm{h\,t}}}_{\text{magnetizing current}}}$$

force–related:

Literature suggests: Reluctance Networks (RNs), **but:**

- Although accurate for static case, only insufficient consideration of magnetic skin effect
- Challenging to calculate (analytically), inefficient to implement in real–time
- Constant correction factors with higher accuracy over entire frequency range
  - **Correction factors are simple, accurate and efficient!**
  - If FEA is available: **Reluctance Networks have no practical benefits! *Are they obsolete?***

Actually, it is not that complicated...

with the *Riemann-Liouville* definition:

$$D^{\alpha} f(t) = \frac{1}{\Gamma(1-\alpha)} \frac{\mathrm{d}}{\mathrm{d}t} \int_0^t \frac{f(\tau)}{(t-\tau)^{\alpha}} \, \mathrm{d}\tau$$

one determines *the half derivation* of t^2:

$$ {}_t^0 D^{\frac{1}{2}} (t^2) = \frac{1}{\Gamma(1-\frac{1}{2})} \frac{\mathrm{d}}{\mathrm{d}t} \int_0^t \frac{\tau^2}{(t-\tau)^{\frac{1}{2}}} \, \mathrm{d}\tau = \frac{8t^{\frac{3}{2}}}{3\sqrt{\pi}}$$

Thank you for your attention!

Publications and Literature

[Ackermann1985]
[Amrhein2016]
[Bahr2016]
[Baker1996]
[Bertotti1998]
[Bleuler1984]
[Bleuler1994]
[Bañuelos2017]
[Cardelli2003]
[Cauer1954]
[Chassaing2008]
[Dastjerdi2019]
[Deschrijver2008]
[Dirscherl2017]
[Doyle1981]
[Efe2011]
[Elwakil2010]
[Ernst2020]
[Faiz2010]
[Feeley1996]
[Ferreira2017]
[Flax1966]
[Fleischer2011]
[Fleischer2013]
[Fleischer2017]
[Gähler1998]
[Ghasemi2014]
[Grünwald1867]
[Gustavsen1999]
[Gustavsen2006]
[Han2013]
[Hecht2021]
[Hemenway2021]
[Herzog2009]
[Horowitz2001]
[Hutton1975]
[Jaatinen2013]
[Jackson1970]
[Jackson1989]
[Jalloul2013]
[Keith1993]
[Kessler1955]
[Kessler1958]
[Köhring2010]
[Krasnoselskii1983]
[Krishna2011]
[Kucera1996]
[Lammeraner1966]
[Langholz1978]
[Larsonneur1988]
[Le2016]
[León2014]
[Levy1959]
[Liebfried2018]
[Liebfried2021]
[Lino2017]
[Luo2009]
[Lutz2014]
[Maione2006]
[Maione2013]
[Maslen2017]
[Matignon1996]
[Matsuda1993]
[Mayergoyz1985]
[McLachlan1955]
[Meeker1996]
[Milovanovic2015]
[Mönch2015]
[Monje2010]
[Moon1961]
[Müller2006]
[Noda2005]
[Nonami1994]
[Nonami1996]
[Novak2018]
[Oldham1974]
[Onyedi2020]
[Oustaloup1983]
[Oustaloup1995b]
[Oustaloup1995a]
[Oustaloup2000a]
[Oustaloup2000a]
[Oustaloup2000b]
[Paszek1979]
[Pecat2014]
[Petràš2009]
[Podlubny1999]
[Preisach1935]
[Rabinovici1992]
[Radwan2009]
[Retière1999]
[Ribbenfjard2008]
[Riemann1876]
[Riu2003]
[Rodriguez2007]
[Roters1941]
[Roy1967]
[Rudolph2019]
[Rüdenberg1953]
[Sabatier2012]
[Sanathanan1963]
[Schröder2009]
[Schuhmann2006]
[Schuhmann2011]
[Schweitzer1993]
[Schweitzer2009]
[Schweitzer2011]
[Schwenk2012]
[Scott1994]
[Seifert2015]
[Seifert2016]
[Seifert2017b]
[Seifert2017a]
[Seifert2019a]
[Seifert2019b]
[Seifert2019c]
[Seifert2021b]
[Seifert2021a]
[Shirriff2016]
[Smith1996]
[Spece2018]
[Stiebler2005]
[Stoll1974]
[Sun2009]
[Svaricek2016]
[Swann2009]
[Tepljakov2011]
[Tepljakov2014]
[Tepljakov2018]
[Tepljakov2019]
[Tepljakov2021]
[Välimäki2016]
[Vinagre2000]
[Vinagre2003]
[Vischer1988]
[Weiner2018]
[Weniger1990]
[Whitlow2014]
[Whitlow2016]
[Whitlow2018]
[Wiedemann1967]
[Wong2008]
[Yi1995]
[Zhong2013]
[Zhong2014]
[Zhong2015]
[Zhou2016]
[Zhu2004b]
[Zhu2004a]
[Zhu2005b]
[Zhu2005a]
[Zhu2010]
[Zingerli2010]
[Zlatnik1990]
[Zmood1987]

List of Slides